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“The goal of a scientist is to uncover new ideas, concepts and tools, practical or theoretical, that extend our understanding of the world around us and enable us to do new things. One must believe in what one is doing and stay the course. Now of course, in science one can ultimately prove the correctness of one’s work by appeal to experiment and established theory. But even with this buttressing of one’s ideas, acceptance can be a long and difficult road.”

Richard F.W. Bader (1931 – 2012)
Grand Fellow of the MIRCE Akademy

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MIRCE Science

According to Knezevic [1] the purpose of existence of any functionable system¹ is to do functionability work, which is considered to be done when the expected measurable function is performed through time, like miles travelled, units produced, energy supplied and similar. However, experience teaches us that in-service life of functionable systems is frequently beset by undesirable negative functionability events, resulting from a variety of negative functionability actions (overstress, wear out, natural events, and human interventions). For the work to be continued, positive functionability actions, (servicing, repairing, testing, replacing, changing the mode of operation and similar) must be performed on the system. Thus, the complex interactions between positive and negative functionability actions govern the functionability performance of functionable systems, primarily measured through work done and resources consumed expressed through monetary values (functionability cost).

Regrettably the functionability performance becomes known only at the end of the life of functionable system², when nothing could be done to influence it. Hence, the ability to accurately and quantitatively predict functionability performance of the future functionable systems at the design stages, when all possible changes could be done, would be invaluable for all project: engineers, planners, managers and strategist. The mixture of technical systems and management methods chosen to govern the behaviour of functionability systems through time uniquely determine the expected: functionability work, cost and the expected return on the investment (profit, public benefit, reputation and so forth).

Five decades of research conducted by Knezevic [1] have generated a theoretical body of knowledge, named MIRCE Science, which comprises of axioms, system of formulas and methods that enable predictions of functionability performance of the future functionable systems to be done, by the modelling complex interactions between: physical properties of consisting components, operational rules, maintenance policies, support strategies and expected environmental conditions.

MIRCE Science is based on the scientific understanding of the mechanisms that generates the occurrences of functionability events, considered within a physical scale between 10^{-10} m (atomic scale) and 10^{10} m (solar system scale). [1] These mechanisms, together with the applied human rules, shape the expected pattern of the motion of a functionable system through MIRCE Space³. The “normalised” life-long pattern expected to be generated by each feasible type of functionable system is predictable, from the early stages of the design, by making use of the MIRCE Functionability Equation, which is the bedrock for the calculation of the expected functionability performance.

Reference: [1] Knezevic, J., The Origin of MIRCE Science, pp. 232, MIRCE Science, Exeter, UK, 2017, ISBN 978-1-904848-06-6

¹ Functionable system is a well defined collection of atomic, natural and human elements put together to do functionable work.[1]

² Pan Am's Boeing 747, registration number N747PA, during the 22 years of in-service life, has delivered 80,000 hours of positive work (transported 4,000,000 passengers, burned 271,000,000 gallons of fuel) while receiving 806,000 man-hours of maintenance work (consuming: 2,100 tyres, 350 brake systems, 125 engines, among other parts.

³ MIRCE Space: a conceptual 3-dimensional space containing MIRCE Functionability Field, which is an infinite but countable set of all possible functionability states that a functionable system could be found in, and the probability of being in that state at each instance of calendar time. [1]

Minimum Equipment List as a Mechanism of Motion in MIRCE Mechanics

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Abstract

To avoid the loss of consumer trust, revenue or capability any disruption to a system's functionality is unacceptable to the providers, on one hand and also to their receivers, on the other. Consequently, every effort must be made to ensure the continuity of the provision of the system's functionality through calendar time. One of the methods used to minimise disruption to operational capability, especially in the aviation industry, was the creation of the Minimum Equipment List (MEL). This list identifies the equipment/components present into system that are not necessary to be operational for the safe provision of the functionality of the system, in accordance with the prescribed operational and maintenance restrictions, and approved by the regulatory authorities. Consequently, the main objective of this paper is to present the concept of the MEL as one of the potential mechanism to be used outside aviation community to further influence the motion of a functionable system type through MIRCE Space and potentially enhance its functionability performance as perceived by MIRCE Science.

1. Introduction

“Motion does not mean travel of the ball-type electron along some orbit around the nucleus. Motion is the change in the state of the system “atom” in time.”
Werner Heisenberg

To facilitate the flow of functionality through calendar time provided by the functionable system types MIRCE Science is focused on the scientific understanding and description of the physical phenomena and human rules that govern their in-service behaviour. According to Knezevic [1], functionable system type is “a set of mutually related components uniquely put together to perform at least one measurable function and a set of functionability rules that govern its functionability performance.”

In MIRCE Science, at any instant of calendar time a given functionable system type could be in one of the following two states:

- Positive Functionability State (PFS), a generic name for a state in which a functionable system type is able to deliver the expected measurable function(s),

- Negative Functionability State (NFS), a generic name for a state in which a functionable system type is unable to deliver the expected measurable function(s), resulting from any reason whatsoever.

The motion of a functionable system type through the functionability states, in the direction of calendar time, is generated by functionability actions, which are classified as:

- Positive Functionability Action (PFA), a generic name for any natural process or human activity that compels a system to move to a PFS.
- Negative Functionability Action (NFA), a generic name for any natural process or human activity that compels a system to move to a NFS.

The motion of a functionable system type through the functionability states is manifested through the occurrences of functionability events, which are classified as:

- Positive Functionability Event (PFE), a generic name for any physically observable occurrence in time that signifies the transition of a functionable system type from a NFS to a PFS.
- Negative Functionability Event (NFE), a generic name for any physically observable occurrence in time that signifies the transition of a functionable system type from a PFS to a NFS.

Transition of a functionable system type from PFS to NFS and loss of functionality is undesirable in private sector due to loss of revenue and to public sector due to loss of benefits. For example, in airline business loss of service is unacceptable due to negative consequences of the following types:[2]:

- Loss of income generated by transporting passengers and cargo
- Poor customer relationships
- Increased demand for support resources (spares, tools, equipment, etc.)
- Increased numbers of maintenance facilities, including skills and training of personnel required to deal with the consequences of cancellations.
- Costs arising from re-routes, aircraft substitution, passenger handling (hotels, buses, meal vouchers)

Cancelled flights generate the cost to the customer too, due to disrupted plans, missed business appointments, lost time and potential consequences to the cargo due to late shipments.

Generally speaking, all affords must be made to enable passengers and cargo to go to their destinations on time, in safe manner. Legendary Chief Mechanic on Boeing 777, Jack Hessburg, has immortalised this sentiment by saying, “All I want to do is to go to Cleveland on time and never crash.” [1]

Consequently, the main objective of this paper is to present the concept of the MEL as one of the potential mechanism to be used outside aviation community to further

influence the motion of a functionable system type through MIRCE Space⁴ and potentially enhance its functionability performance as perceived by MIRCE Science.[1]

2. Minimum Equipment List in Commercial Aviation

According to Hessburg, [2] the structure and approval of the early Minimum Equipment Lists (MEL) lists were principally in the hands of the individual CAA Air Carrier Inspectors. Technical evaluation of items for inclusion into a list was based upon the individual inspector's knowledge, competence, and subjective analysis of a specific aircraft type. The result was that the MEL for operator "A" and that operator "B" (both using the same model aircraft) were frequently different; one airline's inspector being very conservative and disallowing all but the simplest of equipment to be inoperative, the other being far more liberal. Individual operators would claim favoritism when one discovered that their competitor had a less restrictive MEL.

This lack of objective analysis and standardisation of MEL resulted in the institutionalisation of the process by the mid-1960s. The FAA adopted centralised control and publication of separate Master Minimum Equipment Lists (MMEL) for each large aircraft type.

Present regulations continue to recognise the original MEL concept. FARs 125, and 135 operators were included in the concept by the late 1970s. In 1991, single engine operations under FAR 135 were added to the concept. Lastly, FAR Part 91 operations are also now covered [3].

It is necessary to stress that nothing in this concept disallows the authority of the pilot-in-command. The pilot may, at his or her discretion, require that any item covered by the MEL be repaired before flight.

Operations with certain items of equipment inoperative are not considered an abrogation of the aircraft Type Certificate. When operating under Parts 121, 125 or 135, an approved Minimum Equipment List is recognised as an approved change to the type design. Therefore, the altered status of the aircraft under the MEL remains an acceptable certified configuration. Consequently, adoption of an MEL item does not require re-certification of the type design [3].

Operating with an approved MEL and a letter of authorisation under FAR Part 91 constitutes a Supplemental Type Certificate for the aircraft. As such, an MEL approved under Part 91 is issued against a specific aircraft(s) i.e. aircraft serials number(s). The aircraft(s) will be listed on the cover sheet of the approved MEL.

Is necessary to stress a mechanic or inspector is not in violation of the FAR for releasing an aircraft as airworthy when certain items are inoperative under an

^{4 4} In MIRCE Science, there are a countable infinite number of discrete functionability states that a functionable system type could be observed in, each representing a functionability state. This set of possible outcomes is the Functionability Sample Space (FSS_s). As each functionable system type has its own operational life, its functionability state within the FSS_s will change with time. Combining the calendar time dimension with the FSS_s forms the MIRCE Functionability Field (MFF_s). The probability that a functionable system type will be observed in a particular functionability state along calendar time constitutes the MIRCE Space, in MIRCE Science [1]

approved MEL. Because an air carrier airworthiness release requires certification that the work performed is in accordance with the certificate holder's manual. Because an approved MEL is a part of the certificate holder's manual, a mechanic is relieved of responsibility for the inoperative status of MEL items. The actions taken under the requirements of an approved MEL would "clear" the discrepancy from the aircraft maintenance record and would consequently revalidate the maintenance release.

A mechanic is not responsible for any contingent maintenance required by the MEL for any previously deferred items unless additional or repetitive maintenance is required. An aircraft maintained under FAR Part 91 is returned to service under the provisions of FAR 43.5 and is unaffected by this dilemma as an approved MEL under Part 91 is considered a supplemental type certificate.

3. Creation of the Master Minimum Equipment List

During the initial design of an aircraft the development of Master Minimum Equipment List, MMEL, begins. For new designs, the manufacturer submits a preliminary list of items to be considered by the relevant aviation authorities. Aircraft operators, interested public (safety organisations, foreign regulatory agencies, union representatives, and the like), use this list to develop the master. The final MMEL is released, after approval by designated authority.

Once adopted, an MMEL is periodically revised. These revisions arise from individual operators petitioning the relevant authorities for additions, deletions, or clarification of items. These changes continue throughout the useful life of the aircraft type. There is no set schedule for the revisions; they take place on an as needed basis. Early in an aircraft model's life, meetings might be held yearly, whereas later in its life, the meetings can be several years apart.

4. MMEL is for Aircraft not Airline

The MMEL is a generic list for a given aircraft type. Thus, items are included in the master that may not be installed in a given airline's fleet. There is no system for tracking recording, crew notification and clearing of a deferred item contained in the list. The list also contains time limits on how long a given item may be deferred. It identifies requirements for placarding the cockpit. It requires which items must have maintenance and flight operations procedures or limits.

Each airline must prepare its own MEL using the master as the source. Operators are responsible for exercising the necessary control to insure that an acceptable level of safety is maintained. This includes a repair program embracing the parts, personnel, facilities, procedures, and schedules to insure timely clearance of deferred items.

An individual airline's MEL may be more restrictive but not less than the Master Minimum Equipment List. They may include, with appropriate conditions and limitations, items not contained in the master list such as equipment not required for a given flight operation; that which is more than required by the FAR; and

equipment that, for internal administrative control reasons to the operator, is best placed within the context of his MEL

5. Deferring Process under MEL

The specific process for deferring at any given airline will differ. However, once it has been determined that an item is deferrable, a decision is made to defer or fix. This normally involves, at the minimum, station maintenance personnel and the pilot-in-command. However, in many instances, flight dispatch, maintenance engineering and a quality control organisation will be party to the decision. Some airlines designate in the body of their MEL, specific individuals or organisations with deferral authority for each item listed.

Station maintenance personnel have several responsibilities that include properly securing the deferred item, logging item correctly in required documents, notifying specific individuals and organisations to ensure that the necessary bookkeeping will take place, thus insuring that the item is properly tracked and scheduled for later repair within allowable time limits.

Dispatch and/or the pilot-in command shall, as appropriate observe any special limitations or modified operating procedures attendant to the deferred item and notify other operations organisations and down line stations that are affected by the deferral.

Maintenance control or other appropriate organisation charged with tracking deferred items and scheduling will take appropriate action to clear the item from the deferred log within the allowed time for deferral.

6. An Example of Minimum Equipment List

To illustrate the concept and a practical application of MEL the vacuum pump of Piper Seminole PA-44-180 is addressed, for no particular reason. It is a four seat light twin aircraft, which has been in-service since 1978. it is at twin engine development of PA-28 Archer aircraft with new T-tail and semi-tapered wings. Production ceased in 1981, restarted in 1988 and ceased once more in 1990.

Main technical and functionality characteristics of this aircraft are as following:

- Powerplants: Two 135kW (180hp) Lycoming O-360-E1AD flat four piston engines driving two or optionally three blade constant speed Hartzell propellers.
- Performance: Max speed 311km/h (168kt), max cruising speed 309km/h (167kt), long range cruising speed 280km/h (151kt). Initial rate of climb 1200ft/min. Service ceiling 17,100ft. Range with reserves 1630km (880nm). Weights: Empty 1070kg (2360lb), max takeoff 1723kg (3800lb).
- Dimensions: Wing span 11.77m (38ft 8in), length 8.41m (27ft 7in), height 2.59m (8ft 6in). Wing area 17.1m² (183.8sq ft).

- Production: Total Seminole production through to end 2004 amounted to 672, including 86 Turbo Seminoles.

The Piper PA-44 Master Minimum Equipment List (MMEL) for Part 91 operations lists all items of installed equipment that are permitted to be inoperative. The MMEL states, in part, that “it is incumbent on the operator to endeavour to determine if Operations and/or Maintenance] procedures for that equipment must be developed.

The MMEL is intended to permit operations with inoperative items of equipment for the minimum period of time necessary until repairs can be accomplished. It is important that repairs be accomplished at the earliest opportunity in order to return the aircraft to its design level of safety and reliability. Operators are responsible for exercising the necessary operational control to ensure that an acceptable level of safety is maintained.” [4]

According to Section 37 “Vacuum/Pressure,” sequence title “1. Vacuum Pump” states “two vacuum pumps are installed and one is required for dispatch. It further provided, under the “Remarks or Exceptions,” that “One may be inoperative for day VFR⁵ flights.”

The *PA-44 Scheduled Maintenance Manual* includes a checklist to be utilised for inspections every 50 and/or 100 hr. Subsection B.36 states “Inspect and operationally test vacuum pumps and lines.” It further requires that the vacuum pump installed on each engine is inspected every 100 hr. Note 7 further states “Replace or overhaul, as required, or at engine overhaul.”

The *Pilot’s Operating Handbook* states in Section 7.19, “The vacuum system operates the air-driven gyro instruments. The vacuum system consists of a vacuum pump on each engine, plus plumbing and regulating equipment. . . A shear drive protects the engine from damage. If the drive shears, the gyros will become inoperative. The vacuum gauge mounted on the right instrument panel to the right of the radios provides valuable information to the pilot about the operation of the vacuum system (a low vacuum indicator light is provided in the annunciator panel).. In the event of any gauge variation from the norm, the pilot should have a mechanic check the system to prevent possible damage to the system components or eventual failure of the system .A vacuum regulator is provided in the system to protect the gyros. The valve is set so the normal vacuum reads 4.8 to 5.2 in. of mercury. . .” [4]

Should suction drop below 4.5 in. Hg, pilots are cautioned to increase rpm to 2,700, descend to maintain 4.5 in. and use the electric turn indicator to monitor directional indicator and attitude indicator performance.

⁵ *Visual flight* rules (VFR) are a set of regulations under which a pilot operates an aircraft in weather conditions generally clear enough to allow the pilot to see where the aircraft is going. Specifically, the weather must be better than basic VFR weather minima, i.e. in visual meteorological conditions (VMC), as specified in the rules of the relevant aviation authority. The pilot must be able to operate the aircraft with visual reference to the ground, and by visually avoiding obstructions and other aircraft.

7. Impact of Minimum Equipment List on Functionability Performance

“We did not buy the airplane to make a roost for pigeons on the vertical fin, fouling the logo. So equipment availability is a fundamental tenant which we forget about.” Bob Six, CEO Continental Airlines⁶

According to the philosophy of MIRCE Science the main objective of existence of any functional system is to do a work during the calendar time. [1] To differentiate the concept of work in physics and in MIRCE Science, the author has named the latter as a functionability work. Hence, functionability work is considered done when a system delivers a measurable function over an interval of time, in a similar way that classical physics considers work done when an external force displaces an object over a distance.

Consequently, in MIRCE Science functionability work is classified as [1]:

- Positive Functionability Work (PFW): a generic name for the physically measurable performance of a functionable system type proportional to the duration of the calendar time during which the expected function(s) are performed, measured in hours [Hr],
- Negative Functionability Work (NFW): a generic name for the physically measurable performance of a functionable system type proportional to the duration of the calendar time during which required positive functionability actions are performed, measured in hours [Hr].

Although the concept of functionability work is the main measure of functionability performance, it is necessary to take into account the physical resources related to the execution of functionability works, like material, personnel, spares, tools, equipment, facilities, energy and similar must be taken into account. As all of them have individual monetary values, in MIRCE Science, they are brought together under the single umbrella of functionability cost, and it is classified into following two types [1]:

- Cost of Positive Work (CPW): a generic name for the physically measurable performance of a functionable system type determined by the monetary value of all the resources related to the delivery of positive functionability work, like operational personnel, consumable material, equipment, facilities, energy and similar. Generally speaking, it encompasses all the costs related to delivery of the positive functionability work by the functionable system type during a given interval of calendar time T , denoted as $CPW(T)$. It is equal to the sum of the following cost elements: [1]:

$$CPW_s(T) = CPW_{set} + CPW_{fix}(T) + CPW_{var}(T) \quad [MU]$$

where: CPW_{set} is the Set Up Cost, $CPW_{fix}(T)$ is the Fixed Cost and CPW_{var} is the Variable Cost of delivering positive work.

⁶ Robert Six (1907-1986), Founder and CEO of Continental Airlines (1936-1986), Quote from Jack Hessburg's Lecture at M.I.R.C.E. Centre on 27th January 1998, at Exeter University.

- Cost of Negative Work (CNW): a generic name for the physically measurable performance of a functionable system type determined by the monetary value of all the resources used by a functionable system type to perform the negative functionability work, like spare parts, qualified personnel, material, equipment, facilities, energy and similar. Thus, it encompassed all the costs related to performing the negative functionability work, performed on the functionable system type during a given interval of calendar time T , denoted as $CNW(T)$, is equal to the following sum [1]:

$$CNW_S(T) = CNW_{set} + CNW_{fix}(T) + CNW_{var}(T) \quad [MU]$$

where: CPW_{set} is the Set Up Cost, $CPW_{fix}(T)$ is the Fixed Cost and CPW_{var} is the Variable Cost of delivering positive work.

The delivery of positive and negative functionability work through time uniquely determines the positive and negative functionability costs that correspond to the motion of a functionable system type through the functionability states. As this motion is in the direction of calendar time, it means that the magnitudes of the positive and negative functionability costs are non-decreasing measurable characteristics of the functionable system types, and as such they are “legitimate” measures of their overall functionability performance.[1]

8. Cost of Lost Revenue

The main business of any business is staying in business. For that to happen it is essential to generate a profit, which is commonly accepted as the difference between the revenue generated and the costs incurred to generate the revenue. Generally speaking, the revenue generated by each functionable system type during a given interval of calendar time, denoted as $REV(T)$, could be calculated as the product of the hourly income, denoted as HI , expressed in [MU/Hr] and the amount of the positive functionability work done by the system during the stated interval of calendar time, $PFW(T)$ expressed in [Hr], thus [1]:

$$REV(T) = HI \times PFW_S(T) \quad [MU] \quad 3$$

Financially minded analysts totally ignore the non-generated cost while the functionable system type is in the NFS during a given interval of calendar time. However, MIRCE Science this cost category has been analysed and named the Cost of Lost Revenue, $CLR(T)$ [1]. This cost category could be even higher than that of revenue generated due to the potential consequences of the occurrences of NFEs to the business and environment⁷.

⁷ One of the examples that immediately come to mind is the Deep Water Horizon accident, when British Petroleum was found by the court to have been “grossly negligent” in the offshore rig explosion that killed 11 workers and caused a 134 million gallon crude oil spillage. As a consequence, British Petroleum was forced to pay over 20 billion dollars in settlement to cover the environmental damage and other claims by the five Gulf States and local governments. Of course, it was on the top of the cost of resources used by them to recover from the disaster.

In MIRCE Science a profit, $PRF(T)$, is equal to the difference between the revenue, $REV(T)$ and the Total Functionability Cost, during the stated period of calendar time, $TFC(T)$, thus [1]:

$$\begin{aligned} PRF(t) &= REV_s(T) - TFC_s(T) \\ &= [HI_s \times PFW_s(T)] - [CPW_s(T) + CNW_s(T) + CLR(T)] \quad [MU] \end{aligned} \quad 4$$

The MIRCE Profitability Equation is the only one, known to the author, which unifies all aspects of the functionability performance of a functionable system type including the cost of lost revenue, which, in reality, is an in-separable element of the expected profit. This equation enables more accurate predictions of the expected profit to be made for each operational scenario, maintenance policy and support strategy, including the “length of MEL”. Also, this equation “integrates” the decision makers of functional systems types and the decision makers of corresponding functionable system types into a single “normalised” analytical entity, rather than, as currently considered, two competing parties searching self set targets in isolation.

9. Conclusions

To avoid the loss of consumer trust, revenue or capability any disruption to a system’s functionality is unacceptable to the providers, on one hand and also to their receivers, on the other. Consequently, every effort must be made to ensure the continuity of the provision of the system’s functionality through calendar time. One of the methods used to minimise disruption to operational capability, especially in the aviation industry, was the creation of the Minimum Equipment List (MEL).

A minimum equipment list (MEL) is a list that provides for the operation of aircraft, subject to specified conditions, with particular equipment inoperative (which is) prepared by an operator in conformity with, or more restrictive than, the Master Minimum Equipment List, established for the aircraft type. (ICAO Annex 6: Operation of Aircraft)

The MMEL is a list established for a particular functionable system type by the organisation responsible for the type design with the approval of the State of Design which identifies items which individually may be unserviceable at the commencement of a flight. The MMEL may be associated with special operating conditions and rules.

The impact of introducing the MEL for any aircraft type could be quantified through the functionability performance measures, namely functionability work and functionability cost, positive and negative, which are fully defined by the functionability equations of MIRCE Science.

In summary, this paper has shown that the MEL as one of the potential mechanisms to influence the motion of a functionable system type through MIRCE Space and as such it can enhance its functionability performance as understood through the application of MIRCE Science [1].

10. References:

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Post-Maintenance Flight Test as a Mechanism of Motion in MIRCE Mechanics

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Abstract

MIRCE Mechanics is a part of MIRCE Science that focuses on the scientific understanding and description of the physical phenomena and human rules that govern the motion of functionable system types through MIRCE Space [1]. A full understanding of the mechanisms that influence this motion through MIRCE Space is essential for accurately predicting the functionability performance of functionable system types using MIRCE Science. According to the 5th axiom of MIRCE Science, the probability that a completed maintenance task introduces faults or errors is greater than zero. To reduce the probability of introducing undetected maintenance errors and their consequential impact on the system operational process, the concept of the Post-Maintenance Flight Tests (PMFT) is used in aviation industry. Consequently, the main objective of this paper is to critically assess these types of maintenance verification tests and their impact efficacy on the functionability performance, as understood through the application of MIRCE Science. The physical reality of inducing errors during maintenance and their consequences on post-maintenance flight is illustrated using an incident that regrettably took the lives of two pilots, when their Piper PA 46-350P, N962DA, crashed into the Spokane River on May 7, 2015, following an attempted landing at Felts Field Airport in Spokane, Washington, USA

1. Introduction

“Motion does not mean travel of the ball-type electron along some orbit around the nucleus. Motion is the change in the state of the system “atom” in time.” Werner Heisenberg

MIRCE Mechanics is a part of MIRCE Science that focuses on the scientific understanding and description of the physical phenomena and human rules that govern the motion of functionable system types through MIRCE Space [1]. A full understanding of the mechanisms that influence this motion through MIRCE Space is essential for accurately predicting the functionability performance of functionable system types using MIRCE Science.

According to MIRCE Science, at any instant of calendar time, a given functionable system type⁸ could be in one of the following two states:

- Positive Functionability State (PFS), a generic name for a state in which a functionable system type is able to deliver the expected measurable function(s),
- Negative Functionability State (NFS), a generic name for a state in which a functionable system type is unable to deliver the expected measurable function(s), resulting from any reason whatsoever.

The motion of a functionable system type through the functionability states, in the direction of calendar time, is generated by functionability actions, which are classified as:

- Positive Functionability Action (PFA), a generic name for any natural process or human activity that compels a system to move to a PFS.
- Negative Functionability Action (NFA), a generic name for any natural process or human activity that compels a system to move to a NFS.

The motion of a functionable system type through the functionability states is manifested through the occurrences of functionability events, which are classified as:

- Positive Functionability Event (PFE), a generic name for any physically observable occurrence in time that signifies the transition of a functionable system type from a NFS to a PFS.
- Negative Functionability Event (NFE), a generic name for any physically observable occurrence in time that signifies the transition of a functionable system type from a PFS to a NFS.

At the MIRCE Academy a large number of positive functionability actions have been analysed, including maintenance tasks like: overhauls, tests, inspections, visual checks, scheduled maintenance tasks, repairs, replacements, examinations and many others, in order to understand the mechanisms driving the motion of functionable system types out of their negative functionability states. Based on the information available, Knezevic [2] concluded that, from the point of view of the quality of execution, each physically observable maintenance task could be categorised as:

- Successful Maintenance Task (SMT), where all maintenance activities have been completed successfully in the first attempt.
- Faulty Maintenance Task (FMT), where all maintenance activities have not been completed successfully in the first attempt.

⁸According to Knezevic [1], functionable system type is “a set of mutually related components uniquely put together to perform at least one measurable function and a set of functionability rules that govern its functionability performance.”

By studying numerous maintenance processes regarding the execution of maintenance tasks, in respect to the possibility of detecting maintenance faults and errors, made during the maintenance process, the author grouped them into following two categories: [2]

- Detectable Faulty Maintenance Tasks (FMT_D), are those where the faulty activities could be detected during the execution of consisting activities or at the end of the task and corrective action taken.
- Non-Detectable Faulty Maintenance Tasks (FMT_{ND}) where faults and errors induced during the maintenance process are not detected during the execution of the constituent activities or at the end of the task and are left for the operational process to detect the maintenance faults and suffer their consequences.

In accordance to the 5th axiom of MIRCE Science [1] each maintenance task completed has a certain probability of belonging to the FMT_{ND} category. To reduce the probability of existence of undetected maintenance errors and their consequences on the system operational process, the concept of the Post-Maintenance Flight Tests⁹ (PMFT) is used in aviation industry. Consequently, the main objective of this paper is to analyse this type of maintenance tasks and their impact on the motion of functionable system types through MIRCE Space and their consequential impact on the functionability performance, as perceived by MIRCE Science. The physical reality of inducing errors while performing maintenance tasks and their consequences on post-maintenance flight is illustrated using an incident that took the lives of two pilots, when the Piper PA 46-350P, N962DA, crashed into the Spokane River on May 7, 2015, following an attempted landing at Felts Field Airport in Spokane, Washington, USA.

2. Post-Maintenance Flight Test

The objective of this task is to fly the aircraft using normal operating procedures to validate the functionality of the aircraft under test, after completion of the maintenance tasks or manufacturing process. The test is performed in accordance with a defined test plan, with pilots ready to react if a contingency occurs, so that they can get the airplane back on the ground and address the cause of the contingency.

The functional check flight should be carefully planned with an emphasis on risk management before the aircraft leaves the ground. This must include consultations with maintenance staff and, in some cases, representatives of the aircraft's manufacturer, as well as piloting currency, insurance coverage, crew coordination and other Federal Aviation Authority (FAA) regulations, to name a few. For example, FAR 91.305 regulation states flight-testing must be conducted over open water, or sparsely populated areas having light air traffic.

⁹ Post-maintenance flight in the aviation industry is an accepted nomenclature for an assessment of the functionality of a functionable system at the end of the maintenance tasks. It is also known as a "functional check flight," or FCF. These types of flights also apply to production testing of new aircraft as they "roll off" the assembly line.

Post-maintenance test flying can be risky. Even relatively simple owner-performed maintenance chores, like oil changes or brake-pad replacement, have been known to create airborne drama. Whenever an aircraft comes out of maintenance, some sort of test flight should be conducted with the intention of verifying the work performed. In fact and perhaps unsurprisingly, the FAA has a regulation covering post-maintenance test flights, FAR 91.407. Its applicability to a specific situation hinges on the extent to which, if any, work on the aircraft "appreciably changed its flight characteristics or substantially affected its operation." That's a fairly broad definition, and one an owner or operator should think about whenever some maintenance is planned.

3. Is Post Maintenance Flight Testing Necessary?

Numerous accidents in all types of functionable systems have been maintenance related. It means that as result of an inherent fault or an error that took place during the execution of the maintenance task, functionable systems have experienced transition to a NFS, while in-service. Types, scale and frequencies of the maintenance induced failures and their consequences in commercial aviation can be found in literature. The collection of maintenance error related events, briefly described below, are taken from the report published on 12 August 2002 by the National Transportation Safety Board of the USA, and Civil Aviation Authorities of the UK, thus:

- May 25, 2002. **China Airlines** B747-200. Structural failure at the top of a climb to cruise altitude resulted in a crash into Taiwan Strait; due to the repair of previous tail strike, when steel doubler that are prohibited by structural repair manual., were used. Toll: 225 killed.
- April 26, 2001. **Emery Worldwide Airlines** DC-8-71F. Left main landing gear would not extend for landing. Cause was failure of maintenance to install the correct hydraulic landing gear extension component and the failure of inspection to comply with post-maintenance test procedures. No injuries.
- March 20, 2001. **Lufthansa** A320. Cross-connected pins reversed the polarity of captain's side stick. Post-maintenance functional checks failed to detect the crossed connection. Aircraft ended up in 21° left bank, almost hitting the ground. Co-pilot switched his side-stick to priority and recovered the aircraft. No injuries.
- Feb. 16, 2000. **Emery Worldwide Airlines** DC-8-71F. Crashed attempting to return to Rancho Cordova, California. Cause was improperly installed right elevator control. Toll: 3 crew killed.
- Jan. 31, 2000. **Alaska Airlines** MD-83. Crashed in Pacific Ocean near Port Hueneme due to loss of horizontal stabiliser caused by the maintainer failure to lubricate jackscrew assembly that controls pitch trim. Toll: all 88 aboard killed.

- Jan 21, 1998. **Continental Express** ATR-42. Fire in right engine during landing, due to improper overhaul of lugholes in the fuel/oil heat exchanger. No serious injuries.
- March 18, 1997. **Continental Airlines** DC-9-32. Failure of maintenance personnel to perform a proper inspection of the combustion chamber outer case, allowing a detectable crack to grow to a length at which the case ruptured, causing uncontained failure of right engine. No injuries.
- Nov. 1996. A320 (operator unknown). Both fan cowl doors detached from No.1 engine during rotation. Doors had been closed but not latched during maintenance. According to AAIB, “Similar incidents have occurred on at least seven other occasions.”
- July 17, 1996. **TWA Flight 800**, B747. Fuel/air explosion due to inadequate maintenance on an aging fleet and noncompliant parts. Toll: all 230 passengers and crew killed.
- July 6, 1996. **Delta Air Lines** MD-88. Uncontained engine failure on takeoff due to inadequate parts cleaning, drying, processing and handling. Toll: 2 passengers killed, 2 passengers seriously injured.
- June 8, 1995. **ValuJet Airlines** DC-9-32. Maintenance technicians failed to perform a proper inspection of the 7th stage high compression disk, allowing a detectable crack to grow to a length at which it ruptured. Toll: 1 crew seriously injured.
- Feb. 1995. **British Midland** B737-400. Oil pressure lost on both engines. Covers had not been replaced from borescope inspection the previous night, resulting in loss of almost all oil from both engines during flight. Diverted and landed safely. No injuries.
- March 1, 1994. **Northwest Airlines** B747. Narita, lower forward engine cowling dragged along runway. During maintenance, the No. 1 pylon diagonal brace primary retainer had been removed but not reinstalled. No injuries.
- Aug. 1993. **Excalibur Airways** A320. Un-commanded roll in first flight after flap change. Returned to land safely at Gatwick. Lack of adequate briefing on status of spoilers (in maintenance mode) during shift change. Locked spoiler not detected during standard pilot functional checks. No injuries
- Sept. 11, 1991. **Continental Express Airlines**, EMB-120. Horizontal stabilizer separated from fuselage during flight because maintenance personnel failed to install 47 screw fasteners. Toll: all 14 passengers and crew killed.

- Aug. 21, 1990. **United Airlines** B737. Flashlight left by maintenance, sandwiched between cargo floor and landing gear retract/extend linkage, causing the crew to make a gear up landing. No injuries.
- July 22, 1990. **USAir** B737. Fuel pump control failure due to improper machining. No injuries.
- June 1990. **British Airways** BAC1-11. Captain sucked halfway out of windscreen, which blew out under effects of cabin pressure, as 84 of 90 securing bolts were smaller than the specified diameter. Toll: 1 serious injury.
- Aug. 12, 1985. **Japan Air Lines** B-747SR. Improper repair of aft pressure bulkhead led to sudden decompression in flight that damaged hydraulic systems and vertical fin. Aircraft struck Mt. Ogura. Toll: 520 passengers and crew killed; 4 surviving passengers injured.
- May 25, 1979. **American Airlines**, DC-10. Separation of No.1 engine and pylon assembly on takeoff at Chicago's O'Hare. Toll: all 298 passengers and crew plus 2 killed and 2 seriously injured on the ground.

Based on the examples presented above, which only “scratching the surface” of the problems related to the faulty execution of maintenance tasks, it seems that the post maintenance flight test could be a good mechanism for detecting the faults prior returning the aircraft to scheduled service. In some extreme cases, the post maintenance flight tests might end in accidents, but the consequences of these occurrences on the environment and flying public should be significantly smaller.

The contra argument could be that each post maintenance flight test prevents the return of the aircraft to its revenue generating purpose, which could have a significant impact on the “bottom line” of the airline. Hence, a rational trade-off has to be made between the benefits of doing the test and the lost revenue sustained while conducting it.

4. Preparation for the Post Maintenance Flight Test

The process begins with a thorough understanding of the work that was done on the aircraft. According to many operators, the first question to ask is whether a functional check flight is really necessary for the maintenance that was performed. Generally speaking, most maintenance procedures on modern aircraft do not require flight checks. Maintenance departments rely on the Aircraft Maintenance Manual (AMM) for guidelines on post-maintenance flight testing, as it gives a specific direction on checking the components that have to be flight-tested. The task cards for the event will cover the specific things the flight testing shall include. For example, once a hot-section inspection has been completed, and assuming no deterioration was discovered, runs can be conducted on the ground. After major overhauls, rigorous operating cycles will be conducted in test cells by the engine manufacturer or repair station that did the work before returning powerplants to customers, necessitating only routine check flights after the engine was reinstalled and signed off.

After a major engine maintenance action is completed a static takeoff engine power check will be performed in accordance to the Airplane Flight Manual (AFM) to verify that power and temperature limits were within proper parameters. However, there are some scheduled maintenance actions that require extensive, carefully planned evaluation flights. For example the Gulfstream has an electrical load-shedding system that drops off non-essential equipment to reduce the electrical load on the airplane in an emergency. Testing this feature has to be done in the air because there are designated trip-level altitudes where certain functions will be performed by the systems, so it is impossible to do these tests on the ground. The electrical system does this only in the case of a contingency, and there are certain steps that the flight crew has to perform to make it happen.

Another test, requiring in-flight evaluation, is an Auxiliary Power Unit (APU) start at altitude. In the case of: flap maintenance, it is essential to do a flight test to electrically load the APU and check they are working properly. Although all possible checks are done on the ground, there are some things that have to be checked out in the air, For example “flap rigging” is one of them.

In addition to the AMM and AFM, other references for planning a PMFT include the Aircraft Owner’s Manual (AOM) and various customer support services offered by the original equipment manufacturer (OEM) including advice, publications and training from the OEM flight operations departments. Typically, the factory checklist is used for this purpose. In addition, a Flight Risk Assessment Tool (FRAT) sheet is used in Safety Management System (SMS) for normal as well as maintenance test flights that will be completed prior to flying.

The most generic rules for the preparation of PMFT are as follow:

Rule 1: Think how to prepare for and fly a safe PMFT. In other words, do the “homework” by; studying every source of information available in communication with the aircraft’s OEM. If there’s a choice among flight crews, obviously the best and most experienced pilots should be selected, especially those with the greatest time in the aircraft type, as they should be intimately familiar with the aircraft’s performance envelope and proclivities. Depending on the extent of the maintenance task, the test pilot will sit down with the maintenance department personnel to determine what was done on the airplane and what they expect from flying staff. A lot of times, maintenance technicians are taken on the flight, typically, one of those who performed the maintenance task. Typically, a director of maintenance (DOM) oversees all maintenance on company-operated aircraft; it is their responsibility to prepare a thorough briefing on what was done and what systems were affected. The DOM also prepares a check flight item summary with a list of what is necessary to look for and what checks that additionally have to be done together with normal flight operational checks.

Rule 2, Rely on the maintenance personnel to brief the flight crew and explain everything that was done to the aircraft and how it will be verified on the PMFT. If necessary maintainers should work with the DOM to plan the flight, keeping everyone involved with the maintenance action in the loop. Conducting post-maintenance flight checks safely requires pilots experienced in the aircraft,

intensive preparation and cross-communication with the maintenance provider, and adherence to risk management principles

Rule 3: Plan the PMFT around the maintenance that was performed on the aircraft with an emphasis on risk management and an understanding that the flight should be collaboration between the cockpit crew and maintenance staff. Prior to the flight it is necessary to thoroughly brief all personnel involved and prepare for possible emergencies. The flight should be carried out under Air Traffic Control (ATC) control with radio contact maintained at all times. The flight crew and maintenance personnel should hold a preflight briefing and cover emergency situations that may occur during the intended flight that are related, or may not be related, to the maintenance performed. If an incident or problem arises on the flight, the crew and maintenance technicians will assess and determine if the flight can be continued or a return to base is required.

Rule 4: Make sure the aircraft documentation is up to date, even before going into the airplane. It is important to spend some time reviewing the folder containing all the aircraft documents and all the paperwork to be sure that:

- there are no open write-ups,
- that everything has been signed off,
- that all the dates (maintenance, inspection and overhaul) have been complied with
- that all the squawks have been addressed and signed off,
- that the weight and balance is correct and other things that make the airplane legal to fly.

It is necessary to stress the PMFT cannot start until the airplane has been signed back into service, that it is truly airworthy. Then it is necessary to perform the exterior preflight inspection. This is rather a straight forward task, but takes time to look at everything.¹⁰ To do the job properly it is necessary to touch everything physically, use the flashlight as a pointing device as much as it is used as an illumination device, as it keeps pilots attention focused on what they are looking at, that something is what it is, and not what they are expecting it to be. This process will typically take 2 hrs or so pilots are advised not to try to “rush through it”. Finally, when the flight crew turn the airplane on, that is, strike the battery switches, to make sure that all the lights come on as they’re supposed to. It is necessary to be sure that: the APU start and stop lights come on; the enunciators function; all the lights come on, including the one showing that the enunciators are armed! Then and only then pilots are advised to go through all the function checks, to make sure everything has its proper form and function, before the aircraft is moved on. It is considered best practice to take maintenance representative on the ensuing check flight since maintainers “take as much pride in what they do as the pilots do” and in case things go wrong¹¹.

¹⁰ There is anecdotal evidence that “A crew doing a walk-around noted that the nose wheel tires had been put on backward so the rain-deflectors, or chines, were on the inside. They were doing their job correctly and caught this. It’s the same walk-around pilot do under normal circumstances but more intense, ensuring that the mechanics put the airplane back together correctly.

¹¹ “Once on a check flight, we got a bunch of warning lights,” he recalled, “and the maintenance technician recognised immediately that it was a problem with the breaker, which didn’t pop but was going bad. We returned and they fixed it.”

Rule 5: Before launching on a PMFT, work out a plan for handling contingencies that could happen as a result of the performed maintenance tasks. If something unplanned occurs on the functional check flight, the response should be clear: It is necessary to make an assessment, take corrective action if possible, decide whether to continue the flight, and if not, especially if the aircraft is at risk land as quickly as possible, in accordance with the preemptively prepared risk-management plan and the duties assigned to each crew member, including the maintenance personnel “riding along”. Whether there is a glitch to be corrected or all goes well on the PMFT and the aircraft is deemed safe and ready for reentry to service, the last task is to conduct a post-flight review of the operation. The object here is to learn from the experience, exchange information and points of view, to help avoid problems in the future.

Rule 6: Debrief after the PMFT and review the entire post-maintenance verification process. Encourage feedback from all involved, identify any faults and errors that were made, and update/correct operations manual and SMS accordingly.

In summary any functional check flight is an extraordinary event, which cannot be treated as a normal flight! Nothing should be assumed. When accelerating down the runway, as soon as the flight controls become effective, the pilots need to make sure that they get the proper response to their inputs for all three axes. Whenever someone performs a task, he or she must always perform one operation at a time (e.g. move one switch), wait, and observes the outcome. If all is OK, then they can perform the next task. It is also vitally important, as always, to work as a team.

5. An Example of Maintenance Induced Catastrophic Error

Arguably, among the most challenging and potentially hazardous flights a pilot undertakes are post-maintenance test flights. The National Transport Safety Board (NTSB) database contains dozens of incidents in which post-maintenance flights ended up tragically, often because the pre-flight chores were rushed or carelessly executed. This paper looks at an incident that took the lives of two pilots, when Piper PA 46-350P, N962DA, crashed into the Spokane River on May 7, 2015, following an attempted landing at Felts Field Airport in Spokane, Washington, USA. [4, 5, 6].

Rocket engineering company personnel had just completed several maintenance tasks including an annual inspection. The accident flight was to be a post-maintenance test flight, and was expected to take about 40 minutes. Weather conditions were good. Eleven minutes after making the initial call to ATC, the airplane began the takeoff roll. Almost immediately after takeoff, the aircraft began a climbing turn, 10 deg. to the right, as recorded by radar. After flying on that heading for about 1.5 miles, the airplane began a more aggressive turn to the right, reaching 1,000 feet. The airplane’s turn radius then tightened to about 700 feet, and within 45 seconds it completed almost two spiralling turns, while descending about 700 feet. Control tower personnel later told investigators that during this period the airplane was banking about 90 degrees to the right and descending, and they assumed that it was about to crash. However, moments later the bank angle began to reduce, and the airplane appeared to recover. The airplane then began a

meandering climb to the east, and about 2.5 minutes later the pilot reported, “We are trying to get under control here, be back with you.”

The Piper eventually over flew the town of Newman Lake, about 11 miles east of the airport, having climbed to about 5,600 feet mean sea level (MSL) and the pilot reported, “Things seem to be stabilizing.” When asked his intentions by the tower controller he replied, “We are going to stay out here for a little while and play with things a little bit, and see if we can get back.” Then the airplane began a gradual left turn, and the pilot requested and was approved for a straight in landing for Runway 22R. The airplane became aligned with the runway about 7 miles east of the airport, and a short time later the controller asked the pilot the nature of the emergency, to which he responded, “We have a control emergency there, a hard right aileron.” The flight progressed, and a few minutes later the pilot reported that the airplane was on a 3-mile final. The Piper remained closely aligned with the runway centreline throughout the remaining descent, and control tower personnel observed that it appeared to be flying in a 20 deg, right-wing-low attitude as it neared the runway threshold. A tower controller later reported that as the still airborne airplane passed Taxiway D, the engine sound changed, as if the pilot was attempting to perform a go-around. Suddenly, the airplane began a sharp roll to the right and crashed into the river just north of the airport.

Rescue operations, which started immediately, quickly turned into recovery operations. The river was about 25 feet deep at the accident site, and all major airframe components sank within a few minutes of impact. Divers recovered the airplane over a two-day period during the week following the accident. The fuselage sustained crush damage and fragmentation from the firewall through to the right-side emergency exit door. The engine remained attached to the firewall, and the propeller hub with all four blades remained attached to the engine gearbox. All blades were bent about 90 deg aft, 8-12 in from their roots. Both wings had separated from the airframe at their roots, with the right wing separating into two sections outboard of the main landing gear. The horizontal stabilizer had detached from the tail cone.

The 64-year-old pilot-in-command, held a commercial certificate with ratings for airplane single-engine land, multiengine land, rotorcraft-helicopter, and instrument airplane and helicopter, along with a flight instructor certificate for airplane single-engine land. He also held a repairman, experimental builder certificate, and was rated in the Bell 212 helicopter and Lockheed L-382 (C-130 Hercules) airplane. Rocket Engineering told investigators the pilot had an appointment for his FAA medical examination at 0800 on the morning following the accident, and therefore chose to do the flight test that evening instead of the following day (Friday). The pilot’s wife also stated that he typically did not work on Fridays but would do so if the work schedule required it.

The pilot-rated passenger held a private pilot certificate with an airplane single-engine land rating, issued in 2010. He had accumulated a total of about 122 hours of pilot-in-command flight experience. He was employed at Rocket Engineering as a customer service and sales representative.

The accident aircraft was manufactured by Piper in 1996 as a PA-46-350P equipped with a Lycoming TIO-540-AE2A 350-hp turbocharged piston engine. It was modified by Rocket Engineering in 2007 under a JetProp LLC STC, which included the installation of a 560-hp Pratt & Whitney Canada PT6A-35 turboprop engine.

The airplane was brought to the facilities of Rocket Engineering on April 17 for an annual inspection. During the period leading up to the accident, routine maintenance was performed, along with the replacement of the four aileron cables in the wings and an aft elevator cable. The mechanic who performed the work stated that the aileron and elevator cables were replaced during the three-day period leading up to the accident.

The owner reported that he had decided to pick up the airplane on May 5; however as the work progressed, he was informed that the airplane would not be ready in time, and the date was pushed back to May 7 (accident day) and then May 8. He had made plans to travel from Los Angeles the afternoon of May 7, and was en route via a commercial airline when the accident happened.

The airplane's primary flight controls are conventional, and operated by dual control wheels and rudder pedals through a closed-circuit cable system. The ailerons and rudder are interconnected through a spring system located under the main cabin.

An aileron is mounted on the outboard trailing-edge section of each wing via a series of hinges. Movement of each aileron is controlled through a yoke and pin assembly that interfaces with a sector wheel mounted in each wing forward of each aileron. Each sector wheel is connected to, and driven by, one aileron drive cable and one balance cable. In each wing, both the balance and drive cables are terminated with identical ball swage fittings, and each swage fitting inserts into one of two identically sized receptacles in the sector wheel. Both cables are approximately the same length outboard of the pressure vessel seals, which are located about 1 in apart vertically at the wing root.

In each wing, both cables are routed to the fuselage along the wing trailing edge, and pass through their respective pressure vessel seals in the wing root. Inboard of the pressure vessel seals, the left and right balance cables connect to one another after passing through a centre pulley, while the drive cables are routed forward via pulleys to the control wheel assembly in the cockpit. The balance and drive cables are aligned vertically at the pressure vessel seals and diverge about 3 inches laterally at their respective pulley positions. The sector wheel design is unique within the Piper fleet to the PA-46.

The NTSB said that four aileron cables were replaced during the maintenance operation. "Post-accident examination of the airplane revealed that the aileron balance and drive cables in the right wing had been misrouted and interchanged at the wing root. Under this condition, both the left and right ailerons would have deflected in the same direction rather than differentially. Therefore, once airborne, the pilot was effectively operating with minimal and most likely unpredictable lateral control, which would have been exacerbated by wind gusts and propeller torque and airflow effects."

The sections of the two interchanged cables within the wing were about equal lengths, used the same style and size of termination swages, and were installed into two same-shape and -size receptacles in the aileron sector wheel. “In combination, this design most likely permitted the inadvertent interchange of the cables, without any obvious visual cues to maintenance personnel to suggest a misrouting. The maintenance manual contained specific and bold warnings concerning the potential for cable reversal,” said the Safety Board [6].

“Although the misrouting error should have been obvious during the required post-maintenance aileron rigging or function checks,” said the Safety Board, “the error was not detected by the installing mechanic. The installing mechanic reported that he had another mechanic to verify the aileron functionality, that other mechanic denied that he was asked or that he conducted such a check. The mechanic who performed the work also signed off on the inspection; as the federal regulations do not require an independent inspection by someone who did not perform the maintenance.” [6]

The pilot did perform a pre-flight check; the pre-flight checklist included confirmation of “proper operation” of the primary flight controls from within the cockpit. “Although the low-wing airplane did not easily allow for a differential check of the ailerons during the walk-around,” said the Safety Board, “both ailerons could be seen from the pilot’s seat; therefore, the pilot should have been able to recognize that the ailerons were not operating differentially.”

In analysing the circumstances of the accident, the Safety Board observed that the accident occurred at the end of the business day, and the airplane had been undergoing maintenance for a longer-than-anticipated period. The airplane’s owner was flying in from another part of the country via a commercial airline to pick up the airplane the following morning. The accident pilot, who was an engineer at the company and typically flew post-maintenance test flights, was assisting with returning the airplane to service. As he had an appointment with an FAA medical examiner the next morning (Friday), “It is likely that the mechanic and pilot felt some pressure to be finished that day so the owner could depart in the morning and the pilot could attend his appointment.”

In summary, the Safety Board determined the probable cause(s) of this accident to be: “The mechanic’s incorrect installation of two aileron cables and the subsequent inadequate functional checks of the aileron system before flight by both the mechanic and the pilot, which prevented proper roll control from the cockpit, resulting in the pilot’s subsequent loss of control during flight. Contributing to the accident was the mechanic’s and the pilot’s self-induced pressure to complete the work that day.” [6]

Unfortunately, the significant causal factors involved in this accident are repeated several times each year. Pressure to get the job done; inspection/installation-unfriendly designs; and rushed pre-flight inspections are all potential killers. The record shows that post-maintenance flights should never be considered “routine.” They are fraught with hazards that can kill the unwary crew.

6. Conclusions

According to the 5th axiom of MIRCE Science, the probability that a maintenance task completed contains a fault or an error is greater than zero. Hence, MIRCE Mechanics, as a part of MIRCE Science, focuses on the scientific understanding and description of the physical phenomena and human rules that govern the motion of functionable system types though MIRCE Space [1]. A full understanding of the mechanisms of the motion is essential for accurate predictions of functionability performance of functionable system types facilitated by MIRCE Science. To reduce the probability of existence of undetected maintenance errors and their consequences on the system operational process, the concept of the PMFT is used in aviation industry. Thus, the main objective of this paper was to analyse this type of maintenance tests and their impact on the functionability performance in aviation, on one hand, and to inform functionability engineers and managers in other industries to consider similar tests, on the other.

The physical reality of inducing errors during maintenance and their consequences on a post-maintenance flight is illustrated through an incident that took the lives of two pilots, when their Piper PA 46-350P, N962DA, crashed into the Spokane River on May 7, 2015, following an attempted landing at Felts Field Airport in Spokane, Washington, USA

Arguably, among the most challenging and potentially hazardous flights a pilot can undertake are post-maintenance flights tests. The NTSB database contains dozens of incidents in which post-maintenance flights ended up tragically, often because the pre-flight chores were rushed or carelessly executed. Hence, the closing question is:

“Could the probability of the detection of maintenance induced errors be increased by appropriate design solutions, rather than leaving them to be detected during the potentially risky PMFT?”

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Lightning Strike as a Mechanism of a Motion of an Aircraft through MIRCE Space

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Abstract

MIRCE Science is a theory for predicting expected functionality performance for a functionable system type. For accurate predictions to be made it is essential for the generic random variables contained in MIRCE Functionability Equations to be “physicalised”, for each functionable action that impacts in-service behaviour of functionable system type considered. It requires a science based understanding of the mechanisms that govern the occurrences of negative functionability events before engineering, technological, business and economical decisions are made. Lightning strikes are not uncommon physical mechanisms that cause the motion of functionable systems type through MIRCE Space. For example, airliners in the worldwide fleet average at least one strike per year. Hence, the main objective of this paper is to understand physical mechanisms that generate the occurrences of lightening events and assesses their impacts on the functionability performance of functionable systems types, as well as to assess the available methods for dealing with them in respect to the provision of safety by detection, protection and design.

1. Introduction

During several decades of observing and researching the in-service behaviour of functionable system types, it became clearer and clearer to the author that in order to accurately predict their behaviour, it is necessary to understand the physical mechanisms that govern the occurrences of functionability events, rather than their failure modes¹² that have been the main concern of reliability community for over 50 years. Without a quantum mechanical understanding of these mechanisms it would be impossible to determine the most appropriate probability distribution functions to accurately describe the motion of functionable system types through MIRCE Space in order to quantitatively determine the functionability work expected to be done, together with the corresponding functionability costs. For that to happen, it is essential for the generic random variables in MIRCE Functionability Equations to be “physicalised”, for each applicable functionability action [1]. In author’s view it required a science based understanding of the physical processes and human rules that govern them before any engineering, technological, business and economical decisions are made.

Lightning strikes are not uncommon physical mechanisms that could potentially affect the motion of functionable systems type through MIRCE Space. For example,

¹² FMECA: Failure Mode And Criticality Analysis

airliners in the worldwide fleet average at least one lightning strike per year. Hence, the main objective of this paper is to address lightening as an environmental physical phenomenon and assesses its impact on the functionality performance of functional systems types, as well as to outline existing lightening protection methods and approaches.

2. Mechanics of Lightening

Lightning is an atmospheric discharge of electricity. Despite being the most visible form of electricity and a widely recognised natural phenomenon, lightning remains relatively poorly understood. Even the most basic questions of how lightning is initiated inside thunderclouds and how it then propagates for many tens of kilometres have only begun to be addressed. In the past, progress was hampered by the unpredictable and transient nature of lightning and the difficulties in making direct measurements inside thunderstorms. However, the advances in technology enable creation of instrumentation, remote sensing methods, and rocket-triggered lightning experiments that are now providing new insights into the mechanics of lightning.

Proper understanding of lightning phenomena involves the synthesis of many branches of physics, from atmospheric physics to plasma physics to quantum electrodynamics, and provides a plethora of challenging unsolved problems. In this paper only an elementary review is provided of the scientific understanding of lightning phenomenon.

Generally speaking lightning is the dissipation of static energy stored in cloud clusters. Scientists believe that the static energy stored in clouds comes from the relative motion of precipitation within the clouds that generate free electrons resulting in stored charges collected within the cloud. Positive charge in the cloud will seek negative charges on the Earth's surface. While in the same manner, negative charges in the cloud will seek positive charges on the ground. Lightning begins to move away from the cloud filled with static energy through what is known as leaders. Leaders are electrical energy moving out to seek ground or an object of opposite charge. Leaders stem from what is called a lightning channel. Lightning energy moves from the lightning channel in leader streams. If the leaders do not find anywhere of an opposite charge or "ground" to transfer the energy in an opposite charge or "ground" the leader, the leader is pulled back into the channel and the channel stores the leader charge which increases the energy in the leader channel. This process continues as leader stream away from the lightning channel seeking an opposite charge, constantly growing energy in the lightning channel until a leader finds an oppositely charged object, which could be cloud or ground¹³, creating an electrical circuit and quickly discharges the energy built up in the channel. This transfer of channel energy can be dramatic since the stored plasma often reaches levels of electrical power beyond 1 million volts and reach temperatures of over 25,000 degrees Celsius! When lightening flashes, it finds the faster path down to Earth and then it follows the same route back up to the cloud again. A downward flash of lightening leader travels at up to 1.600 kilometres per

¹³ In a given geographic area, there can be as many as 10 times more cloud-to-cloud as cloud-to-ground strikes. Furthermore, discharges can also occur within individual clouds.

second. The return or upward speed is even faster at up to 140,000 kilometres per second. [3]

Lightening, which is the discharge of electrical energy accumulated, makes the air inside a cloud almost 6 times hotter than the surface of the Sun! The hot air inside a thundercloud expands and vibrates and this makes the loud rumbling crash that is commonly called a thunder. Thunder and lightening happen at the same time but there is always a gap between the flash of light and the crash of a thunderclap. That is because light travels many times faster than sound¹⁴. Rough rule of thumb says if the number of seconds between the flash of lightening and the bang of thunder are counted and divided by 3, the results obtain would represent the approximate distance of the storm in kilometres. [3]

Thunderstorms are most common near the equator. This is because it's hotter, so there is more hot air (energy) to rise and create more thunderclouds and lighting. Hence, geographical areas like South America, Central Africa and Indonesia have on average 100-200 thunderstorms a year. [3]

There are five types of lightening, these are:

- Forked lightening that looks like the letter Y upside down
- Zig-zag lightening that is a giant spark that zig-zags its way to the ground
- Sheet lightening that makes a white light that fills a wide area of the sky
- Ball lengthening that is manifested as a slow moving ball of the fire that can sometimes appear inside structures¹⁵
- St Elmo's fire that is a faint flickering glow around trees, buildings or ships masts.

Lightning doesn't strike the ocean as much as land, but when it does; it spreads out over the water, which acts as a conductor. In existing literature, various different estimates have been given for the distance over which it would dissipate, to the point where it would no longer be a harmful to a person. Fish, which usually move around at greater depths, are safer than human swimmers. Protruding heads or even entire bodies, such as those presented by surfers or paddle boarders, could put people in greater danger. Boats can be fitted with lightning conductors, which direct the charge into the sea, while avoiding their most vulnerable parts, such as passenger areas or equipment rooms.

Lightening also hits deserts and sandy beaches that are high in silica or quartz. As the temperature in the affected areas reaches more than 1800 degrees Celsius, the lighting can fuse the sand into silica glass. The blast of a billion Joules of energy radiates through the ground making fulgurites¹⁶.

¹⁴ The speed of light is $299,792,458 \text{ ms}^{-1}$ whereas the speed of sound in air is between 331 ms^{-1} at 0°C and 360 ms^{-1} at 50°C

¹⁵ In 1984, Russian airline passengers were surprised to see a blob of ball lightening floating over their heads inside the plane. No one was hurt however the plane's radar was damaged.

¹⁶ Fulgurites, from the Latin fulgur, meaning "lightning", are natural tubes, clumps, or masses of sintered, vitrified, and/or fused soil, sand, rock, organic debris and other sediments that can form when lightning discharges into ground.

3. General Impact of a Lightning Strike

Lightning is not only spectacular; it is a rather dangerous natural phenomenon. Each year around 2,000 people are killed worldwide by lightning [2]. Although hundreds more survive strikes, they suffer from a variety of lasting symptoms, including memory loss, dizziness, weakness, numbness, and other life-altering ailments. Strikes can cause cardiac arrest and severe burns, but 9 of every 10 people survive. The average USA citizen has about a 1 in 5,000 chance of being struck by lightning during a lifetime. [3]

Electrical energy discharged by lightning on trees causes water inside them to vaporise, creating steam that may blow them apart.

Many houses are grounded by rods and other protection that conduct a lightning bolt's electricity harmlessly to the ground. Homes may also be inadvertently grounded by plumbing, gutters, or other materials. Grounded buildings offer protection, but occupants who touch running water or use a landline phone may receive a shock by conducted electricity.

In Kruger national Park in South Africa, seven elephants were killed by the same lightning strike! [3]

Lightning may also occur in Volcanic Ash clouds formed in the immediate vicinity of eruptions because the vertical movement and collision between solid particles within the cloud generates static charges.

In June 2006 a total of 17,000 lightning strikes hit Alaska, starting hundreds of fires. By the end of June an area twice of the size of London was destroyed. [3]

Flashes of lightning have been seen on Venus and Jupiter. Lightning on Jupiter is thought to be more powerful than on earth, but happens less frequently.

4. The Impact of Lightning on Aircraft

Through history of aviation there have been cases of aircraft being brought down by lightning strikes that started electrical fires or arced into unprotected fuel tanks, significant damage to aircraft today is a rare functionality event. However, in the early years of jet transport, the in-flight break-up of a Pan American World Airways Boeing 707-121 over Elkton, Maryland, in 1963 while on approach to Philadelphia, killed 81 people on board. The incident was attributed to lightning and became a watershed event in advancing aircraft protection. It was later determined that the break-up resulted from an explosion in a fuel tank due to a lightning strike. Subsequently, the nascent Federal Aviation Administration (FAA) required that lightning safety devices be installed on all commercial aircraft, including the now familiar static "wicks" or dissipaters on the trailing edges of wings and control surfaces.

A few examples of accidents and incidents that have been reported with lightning being attributed as a principal contributing factor:

- On February 8, 1988 a flight from Hanover to Düsseldorf, Germany, a Fairchild Metro III commuter turboprop crashed on approach to Dusseldorf after a lightning strike resulting in “disconnection of all batteries and generators from the aircraft's electrical system” including the termination of the cockpit voice recorder record". After a complete electrical failure the right wing broke off during an uncontrollable descent. The crash was blamed on "a combination of poor pilot judgment or skill and the lightning-caused electrical failure." Twenty-one people died (19 passengers and 2 crew)..
- On 15 December 2014, Loganair Saab 2000 on behalf of Flybe, registration G-LGNO performing flight BE-6780 from Aberdeen, (SC) to Shetland Islands, (SC) with 30 passengers and 3 crew, was descending towards Shetland Islands' Sumburgh Airport when the aircraft received a lightning strike disabling elevator control. The Captain lost control of his serviceable aircraft when he attempted to control the aircraft manually without first disconnecting the autopilot and despite the annunciation of a series of related alerts. The aircraft descended from 4,000 feet to 1,100 feet at up to 9,500 fpm and 80 knots above Vmo¹⁷. A fortuitous transient data transmission fault caused autopilot disconnection, making it possible to respond to EGPWS¹⁸ warnings: 'SINK RATE' and 'PULL UP'. The Investigation concluded that limitations on autopilot disconnection by pilot override were contrary to the type certification of most other transport aircraft.
- An Airbus A330-200 was struck by lightning just after arriving to Perth WA Australia, on 26 November 2014. It was allocated a stand following a one hour post-landing delay after suspension of ramp operations due to an overhead thunderstorm. Adjacent ground services operatives were subject to electrical discharge from the strike and one who was connected to the aircraft flight deck intercom was rendered unconscious. The investigation found that the equipment and procedures for mitigation of risk from lightning strikes were not wholly effective and also that perceived operational pressure had contributed to a resumption of ground operations which hindsight indicated had been premature.
- On 4 December 200, while approaching Bodø (Norway) the crew of a Dornier 228-200 (LN-HTA) lost control of their aircraft resulting from a powerful lightning strike, which temporarily blinded both pilots and damaged the aircraft such that they lost elevator control. After regaining partial pitch control using pitch trim, a second attempt at a landing resulted in a semi-controlled crash that seriously injured both pilots and damaged the aircraft beyond repair. The Investigation concluded that the energy in the lightning had probably exceeded certification resilience requirements and

¹⁷ Vmo is the Maximum Operating Velocity (Velocity Maximum Operating)

¹⁸ GPWS: A Ground Proximity Warning System is a system designed to alert pilots if their aircraft is in immediate danger of flying into the ground or an obstacle.

that up to 30% of the bonding wiring in the tail may have been defective before lightning struck.¹⁹

- On 25 September 2001, an Embraer 145 in descent to Manchester (UK) sustained a low power lightning strike which was followed, within a few seconds, by the left engine stopping without indicating a failure. A successful single engine landing followed. The Investigation concluded that the cause of failure of the FADEC-controlled AE3007 engine (which has no surge recovery logic) was the aero-thermal effects of the strike to which all aircraft with relatively small diameter fuselages and close mounted engines are vulnerable. It was considered that there was a risk of simultaneous double engine flameout in such circumstances which was impossible to quantify.
- In 1969 the US Apollo 12 spacecraft was hit by lightning as it took off for the Moon. It survived. However, in 1987, a rocket launched from Florida crashed after lightning damaged its on-board computer. US shuttle launches were postponed when lightning was around.

5. Mechanics of the Motion of Lightning Through the Aircraft Structure

An aircraft flying in an electrically charged area may also complete the circuit and receive a strike that will continue from the aircraft to the ground or another cloud. These strikes on aircraft commonly occur within 5,000 ft. of the freezing level²⁰.

A lightning strike is accompanied by a brilliant flash of light and often by the smell of burning, as well as noise, which can be very distressing to passengers and crew. However, significant physical damage to an aircraft is rare nowadays and the safety of an aircraft in flight is not usually affected. Damage is usually confined to aerials, compasses, avionics, and the burning of small holes in the fuselage. Of greater concern is the potential for the transient airflow disturbance associated with lightning to cause engine shutdown on both: a FADEC²¹ control and non-FADEC engines with close-spaced engine pairs.

A strike at the aircraft's radome will travel along the outer skin and exit at an extremity like a wingtip, the tail or a control surface. The entry point will vary from pitting to a small hole; at the exit point however, the charge may burn a larger hole. Meanwhile, the path of the charge along the airframe can produce scorching, often at rivets as the charge arcs across the miniscule gaps between rivet heads and adjacent skin.

If the charge exits from a control surface, hinge bushings and bearings may be spelled and require replacement. Strikes can also affect avionics, antennae and, especially, compasses. In any case, after a lightning strike, the airframe will require

¹⁹ https://www.skybrary.aero/index.php/D228,_vicinity_Bod%C3%B8_Norway,_2003

²⁰ The freezing level, or 0 °C (zero-degree) isotherm, represents the altitude in which the temperature is at 0 °C (the freezing point of water) in a free atmosphere.

²¹ FADEC: full authority digital engine (or electronics) control a system consisting of a digital computer, called an "electronic engine controller" (EEC) or "engine control unit" (ECU), and its related accessories that control all aspects of aircraft engine performance.

a thorough inspection and any serious damage repaired, meaning that the most tangible negative result of the lightning encounter will probably be downtime and repair, as necessary. Reportedly, airlines spend millions of dollars annually returning struck aircraft to service.

6. Lightning-Induced Flameouts

FADECs programmed with surge-protection logic can respond to flow disruption temperature spikes by automatically shutting down the engines. This aircraft configuration has proven to be vulnerable to engine flameouts as a lightning strike charge travels longitudinally down the sides of the fuselage seeking an exit point. In the case of closely spaced fuselage-mounted engines, the strike's "aero-thermal effects" can disrupt intake flows of both power plants. FADECs programmed with surge-protection logic can respond to such disruption temperature spikes by automatically shutting down the engines. On the other hand, hydro-mechanically controlled engines, as an indirect result of lightning strikes, will tend to experience transient over-temperature conditions while continuing to operate, as shutdown protocols are manually controlled by the flight crew.

In 2001, an Embraer ERJ 145 regional airliner received a lightning strike while descending for an approach to Manchester International Airport in England, followed by the left Rolls-Royce AE3007 turbofan flaming out without any fault indication or audible warning in the cockpit. The crew was on top of the situation and immediately transitioned to a successful single-engine landing. A post-incident investigation concluded that the failure of the FADEC-equipped engine was due to the aero-thermal effects of the strike characteristic of aircraft with small-diameter fuselages and aft-mounted engines. It further considered that a risk existed for loss of both engines, but investigators were unable to quantify that.

As a precautionary measure when entering areas of electrical activity in aircraft with FADEC-equipped engines, experts recommend that, if within operating limits, flight crews fire up the APUs²² so that, in the event of a double engine failure, electrical power and hydraulics will be maintained while emergency relights of the engines can be attempted. It is worth saying that it is possible that APUs can be affected by lightning strikes, too. It's also recommended that flight crews review memory items for a dual engine relight before venturing into areas of known lightning activity.

7. Designing for Lightning Protected Aircraft Structures

To survive multiple lightning strikes an aircraft has to be designed as "Faraday cage." Back in the 18th century electricity pioneer Michael Faraday created a metal-lattice contraption that conducted high-voltage electricity harmlessly around a hapless volunteer encaged within it. The device is often still used in magic acts and static electricity demonstrations. In the aircraft, the aluminium skin subs for the lattice, carrying the charge along the outside of the airframe to an exit point.

²² APU: Auxiliary Power Unit s a device on a vehicle that provides energy for functions other than propulsion. They are commonly found on large aircraft and naval ships as well as some large land vehicles.

However, ensuring the aircraft's occupants, systems, avionics and fuel are protected, means there must be no gaps in the conductive path, thus keeping the electrical charge on the outside of the aircraft. So, part of what is known as the "hardening" process against lightning damage involves, among other things, metal strapping across any gaps in the skin to maintain that uninterrupted conductive path.

While aluminium is an excellent conductor, composite media, (graphite-epoxy or "carbon fibre"), are less so. That's why a mesh of copper wire or other conductive material is included in the lay-ups of composite aircraft to provide conductivity. Because a radar antenna cannot be contained in a conductive enclosure, radomes are fabricated of composite media, so to protect them, lightning diverter strips consisting of solid metal bars or closely spaced conductive disks are bonded on the outer surface of the dome to carry the charge into the airframe.

Lightning strike hazards include the potential to affect the myriad computers on-board modern aircraft, such as the flight management system (FMS), navigation systems; electronic engine controls and even fly-by-wire systems, due to power surges.

Newton [4] cites an airline incident where a lightning strike "caused the autothrottle to go to idle, the autopilot and yaw damper to disengage, over half the fault lights to illuminate, the captain's flight director and navigation display to fail, and an erroneous indication of an engine failure to occur." These anomalies can happen because, as the lightning charge passes over the exterior of the airframe, induction from the electricity can cause "transients" in wiring inside the aircraft termed "lightning indirect effects." To address this threat, airframe and avionics designers apply a number of hardening techniques and devices to their equipment including simple grounding, various types of shielding and surge-suppression devices to meet aircraft certification requirements imposed by the FAA and other international civil aviation authorities. As everything essential for flight safety must be protected to the maximum extent possible, the risk of lightning being the direct cause of a crash has been greatly reduced during last 50 years.

In designing aircraft today, particular attention is devoted to protection of the fuel system and tanks to ensure that lightning charges cannot produce sparks that could ignite fuel or vapours. Accordingly, the aircraft wings, carry-through structures and other elements involving the fuel system must be sufficiently thick to prevent burn-through, and all brackets, fasteners, structural joints, filler ports, vents, electrical pumps and fuel lines must be designed and insulated to prevent ignition.

The same design philosophy also applies to the engines and their mechanical or electronic controllers. Even further, over the years, petro-chemical refiners have formulated jet fuels with less-explosive vapours.

8. Lightning Detection and Avoidance

Knowing the whereabouts of lightning activity is key to avoiding it, and flight crews now have more resources available than ever to do so. These include a network of ground-based detection tools, as well as airborne systems to complement weather radar, to assist in flight planning and, once airborne, chart paths safely around or through active areas.

During the last four decades, considerable research throughout the world has been devoted to understanding the nature of lightning, predicting and detecting it over large areas, and delivering these data to pilots, ATC²³ facilities and airport operators in near real time. Today, in the United States, much of this research has been conducted under the auspices of the National Oceanic and Atmospheric Administration's (NOAA) National Severe Storms Laboratory (NSSL).

Ground-based lightning detection networks (LDNs) have been established in many countries to monitor thunderstorm development, intensity and movement over wide areas. Some are owned and operated by governments, while others function in the private sector, often under contract to users. Data from these arrays are monitored by a variety of agencies for issuing warnings, forecasting and, in severe cases, deployment of rescue/response teams. Lightning strike data from these networks are also archived for research purposes, post-accident investigations and even insurance risk calculations.

The U.S. component in this array is the National Lightning Detection Network (NLDN) developed by the New Mexico Institute of Mining and Technology and operated by Vaisala Inc.²⁴, out of Tucson, Arizona. It has been in existence in one form or another for 30 years. Its origins derive from research conducted under contract for the Electric Power Research Institute by the State University of New York at Albany, principally to determine how to get lightning detection to users in near real time. Eventually, this research was commercialised by Global Atmospheric.

With more than 100 lightning strike sensors installed throughout North America, the NDLN is considered a precision detection network able to see and record both cloud-to-cloud and cloud-to-ground lightning. The sensors are all ground-based, with more being added every year. They detect electrical discharges in the atmosphere, and their raw data are then transmitted via a satellite communications link to Vaisala's Network Control Center at Tucson for processing. Literally within seconds, Vaisala's software calculates location, time, polarity and amplitude of each strike, which subsequently appears on a digital map or is sent to customers as text data. [4]

In addition to the NLDN, Vaisala operates a global lightning detection network based on a proprietary set of long-range sensors installed in other countries and sells a lightning data package, the GLD360, for it, too. [3] The company also markets its own display software called Thunderstorm Manager that enables users to set up rings around an airport, or any other entity sensitive to lightning, like a powerplant, on a video display at various distances and observe where strikes are occurring. Among Vaisala's U.S. customers for near-real-time lightning data are the FAA and

²³ ATC: Air traffic Control

²⁴ It is a Finish company with headquartered in Helsinki, established more than 80 years ago. It markets meteorological data packages and a broad product line of weather gauging and instrumentation equipment such as wind direction indicators, barometric and temperature measuring devices, and automated weather advisory station (AWAS) equipment. It got into the lightning detection business when it acquired the former Global Atmospheric Inc., in 2002.

National Weather Service (NWS). All data collected, a trove currently representing more than 160 million “flashes,” have been archived since 1989 for research purposes. [4]

Among users of archived data are the NSSL, which manipulates the information to loft 3-D lightning maps to study lightning development and propagation. While it is possible today for meteorologists to forecast the likelihood of lightning activity, being able to predict individual strikes is still beyond reach. So, one of the goals of this work is to construct experimental forecasting models that can accurately forecast the maximum lightning threat every hour. As a related development, the next generation of U.S. weather satellites will contain the Geostationary Lightning Mapper, an instrument that will continuously map both in-cloud and cloud-to-cloud lightning activity over the Americas and adjacent oceanic regions to provide early indication of storm intensification and severe weather events. [4]

9. Weather Surveillance Radar

Nexrad (Next Generation Radar or, technically, WSR-88D, which stands for Weather Surveillance Radar 1988 Doppler), is the ground-based network of 159 high-resolution S-band Doppler weather radars operated by the NWS²⁵, FAA and U.S. Air Force that covers the contiguous U.S., as well as large portions of Alaska, Hawaii, Puerto Rico, Guam, Okinawa, the Azores and South Korea. Nexrad radar station in Puerto Rico was destroyed by Hurricane Maria in September of 2017. It was the first-ever loss of weather radar by the NWS. Essentially this loss left the island without climatological imaging. It was estimated the radar station would be returned to service within six months!

10. Lightning Experience Based Lessons Learned for Aviation

Newton and other lightning experts have produced the following lesson learned, that are related to aviation industry [4]:

- Know the lightning protection features of your aircraft and make sure they are being maintained. This is especially critical for fuel system components as well as electrical system elements.
- If possible, remain at least 20 nm from any cumulonimbus clouds²⁶. Note also that the dangers from turbulence, wind shear and icing are far greater than the threat of a lightning strike.
- Flying at very high altitudes, give thunderstorms a wide berth, particularly when temperatures are below -40°C. At lower altitudes, in areas where there are or have recently been thunderstorms, avoid the temperature range of +/- 5°C as much as possible.
- In the vicinity of cumulonimbus or visible lightning, review your aircraft manufacturer’s guidelines for action items to be taken in the event of a strike. If the aircraft is equipped with gyro-magnetic compasses, select one to gyro and cage it while in the vicinity of lightning.

²⁵ NWS: national Weather Service in USA

²⁶ Cumulonimbus clouds are menacing looking multi-level clouds, extending high into the sky in towers or plumes. More commonly known as thunderclouds, cumulonimbus is the only cloud type that produces hail, thunder and lightning. The base of the cloud is often flat topped with a very dark wall like feature hanging underneath.

- If the airplane is “charging up,” causing crewmembers to feel skin-tingling or a corona is forming around the aircraft while transiting an area of electrical activity that is not part of a thunderstorm as evidenced by P-static or St. Elmo’s Fire, an altitude change may help to avoid a lightning strike. According to Newton, “There is some evidence that layers of clouds containing electric fields high enough to allow an aircraft to trigger a strike [which may not be thunderstorm clouds themselves but may have blown off of thunderstorms] are often fairly shallow, perhaps as shallow as 1,000 ft.” [3] The preferred direction of an altitude change is up. Further, a strike under these conditions will more than likely be an in-cloud flash, carrying far less current (as little as one-tenth) than a cloud-to-ground strike.
- If operating in the weather, always have Jet-A in your tanks. If you’re carrying Jet-B (JP-4) and, particularly, if your aircraft is an older design type that may not reflect modern lightning protection, consider simply staying away from any areas where there are thunderstorms. Same if you’re doubtful about the aircraft’s maintenance history.
- If other aircraft in the area are reporting lightning strikes — or there is evidence your aircraft is charging up — especially if cruising near the freezing level, activate continuous ignition and bring up the air start checklist.

11. Conclusions

The objective of this paper was introducing a lightning strike, which are not uncommon physical phenomena, as a mechanism of a motion of functionable systems type through MIRCE Space. For example, airliners in the worldwide fleet average at least one lightning strike per year.

The paper provides an overview of the current scientific understandings of physical mechanism that generate the occurrences of lightening events and assesses their impacts on the functionality performance of functionable systems types, with a several examples related to the aviation industry.

Finally, the paper provides a brief overview of methods available for dealing with lightening strikes in respect to the provision of safety by detection, protection and design.

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Vibration Monitoring as a Mechanism of Motion of a Gearbox through MIRCE Space

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Abstract

MIRCE Science is a theory for predicting expected functionability performance for a functionable system type. Accuracy of the predictions is governed by the degree of the scientific understanding of the physical mechanisms, and human rules, that govern the motion of functionable system types through MIRCE Space. The main objective of this paper is to address vibration monitoring as one of the possible mechanisms that governs motion of a gearbox through functionability states, which are contained in MIRCE Space. In general, and to illustrate this process through a case study related to heavy gearbox used in Plastics Manufacturing industry, conducted by the author with vibration data collected on site by Ian Graham (The Seasoned Analyst).

1. Introduction

The main objective of this paper is to address the vibration monitoring actions as a mechanism of the motion of functionable system type²⁷ through MIRCE Space²⁸. In general, and to illustrate this process through a case study related to heavy gearbox used in Plastics Manufacturing industry, conducted by the author.

2. MIRCE Science Fundamentals

According to the 2nd Axiom of MIRCE Science the motion of functionable system type through MIRCE Space is a result of imposed natural phenomena or human activities, which are jointly called functionability actions [1]. At any instant of calendar time, a given functionable system type could be in one of the following two functionability states:

- Positive Functionability State (PFS), a generic name for a state in which a functionable system type is able to deliver the expected measurable function(s).
- Negative Functionability State (NFS), a generic name for a state in which a functionable system type is unable to deliver the expected measurable function(s), resulting from any reason whatsoever.

²⁷ According to Knezevic [1], functionable system type is “a generic name for a functional system type and the set of functionability rules that govern functionability performance through calendar time.”

²⁸ MIRCE Space is an analytical concept used in MIRCE Science to describe the motion of functionable system through functionability states in respect to calendar time. Mathematically, it is three-dimensional space whose coordinates are; calendar time, functionability states of a functional system type and a probability of system being in any of these functionable states.

The motion of a functionable system type through the functionability states, in the direction of calendar time, is generated by functionability actions, which are classified as:

- Positive Functionability Action (PFA), a generic name for any natural process or human activity that compels a system to move to a PFS.
- Negative Functionability Action (NFA), a generic name for any natural process or human activity that compels a system to move to a NFS.

To scientifically understand the mechanisms that generate negative functionability events, analysis of the in-service behaviour of several thousands of components, modules and assemblies of functionable systems in defence, aerospace, nuclear, transportation, motorsport, communication and other industries have been conducted at MIRCE Akademy.

In MIRCE Science all negative functionability actions are categorised as following [1]:

- Component-internal actions that consist of:
 - Inherent actions that are introduced into components prior to their introduction into service through the activities associated with the design, manufacturing, handling, transportation, maintenance, storage and similar processes.
 - Cumulative continuous actions that are an inevitable part of the components in-service life resulting from natural decay processes such as: corrosion, fatigue, creep, wear and similar.
- Component-external actions, which are originated by:
 - Environmental phenomena that cause discrete overload, like foreign object damage; birds strike (domestic and wild animals), weather (hail, rain, snow, lightening, solar radiation, etc..) and so forth.
 - Human activities:
 - Errors that are related to phenomena that cause overload, for example use and abuse by operators, (pilots, driver and other users), maintainers (maintenance induced errors) and logistics support personnel (bogus parts, shelf life, etc.)
 - Rules that are related to organisational policies, legal requirements, national and international, best practices or any other human imposed functionability related actions (scheduled and condition based maintenance tasks).
- System-internal actions: resulting from processes that are taking place within a system, like a change from passive to active state for certain components and modules, a change in functionability states of some of its constituent components that impact the functionability of the system.
- System-external actions: which are generated by:
 - Discrete environmental phenomena related to weather (hail, rain, snow, lightening, volcanic eruptions, strong wind, solar radiation, etc..) and other causes that impact on the functionability of a functionable system type.
 - Human activities:
 - Errors, which are related to the phenomena of use and abuse by: operators, maintainers or supply chain personnel.

- Rules, which are related to organisational policies, legal requirements, national and international, best practices or any other human imposed functionality actions that cause the occurrence of NFEs for the functional systems.

3. Condition Monitoring Techniques

The objective of Condition Monitoring is to provide information with respect to the actual condition of the component/system and any change in that condition. This information is required to schedule conditional maintenance task, on a needed basis instead of relying on predetermined instances of operational or calendar times.

Generally speaking, Condition Monitoring techniques use instrumentation to gather regular or continuous measurements of condition parameters, in order to determine the physical state of an item or system. Most frequently used Condition Monitoring techniques are: Vibration monitoring, Lubricant analysis, Infrared Thermography, Ultrasonic and Acoustic Emission. [2]

Condition Monitoring basically is a measurement technology, where various methods are used to determine the condition of the item under consideration, while measuring physical phenomena like: vibration, temperature, crack length, resistance, pressure, wall thickness, conductivity etc. which are used to determine the physical condition of the item.

4. Vibration Monitoring

Equipment, which contains moving parts, in general vibrates at a variety of frequencies, which are governed by the nature of the vibration sources. If any of these parts is to change its physical state, its vibration frequencies change, and vibration analysis can be used to detect and analyse these changes. Vibration monitoring is based on the fact that rotating machines such as pumps, compressors, motors, gearboxes, turbines and so forth produce vibration change as machines deteriorate.

Changes in vibration levels can be used as an indicator for an impending incipient negative event (failure) and can sometimes be used in defining the possible cause of the malfunction. Therefore measuring and analysing the vibration level gives a good indication of the machine's condition and can be used with confidence in condition-based maintenance program either as continuously monitored parameter or in a periodic program. Vibration is characterised in terms of three parameters, namely displacement, velocity and acceleration with respective transducers, which are used to collect data on rotating machinery.

Vibration monitoring, especially, while dealing with rotating machinery, is becoming increasingly important and is one of the best-developed techniques in condition-based maintenance. The recent developments in artificial intelligence techniques have enormously helped these developments by automating the interpretation of vibration data. [2]

5. Vibration Monitoring as Negative Functionability Event

According to the 1st Axiom of MIRCE Science, functional system type begins in-service life in Positive Functionability State [1]. Hence, a system will stay in PFS until is compelled to change it due to imposing a negative functionability action

(NFA). Vibration monitoring is one of numerous possible negative functionability actions that could generate a negative Functionability Event [1].

This paper addresses vibration monitoring as a NFA that causes the motion of functionable system type from PFS to NFS, as well as the positive functionability actions taken to return a system to PFS.

Unlike scheduled maintenance tasks, which take place at predetermined instances of usage or calendar time, Condition Monitoring activities are initiated by changes in the condition of a system. This is so that necessary positive functionability action can take place, when it's needed - not before and not too late. Hence, the results of vibration monitoring analysis will trigger, the human approved, transition of a system considered from PFS to NFS in order to reduce consequences of allowing system to run until the NFE is generated by the natural causes. By doing this, the consequences of the occurrences of NFE are almost eliminated and the duration of the time a system spent in NFS is shorter, in majority of cases, as the logistics support resources; qualified personnel, spare part, tools and equipment could be provided in advance.

In the remaining part of the paper, the above theoretical propositions of MIRCE Science are supported with a real life case study, conducted by the author.

6. Gearbox Based Case Study

The Condition Monitoring expert of the reliability services department was requested to inspect a gearbox at a production facility as the operator had reported an abnormal sound from it. The gearbox was still in PFS producing the product. It was a very large old extruder high torque gearbox with a single input and dual output shafts. The repair history of this gearbox was unknown but it is around 15 years old.

6.1 On Site Initial Assessment

The gearbox vibrational levels as measured under full load conditions were $>20\text{mm/s RMS}$. This is considered "Vibration Causing Damage" as per ISO 10816-3. The Acceleration Peak to Peak impactions at Gearmesh #1 was excessive at 162G's . There were also indications of misalignment on the 1st intermediate shaft and considerable looseness present. In addition the 1st intermediate shaft 'binds' for $\frac{1}{4}$ to $\frac{1}{3}$ of a revolution when rotated by hand.

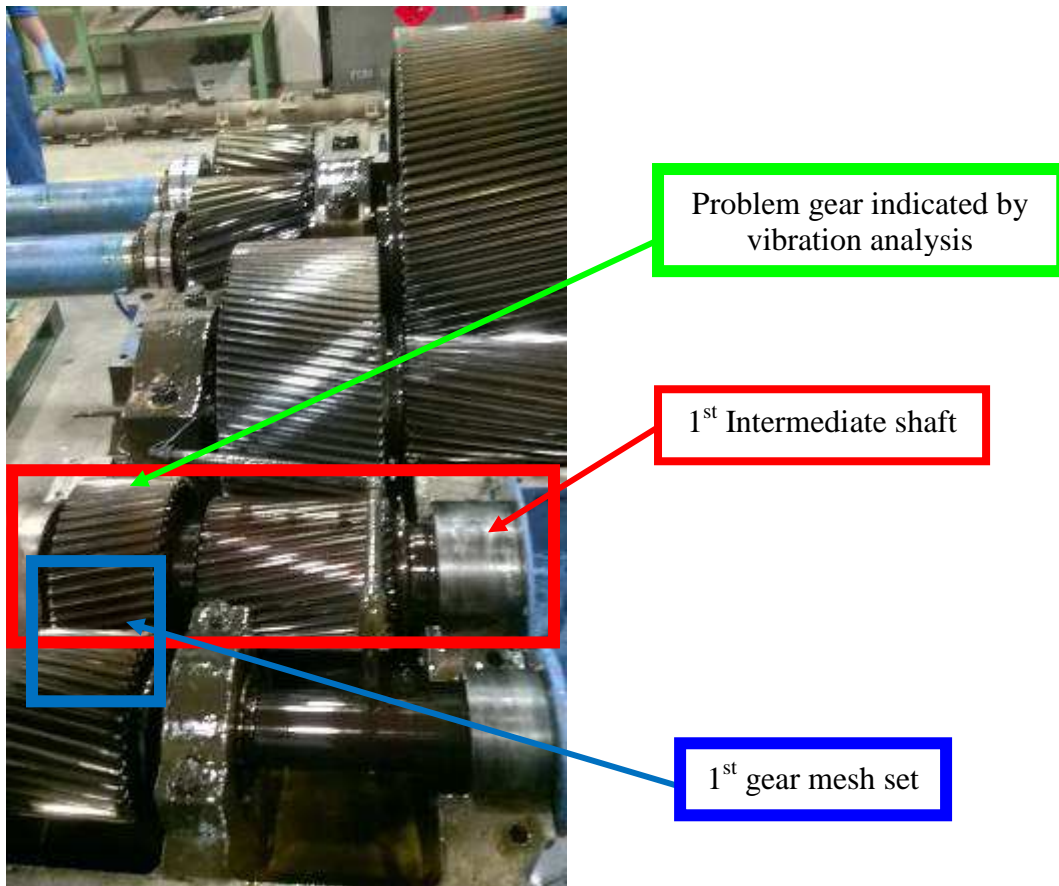


Image 1: Gearbox internals with the input shaft at the bottom of the image the two output shafts at the top left. The problem shaft indicated by the vibration analysis is highlighted by the red frame.

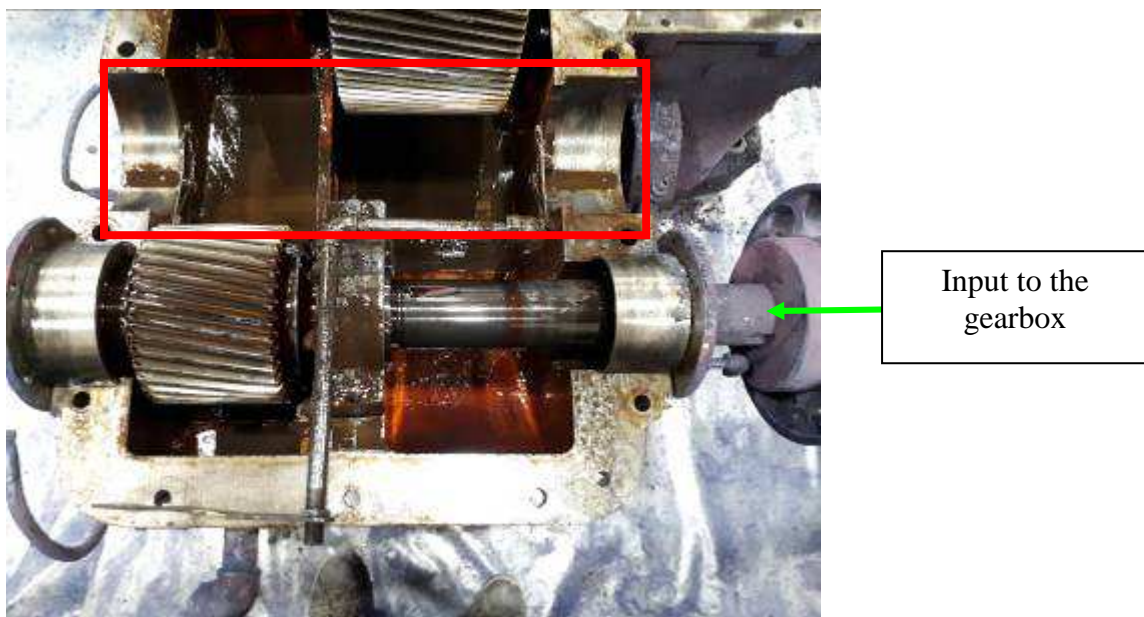


Image 2: A close view up of the problem shaft location after removal for repair.

6.2 Vibration Analysis Data

The input shaft high frequency Acceleration spectrum, shown in the Figure 1, clearly indicates a high 2x gearmesh frequency for the first gearmesh set. This also indicates that there was misalignment within the gearing setup. The sidebanding at 19.20Hz indicated that it was relative to the 1st intermediate shaft.

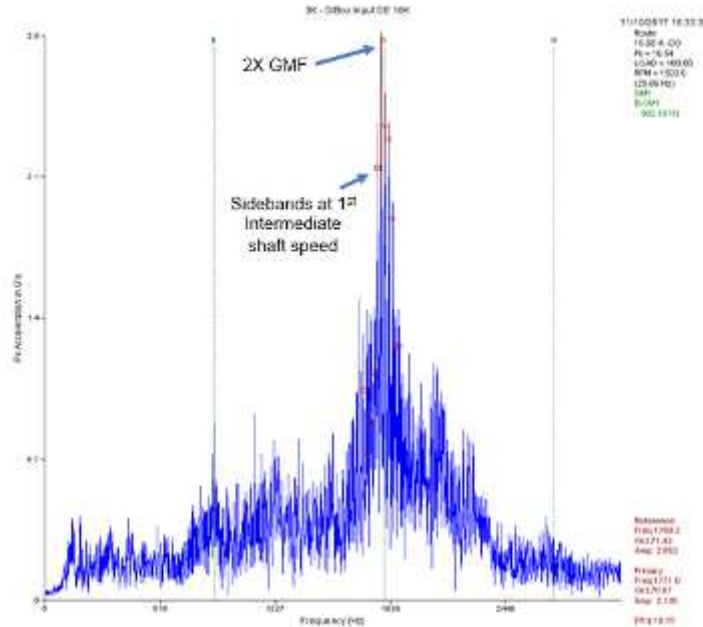


Figure 1: The input shaft high frequency Acceleration spectrum.

The peak-to-peak measurements on the Acceleration time waveform, shown in Figure 2, indicated that the Acceleration forces are generated from the 1st Intermediate shafting. The total reading of 162G's is highly destructive and is impacting at frequency of 19.2Hz, the 1st intermediate shaft speed. This displayed that the gear is loose and impacting very heavy once per revolution of the shaft.

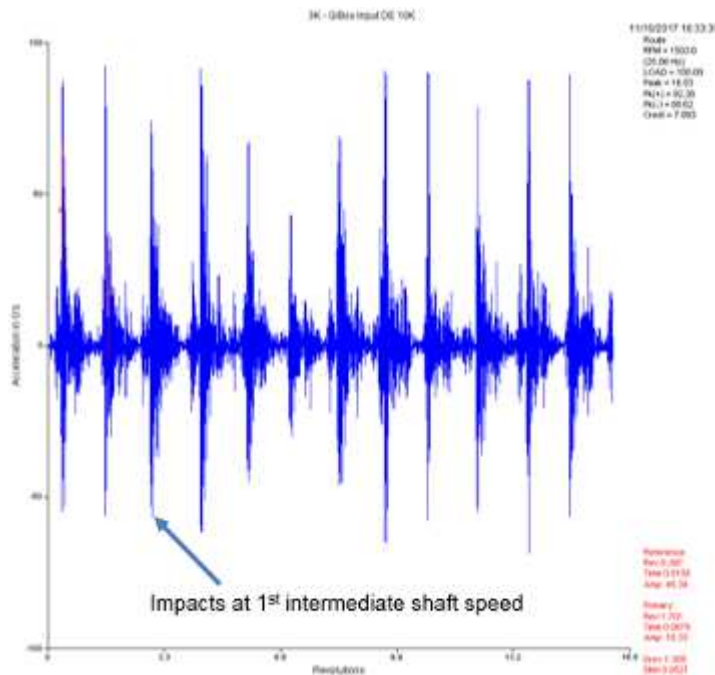


Figure 2: The peak-to-peak measurements on the Acceleration time waveform.

Figure 3 below is the Velocity spectrum taken from the non-drive end (NDE) of the 1st intermediate shaft, and shows a considerable amount of run speed harmonics attributed to the shaft speed. This is an indication of looseness.

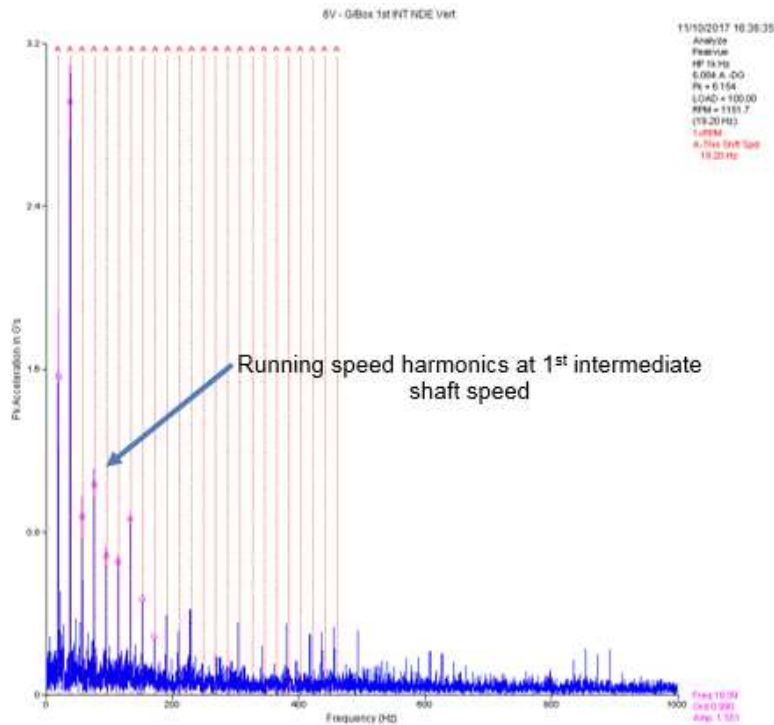


Figure 3: Velocity spectrum taken from the non-drive end (NDE) of the 1st intermediate shaft.

6.3 Vibration Analysis Summary Initiated Negative Functionability Event

The vibration analysis data collected clearly indicated a high impact once per revolution from the first gear set, highest on the 1st intermediate shaft (2nd shaft). Also, there were indications of component looseness from the same location. This all pointed to the gear and bearings on the 1st intermediate shaft. This knowledge enabled the bearings for the shaft to be pre-ordered so they arrived at the repair shop the same time as the gearbox.

Based on the evidential data gathered during the vibration measurement and analysis performed on the data obtained, the management of the company decided to stop the production process and performed necessary maintenance actions. By doing that, they would prevent further deterioration of the gearbox and avoid the consequences of gearbox failure and the transition of production system into an unplanned NFS.

6.4 Positive Functionability Actions

The negative functionability event has initiated positive functionability actions, which started with dismantling the gearbox. The inspection performed shown that the tab washer on the first intermediate shaft outer bearing had failed (Image 3). The most probable mechanism of this failure is fatigue of a washer resulting from the high shock acceleration levels (162Gs). The function of a tab washer is to lock

the bearing sleeve to set the correct bearing clearances and to prevent the bearing inner raceway spinning on the shaft.

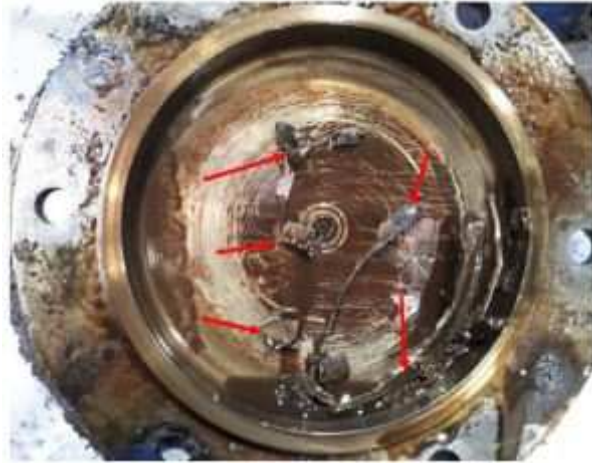


Image 3 of the failed tab washer found in the bearing cap from the 1st Intermediate shaft.

Further inspection has shown that the suspected gear on the 1st intermediate shaft was extremely loose. It was found that this shaft had been previously repaired with metal spray coating²⁹ and this had failed. On closer inspection the stress raiser appears to be around the keyway, as there were no strengthening welds around the keyway to support the metal spray. The metal spray was to the edge of the key way at a 90 degrees angle to the keyway, this was the weak point and the stress raise. Therefore over time fatigue set in and started to crack the metal spray around the keyway that then rapidly progressed to a catastrophic failure of the metal spray [4], as shown in Image 4.



Image 4: Metals spray coating that was under the 1st Intermediate shaft gear. This failed initially at the metal spray coating at the keyway.

²⁹ Metal spray coating (Thermal spraying) are coating processes in which finely divided metallic powder are deposited in a molten or semi-molten state to form a coating melted onto a surface. This is often used as a cost effective process to repair worn shaft journals.

7. Conclusions

This paper set out to prove that vibration monitoring is one, of numerous, mechanisms that cause the motion of functionable system type through MIRCE Space, and as such it has impact on the final functionability performance. Theoretical considerations of MIRCE Science were presented in the first part of the paper, with evidential proof through the data obtained during in-service events conducted by the author.

MIRCE Science perceives in-service life of functionable system type as a motion through positive and negative functionability states, governed by natural phenomena of human activities, jointly named, functionability actions. Vibration monitoring is one of these functionability actions that is initiated and performed by humans in order to determine the change in the state of a system in the direction of calendar time and based on the analysis of the data obtained, the decisions are made regarding the timing and the content of the future functionability actions in a such way that the probability of delivery the expected business plan is maximised.

The case study used in the paper, conducted by the author, supports the hypothesis that a vibration monitoring is a mechanism of the motion of a heavy gearbox, used in Plastics Manufacturing industry, through MIRCE Space. Through onsite vibration analysis it was possible to pinpoint that the first intermediate shaft was generating the abnormal noises and the probable failure mode(s). This knowledge enabled the bearings for the shaft to be pre-ordered so they arrived at the repair shop the same time as the gearbox.

The vibration levels recorded enabled an assessment of whole risk of failure and this was deemed to be high due to the unavailability of the gearbox gears/shafts (due to the age of the gearbox) and the very high impacting levels. Consequently, the gearbox was removed from service, introducing a human made NFA, which was performed before imminent functional failure of the system due to natural causes. In return, this NFA initiated PFA, which in this case was a quick turnaround, removed the risk of secondary damage and was completed with minimal production loss.

Even though this did cause an interruption to the function of the asset and production levels it was agreed, by all concerned, that inconvenience caused during a four day stay in NFS of a system was the better option over the risk of a catastrophic failure and the possibility of production ceasing operations for two months.

8. Acknowledgement

The author wishes to acknowledge the support received from Dr Knezevic, MIRCE Academy, Exeter, UK, while preparing this paper. As the “father” of MIRCE Science, Dr Knezevic, has inspired me to view how every day Condition Based Monitoring can have a significant impact on functionability performance of the whole system. Consequently, I can now understand how many companies are performing Condition Based Monitoring but are not linking this to the business performance of the whole organisation/company. MIRCE Science is the body of knowledge that bring together these two very different but related disciplines, for the ultimate benefit of the user.

9. References

- [1] Knezevic, J., The Origin of MIRCE Science, pp. 232, MIRCE Science, Exeter, UK, 2017. ISBN 978-1-904848-06-6
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Precision Alignment as a Mechanism of the Motion of Rotating Machines through MIRCE Space

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Abstract

MIRCE Science is a theory for predicting expected functionability performance for a functionable system type. Accuracy of the predictions is governed by the degree of the scientific understanding of the physical mechanisms, and human rules, that govern the motion of functionable system types through MIRCE Space. The main objective of this paper is to address precision alignment as one of the possible mechanisms that governs motion of rotating machines through functionability states, which are contained in MIRCE Space, In general, and to illustrate this process through a case study related to Laser alignment of a pump used in Power Generation industry, conducted by the author with vibration data collected on site by James Pearce (The Seasoned Analyst).

1. Introduction

The main objective of this paper is to address the precision alignment actions as a mechanism of the motion of rotating machines through MIRCE Space³⁰. To strengthen the claim a case study related to a laser alignment of a pump set used in Power Generation industry, conducted by the authors, is presented in the paper.

2. MIRCE Science Fundamentals

According to the 2nd Axiom of MIRCE Science the motion of functionable system type³¹ through MIRCE Space is a result of imposed natural phenomena or human activities, which are jointly called functionability actions [1]. At any instant of calendar time, a given functionable system type could be in one of the following two functionability states:

- Positive Functionability State (PFS), a generic name for a state in which a functionable system type is able to deliver the expected measurable function(s).
- Negative Functionability State (NFS), a generic name for a state in which a functionable system type is unable to deliver the expected measurable function(s), resulting from any reason whatsoever.

³⁰ MIRCE Space is an analytical concept used in MIRCE Science to describe the motion of functionable system through functionability states in respect to calendar time. Mathematically, it is three-dimensional space with the following coordinates are; calendar time, functionability states of a functional system type and a probability of system being in any of these functionable states.

³¹ According to Knezevic, a functionable system type is “a generic name for a functional system type and the set of functionability rules that govern functionability performance through calendar time.”[1]

The motion of a functionable system type through the functionability states, in the direction of calendar time, is generated by functionability actions, which are classified as:

- Positive Functionability Action (PFA), a generic name for any natural process or human activity that compels a system to move to a PFS.
- Negative Functionability Action (NFA), a generic name for any natural process or human activity that compels a system to move to a NFS.

MIRCE Science comprises of mathematical axioms, equations and methods that enable predictions of functionability performance of each feasible option of the future functionability system type to be done, based on the complex and time-dependent interactions between: physical properties of consisting components, operational rules, maintenance policies, support strategies and expected environmental conditions

3. Positive Functionability Actions

To scientifically understand the mechanisms that generate positive functionability events, analysis of the motion of several thousands of components, modules and assemblies of functionable systems in defence, aerospace, nuclear, transportation, motorsport, communication and other industries through NFS state have been conducted at MIRCE Academy. Consequently, in MIRCE Science all positive functionability actions are categorised as following [1]:

- **System-Internal actions**, commonly known as maintenance tasks, are further categorised as following³²:
 - Servicing: replenishment of consumable fluids, cleaning, washing and similar.
 - Lubrication: installing or replenishing lubricant.
 - Inspection of a component against a defined physical standard.
 - General visual inspection: performed to detect obvious unsatisfactory conditions.
 - Detailed visual inspection: consists of intensive visual search for evidence of any irregularity, usually assisted by inspection aids.
 - Special visual inspection: an intensive examination of a specific area using special inspection equipment such as radiography, thermography, dye penetrant, eddy current, high power magnification or other Non-Destructive Testing (NDT).
 - Examination: a quantitative assessment of one/more functions on a component to determine whether it performs within acceptable limits.
 - Restoration: perform to return a component to a specific standard. This may involve cleaning, repair, replacement or overhaul.
 - Discard: removal of from in-service life.
- **System-External actions**: related to activities that are affecting the whole functionable system and they are grouped in the following manner:

³² Ben-Daya, Duffuaa., Raouf, Knezevic and Ait-Kadi, D. (2009), *Handbook of Maintenance Management and Engineering*, Springer, Dordrecht, Heidelberg, London and New York, NY, USA.

- Environmental positive actions: fog lifting, de-icing, decontamination, washing and so forth.
- Legal positive actions: related to all activities that are required to be performed due to health and safety regulations at national and international level of jurisdictions and restrictions.
- Organisational positive actions those are specific to a user or group of users of functional systems, which could relate to marketing, operational, political, economical and other functions.

4. Misalignment Driven Negative Functionability Events

It is universally recognised that misalignment is the leading cause of the occurrence of NFE throughout the life of rotating machines³³. It exists when the centrelines of two adjacent machines deviate from each other. Potential problems that it causes include soft foot, pipe strain, inadequate bases and so forth.

The governing mechanisms of misalignment are as follows:

- Poor Tolerances and Poor Methods
- Inadequate practices regarding implementation of good methods
- Lack of understanding of precision alignment process
- Dynamic movement (thermal growth, pipe strain, etc.)
- Misdiagnosis with unbalance or looseness mechanisms
- Lack of appropriate standards, specifications and training

5. Alignment Techniques as a Positive Functionability Action

Precision alignment is obtained by using optical or laser technologies. Optical alignment is used for new installations as well as refits and general repair work in conjunction with laser alignment. Precision alignment is a process to make rotating shafts co-linear (in the same straight line), both vertically and horizontally.

Precision alignment extends the life of machinery and improves productivity of machinery by increasing efficiency and preventing premature NFEs. Laser alignment can alleviate many issues, such as: engine overloading, decreased fuel efficiency, excessive wear on bearings and related machinery while offering a smoother, quieter running machine. With a reduction of the time spend in NFS a machine will deliver more of Positive Functionability Work (PFW), which is the main purpose of their existence, according to MIRCE Science [1]

Laser alignment achieves the following benefits to the following rotating machines:

- **Pumps:** correctly couples shafts of a pump making its drive unit to rotate on a common axis, which minimises vibration and keeping the forces across the coupling within tolerance. Accurate alignment is critical with sealed pumps, particularly when rotating seal designs where the springs or bellows rotates with the shaft are being used. Misaligned pumps and drives result in vibrations and premature wear of bearings, seals, couplings and the surrounding environment.

³³ For the same level of vibration it is much more serious than unbalance for its effect in reducing bearing life, largely because of the parasitic axial thrust.

- **Motors:** increases friction on a misaligned shaft makes it harder to turn resulting in the drive motor drawing more power or running speed increasing.
- **Fans:** accurately and efficiently align cooling tower fans, making plant maintenance easy and affordable.
- **Turbines:** provides easier measurements of tower flanges and monitoring of machinery positional change
- **Generators:** aligns generators with main shafts and reduce vibration.

6. Laser Based Precision Alignment Case Study

This case study shows the importance of precision alignment including soft foot check and the importance of training and mentoring of the users of laser alignment equipment, as both are the drivers of the motion of rotary machines through MIRCE Space. This survey was conducted by James Pearce³⁴ from the Seasoned Analyst.

The ‘Seasoned Analyst’ was called to investigate an apparent increase in vibration levels after a high-pressure hot water pump was replaced with a new pump end and a reconditioned drive motor. The boiler house operator felt that it was not running as smooth as the old pump set.

For this survey authors used the CSI 2140 Dual channel Machinery Health Analyser. Data analysis was carried out using the CSI AMS Machinery Health manager software V5.61. Vibration data including Velocity, Acceleration and bearing condition unit PeakVue was collected from each bearing location as close as possible to the source. Where was applicable the additional data, including high-resolution vibration data, was collected.

The analysis performed by the vibration specialist from the Seasoned Analyst has revealed that there were elevated directional Velocity vibration levels when running at 2680 RPM (low speed). This is due to a coincidence of a system natural frequency being excited by a motor Soft Foot condition (Forcing function of 2 times Electrical Drive Frequency).

Based on the information obtained, the following maintenance recommendations were made:

- Perform precision alignment that must start with a soft foot check and soft foot elimination, followed by precision laser alignment.
- Check/inspect condition of the foundation, looking for looseness and any deterioration in the base plate.

In the case that the above actions are not successful then stiffening of the base may allow for improved precision alignment and may move the system resonance out of the running speed range.

6.1 Results of the Functionability Analysis

After reviewing the vibration data it was decided to perform further checks and the motor holding down bolts was loosened one time when in operation, this is to check

³⁴ [linkedin.com/in/james-pearcevibrationanalysis](https://www.linkedin.com/in/james-pearcevibrationanalysis)

for distortion of the motor rotor to stator air gap. During this test it was found that the Velocity amplitude reduced. The amplitude reduced to its lowest level when the motor non-drive end foot bolt (bolt closest to pump #1) was loosened (see Figure 1 and 2).

When tightening the foot bolt changes the resonance such that it equals a forcing function and therefore excites the resonance, in this case 2xLF (2 times Electrical Line Frequency). This is a soft foot condition, as the dynamics of the system have changed when tightening the foot bolt.

In addition an overall vibration coast down test and resonance bump test was performed. This data confirmed a natural frequency at 5336RPM, which is being excited by 2xLF excitation at 90Hz (VFD frequency of this 2 Pole motor at 45Hz gives 2xLF to be 90Hz/5400CPM) (see Figure 3).

The motor has elevated directional Velocity vibration levels. By loosening one motor fixing foot bolt at a time, the Velocity amplitude reduced. The amplitude reduced to its lowest level when the motor non-drive end foot bolt (bolt closest to pump #1) was loosened.

6.2 Vibration Data

Comparison between the Velocity spectra when running at 2680RPM, for the as found state (4.332mm/sec RMS) and where the amplitude decreased the most after the motor foot bolt was loosened (2.651mm/sec RMS) is shown in Figure 1.

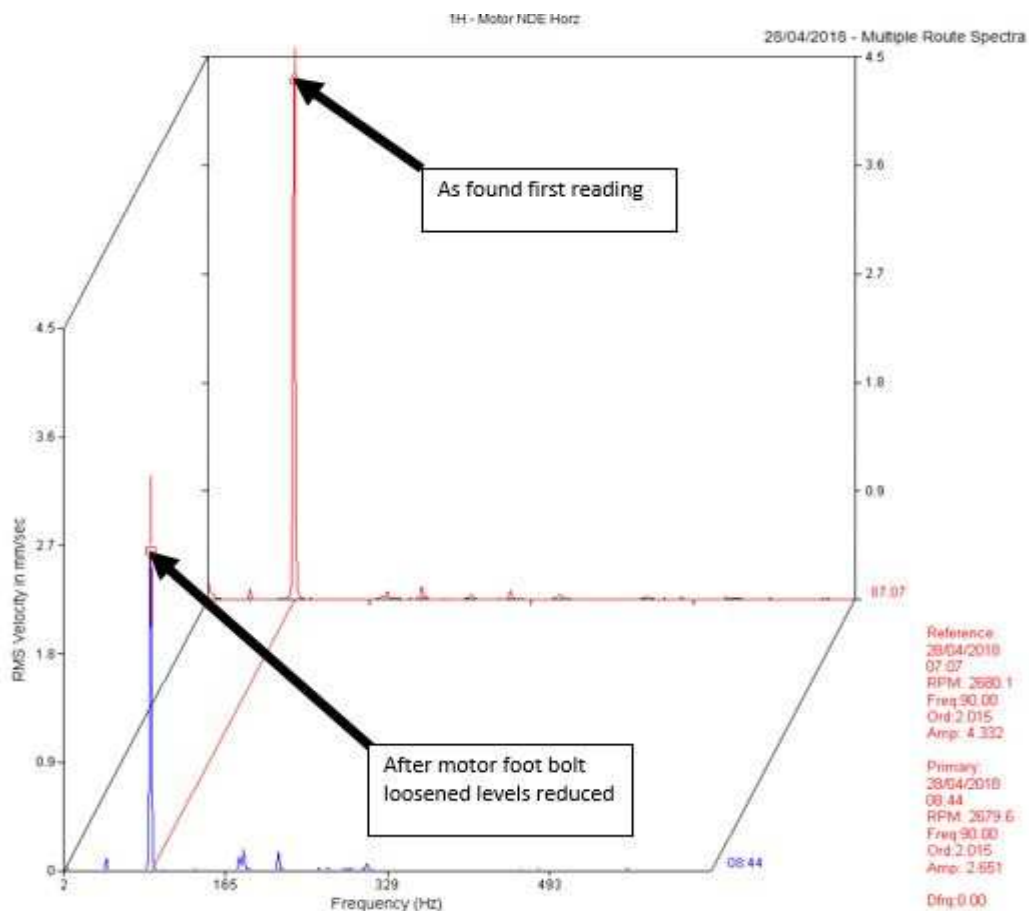


Figure 1: Spectral comparison

The data from a resonance bump test, performed at the motor drive end, are shown in Figure 2. The bump test result indicates a system natural frequency that will coincide with twice the running speed (when running at the low speed) and amplify the vibration levels.

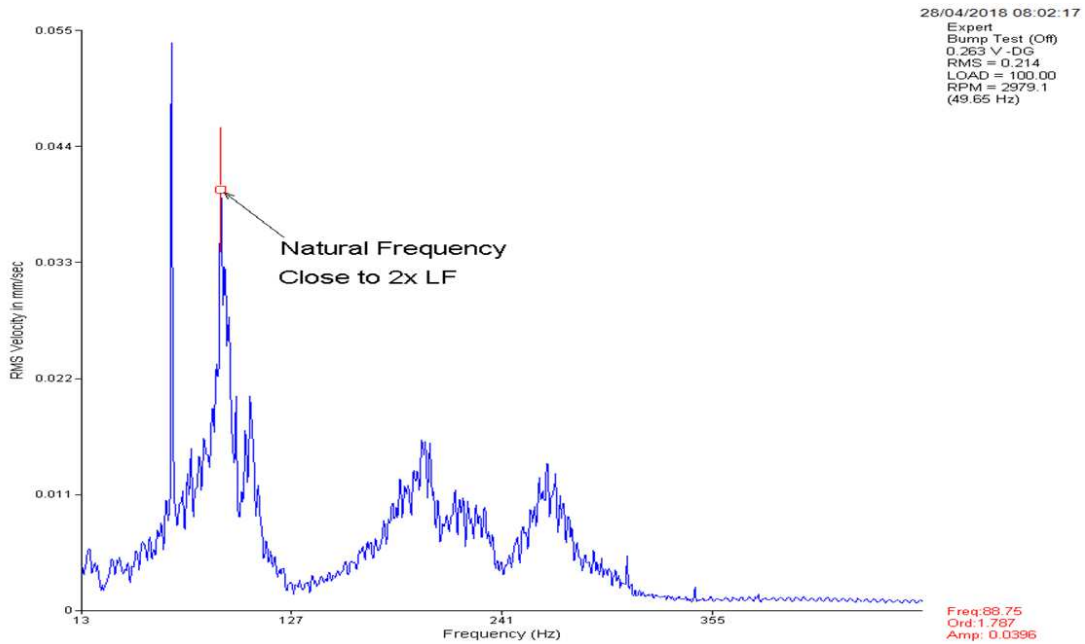


Figure 2: Bump Test (Resonance Test)

The data from an overall vibration coast down test, performed at the motor drive end, are shown in Figure 3. This test also confirms this condition with a peak at 5336 RPM, confirming a forcing function of twice the electrical line frequency.

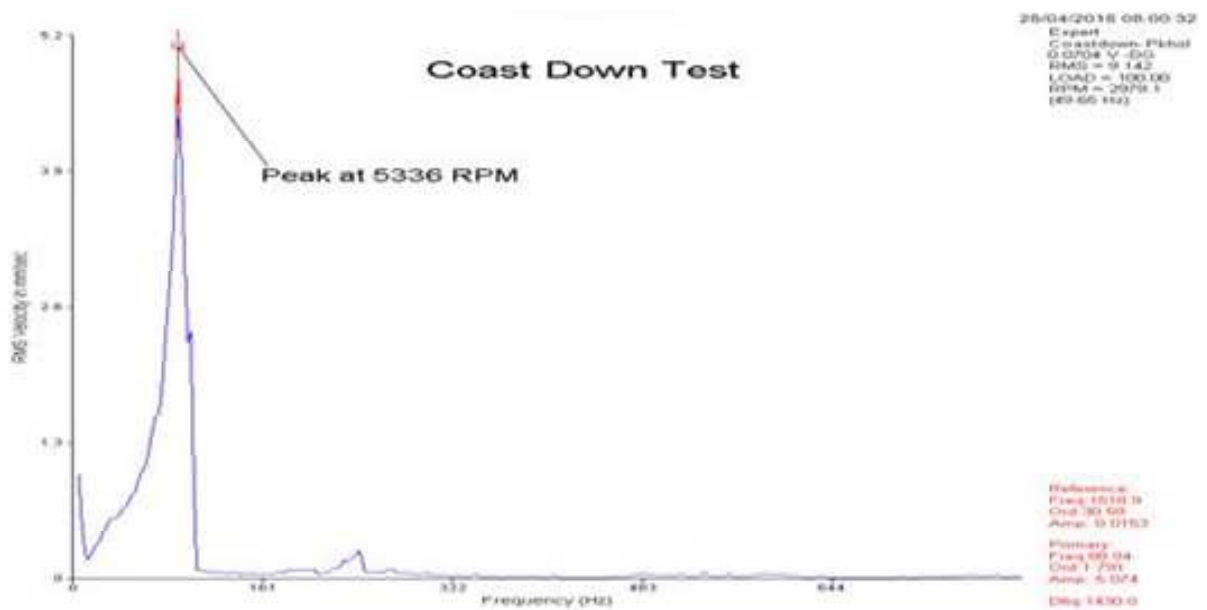


Figure 3: Vibration Coast Down Test (Resonance Test)

A photo of the motor indicating the loosened foot bolt that resulted in the best decrease in amplitude is shown in Figure 4 and a photo of the pump set is in Figure 5.

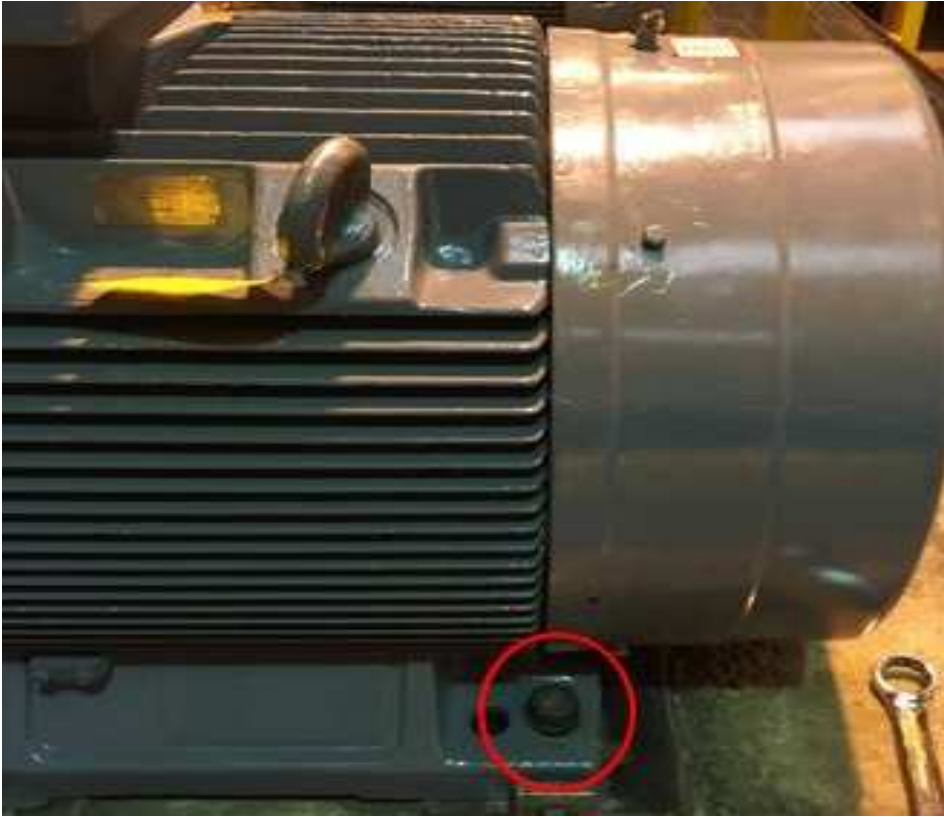


Figure 4: Image of the soft foot location



Figure 5: Pump set

7. Motion of Functionable System through Negative Functionability State

“The main purpose of existence of any system that humans have ever created is to do something, as it is inconceivable to me that something would be specified, designed, produced and acquired by somebody in order to do nothing.” J. Knezevic [1]

According to MIRCE Science philosophy a positive functionability work is done when a functionable system type is delivering functionality performance, which means that it must be in positive functionability state. Hence, the main task of maintenance organisation is to manage negative functionability events through calendar time in a manner that will keep a system in positive functionable state, to do the “work”, as long as practically possible. [1]

The pump considered in the case study was provided as a new from the Original Equipment Manufacturer (OEM), while the motor was overhauled by an aftermarket engineering Repair Company. The pump OEM performed the alignment of the motor to pump, which took 2 days. However, the operator noticed a vibration issue on start up and did not run the pump due to this concern. It took 14 days to decide to and organise the visit of vibration analysis experts to diagnose the functionability state of the pump concerned regarding the experienced during the start up. In due course, and on recommendation of the vibration analyst, the asset owner operator sourced an independent company to fit and precision align another drive motor. This introduced additional costs and another 7 days additional downtime. Once the motor was precision-aligned removing ‘soft foot’ the vibration issue was no more and the pump set ran with low vibration levels.

In summary, the functional system considered has spent over 3 weeks in the NFS, not doing the expected work, consuming resources needed for the successful execution of positive functionability action. The monetary value of the resources consumed constitute the cost of positive functionability action, which together with the cost of loss revenue during those 3 weeks, constitute the total cost to the business caused by non-precision alignment of the pump by the OEM, proving that the precision alignment is “legitimate” mechanism that drives the motion of functionable system type through MIRCE Space.

8. Conclusions

This paper set out to prove that precision alignment is one, of numerous, mechanisms that cause the motion of functionable system type through MIRCE Space, and as such it has impact on the final functionability performance. Theoretical considerations of MIRCE Science were presented in the first part of the paper, with evidential proof through the data obtained during in-service events conducted by the Seasoned Analyst.

MIRCE Science perceives in-service life of functionable system type as a motion through positive and negative functionability states, governed by natural phenomena or human activities, jointly named, functionability actions. Precision alignment is one of these functionability actions that is initiated and performed by humans in order to determine the change in the state of a system in the direction of

calendar time and based on the analysis of the data obtained, the decisions are made regarding the timing and the content of the future functionality actions in a such way that the probability of delivery the expected business plan is maximised.

The case study used in the paper, conducted by the authors, supports the hypothesis that a precision alignment is a mechanism of the motion of rotating machines extensively used in industry throughout the world, through MIRCE Space.

9. References

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Fuel Tank Explosion as a Mechanism of Motion of an Aircraft through MIRCE Space

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Abstract

MIRCE Science is a theory for predicting expected functionability performance for a functionable system type. The accuracy of the prediction is governed by the extent of the scientific understanding of the mechanisms, natural and human rules, that govern the motion of a functionable system types through MIRCE Space. Thus the main objective of this paper is to analyse the mechanisms that cause the fuel tank explosion and move an aircraft from a positive to a negative functionability state. The paper starts with a brief analysis of the major fuel tank explosions that took place in commercial aviation during last 50 year. There is then a brief overview of a typical aircraft fuel system and its constituent elements, including the aviation fuel, followed by the analysis of sources and causes of the explosions in the commercial aviation fuel tanks. Also a brief description of the mechanisms that result in spark initiations due to electric effects is given in the paper. The design measures taken to preclude ignition sources from the fuel tanks are presented at the end of the paper. Finally, the paper illustrates the need for taking existing Engineering knowledge further; to enable prediction of "emerging in-service risk" earlier in the design process. For example, it is essential to link the impact of internal architecture of the aircraft (near air-conditioning units) and its location in the universe (sitting on a runway in Abu-Dhabi) with the increased risk of fuel tank explosion. That extension is provided through MIRCE Science, where the functionability phenomena are recognised, through MIRCE Mechanics, which requires understanding of all internal and external mechanisms that influence the motion of the functionable system type through MIRCE Space, into MIRCE Engineering and MIRCE Management that look at avoiding unwanted risk through engineered solutions or managing the impact of the risk as an integral part of the business plan.

1. Introduction

Scientifically speaking, an explosion is a rapid increase in volume and release of energy, usually with the generation of high temperatures and the release of gases. The prerequisite elements for an explosion are: fuel, oxidiser, and an ignition source. The prerequisite conditions for an explosion are: the existence of a molecular mixture of the fuel and oxidiser in the correct flammable proportions and the existence of an appropriate size and duration of ignition source in the flammable portion of the mixture.

Commercial aviation is one, out of many industries that experience explosions in fuel tanks. The most noticeable events where the prerequisite elements and

conditions have been met and the inevitable fuel tank explosions took place, during last 50 years, are listed below:

- 1963, December 8, Boeing 707, Elkton, MD, USA, JetA/JP-4 mixture, descent for the approach to Philadelphia airport, left wing reserve tank on fire;
- 1967, September 17, Boeing 727, Taiwan, during ground maintenance, rupture of the centre wing tank. The precise source of ignition of fuel Jet A, could not be determined;
- 1970 May 3, Boeing 727, Minneapolis, MN, USA, during refuelling with a fuel Jet A, heavy muffled explosion of the centre wing tank, it is presumed that ignition resulted from a static discharge within the centre wing tank;
- 1970 December 23, Boeing 727, Minneapolis, MN, USA, fuel Jet A, during refuelling, muffled explosion, combustion of the fuel vapour as a result of static discharge internal to the centre wing tank;
- 1973 June 21, Mc Donnell Douglas DC-8, Toronto, Canada, JP-4/Jet A mixture, during refuelling, fuel tank explosion blew off pieces of the right wing top skin and spar structure, ignition of fuel vapour-air mixture in the wing tank vent system;
- 1974, March 23, Mc Donnell Douglas DC-8, Travis AFB, CA, USA, JP-4, during ground maintenance; after removal inoperative fuel boost pump in the left wing fuel tank and installation of a different boost pump an explosion occurred in the left wing centre section, no conclusive evidence of an ignition source was established.
- 1976, May 8, Boeing 747-IIAF, Madrid, Spain, Jet A/JP- 4 mixture, descent for the approach to Madrid airport, explosion and separation of the left wing.
- 1982 June 2, McDonnell Douglas DC-9, Montreal, Canada, Jet A-1, at parking, over-pressure in the forward auxiliary fuel tank, the most probable source of sparks igniting the fuel vapour-air mixture was the transfer pump power supply harness;
- 1989 June 6, Beech jet 400, Washington DC, USA, fuel JP-4/Jet A mixture, during refuelling, fuel surged out of the filler opening, hissing noise followed by a bang, electrostatic charge has been built-up in the aft tank;
- 1990 May 11, Boeing 737-300, Manilla, Philippines, Jet A, at parking, explosion and burning of the centre wing tank. An electrical failure was the source of ignition of the fuel-air mixture;
- 1996 July 17, Boeing 747-100, New York, USA, Jet A, during climbing, in-flight explosion in the central wing tank, at the altitude of 4200 m; Investigators suspect that high voltage from the fuel flow meter passed to the fuel quantity indication system because of a short circuit in the wire bundle;
- 2001 March 3, Boeing 747-400, Bangkok, Thailand, Jet A, parking at the gate, empty centre wing tank exploded as a result of ignition of fuel vapour-air mixture. Only the crew were on board at the time (5 cabin and 3 ground crew), one of whom was killed in the incident;
- 2006, July 13, the left wing fuel tank of a Boeing 727 of Transmile Air Service exploded in Bangalore while being towed on ground,. Explosion destroyed the structural integrity of the left wing. Investigators have found

damaged electrical installation and electrical arcing in aluminium tube with 115 V AC cable feeding the fuel pump motor in the left wing tank. Fuel pump motor wires have melted through the aluminium conduit, exposing the fuel vapours to ignition energy.

- 2012, April 21, Boeing 737 of the Bhoja Airlines, the fuel tanks exploded in mid-air., killing 127 passengers and crew.

The main objective of this paper is to consider the role of the fuel tank explosions as a mechanism of the motion of a commercial aircraft type through MIRCE Space³⁵, among other mechanisms that have been studied in MIRCE Science.

2. MIRCE Science Fundamentals

According to the 2nd Axiom of MIRCE Science the motion of a functionable system type³⁶ through MIRCE Space is the result of an imposed natural phenomena or human activities, which are jointly called functionability actions [1], at any instant of calendar time. A given functionable system type must be in one of the following two functionability states:

- Positive Functionability State (PFS), a generic name for a state in which a functionable system type is able to deliver the expected measurable function(s).
- Negative Functionability State (NFS), a generic name for a state in which a functionable system type is unable to deliver the expected measurable function(s), resulting from any reason whatsoever.

Axiom 4 of MIRCE Science states that “*The probability that a functionable system type will move to a negative functionability state at any instant of time is greater than zero.*” According to Federal Aviation Association (FAA) in USA, the probability of an explosion in a commercial aircraft fuel tank is stated to be 1 in 10⁸ of flight hours³⁷, or 1.4x10⁸ of flight hours, based on statistics of the Association of European Airlines (AEA). Although actual explosions of fuel tanks in commercial aviation are rather rare, it is necessary to understand how they occur, in order to prevent them through design, operational and maintenance actions in the future.

To scientifically understand the mechanisms that generate negative functionability events, analysis of the in-service behaviour of several thousands of components, modules and assemblies of functionable systems in defence, aerospace, nuclear, transportation, motorsport, communication and other industries have been

³⁵ MIRCE Space is an analytical concept created by Dr Knezevic to describe the motion of functionable system type through functionability states in respect to calendar time [1]. Mathematically, it is three-dimensional space with the following coordinates: calendar time, functionability states of a functional system type and a probability of system being in any of these functionable states.

³⁶ According to Knezevic, a functionable system type is “a generic name for a functional system type and the set of functionability rules that govern functionability performance through calendar time.”[1]

³⁷ It is rather confusing to the author that the rate of fuel tanks explosions are expressed in number of occurrences per flying hours, when a reasonable proportion of the explosions took place while the aircraft was on the ground, and often during maintenance!

conducted at MIRCE Academy, under the auspices of MIRCE Mechanics, which is an integral part of MIRCE Science³⁸.

3. Aircraft Fuel System

All powered aircraft require fuel on board to operate the engine(s). Thus, a function of any fuel system is to store and deliver clean fuel to the engine(s) at a required pressure and flow rate regardless of the operating conditions of the aircraft.

A typical fuel system consists of: storage tanks, pumps, filters, valves, fuel lines, metering devices, and monitoring devices. Since fuel load can be a significant portion of the aircraft's weight, a sufficiently strong airframe must be designed. Varying fuel loads and shifts in weight during manoeuvres must not adversely affect control of the aircraft in flight.

Each fuel system for a multiengine airplane is designed in such a way that the malfunctioning of any one component, apart from a fuel tank, does not result in the loss of power of more than one engine or require immediate action by the pilot to prevent the loss of power of more than one engine.

3.1 Fuel Tanks

According Federal Aviation Authorities (FAA) in USA "Each fuel tank must be able to withstand: the vibration, inertia, fluid, and structural loads to which it may be subjected in operation. Fuel tanks with flexible liners must demonstrate that the liner is suitable for the particular application. The total usable capacity of any tank(s) must be enough for at least 30 minutes of operation at maximum continuous power. Each integral fuel tank must have adequate facilities for interior inspection and repair."³⁹

Commercial aircraft primarily use the wing structure to store the fuel, while in larger aircraft the fuel is also stored in the central wing tank (CWT). For example, in the Boeing 747-400 the fuel is stored in the: wing fuel tanks, central wing tank, aft fuel tanks and sometimes in horizontal stabiliser fuel tank. A typical wing tank is irregular, long and shallow. The fuel is in direct contact with the outside skin. Depending upon the aircraft configuration and the degree of control, the aft tank may be used as means of controlling the aircraft centre of gravity (CG). The vented surge tanks are located near each wing tip in a semi-isolated location. These surge tanks function as fuel collectors for relatively small amounts of fuel that may be trapped in the climb vent line during flight manoeuvres and climb attitudes, or during thermal expansion of the fuel. Each surge tank is vented to atmosphere.

³⁸ MIRCE Science comprises of mathematical axioms, equations and methods that enable predictions of functionality performance of each feasible option of the future functionality system type to be done, based on the complex and time-dependent interactions between: physical properties of consisting components, operational rules, maintenance policies, support strategies and expected.

³⁹ https://www.faa.gov/regulations_policies/handbooks_manuals/aircraft/amt_airframe_handbook/media/ama_ch14.pdf, (accessed on 12th July 2018).

Fuel tanks for commercial aircraft are usually made of aluminium alloy, stainless steel or other fuel-resistant materials. Metal fuel tanks are required to withstand an internal test pressure of 24 kPa without malfunction or leakage. Fuel tanks located within the fuselage are required to withstand rupture and retain the fuel underneath the inertia forces during emergency landing, (4.5g downward, 2.0g upward, 9.0g forward, and 1.5g sideward) [4].

3.2 Electric Equipment and Wiring of Fuel Tanks and Wings

Generally speaking, there are two types of fuel pumps on typical aircraft, namely:

- Fuel transfer pumps which perform the task of transferring fuel between the aircraft fuel tanks to ensure that the engine fuel feed requirement is satisfied;
- Fuel booster pumps also called engine feed pumps, which are used to boost the fuel flow from the aircraft fuel system to the engine/

Fuel pumps are driven by 115/220 V induction motors and/or 28 V DC brush motors. Hence, in-tank electric wiring is necessary to provide power to the electric motor-driven fuel pumps submerged in the fuel. As electric wiring and electric equipment always create a potential hazard of short-circuit (SC) and arcing the power cables in fuel tanks are in aluminium conduits (tubes). It is required that wire bundles carried in conduits through fuel tanks be wrapped with an additional protective layer of Teflon

4. Flammable and Combustible Liquids as Explosion Hazard

Flammable and combustible liquids are liquids that can burn⁴⁰. They are classified in accordance to their flashpoints⁴¹. Generally speaking, flammable liquids will ignite and burn easily at normal working temperatures. Combustible liquids have the ability to burn at temperatures that are usually above working temperatures.

There are several specific technical criteria and test methods for identifying flammable and combustible liquids. Under the Workplace Hazardous Materials Information System (WHMIS) 1988, flammable liquids have a flashpoint below 37.8°C. Combustible liquids have a flashpoint at or above 37.8°C and below 93.3°C.

A material's flammable or explosive limits also relate to its fire and explosion hazards. These limits give the range between the lowest and highest concentrations of vapour in air that will burn or explode. The lower flammable limit or lower explosive limit (LFL or LEL) of gasoline is 1.4 percent; the upper flammable limit or upper explosive limit (UFL or UEL) is 7.6 percent. This means that gasoline can

⁴⁰ Flammable and combustible liquids themselves do not burn. It is the mixture of their vapours and air that burns. Gasoline, with a flashpoint of -40°C (-40°F), is a flammable liquid. Even at temperatures as low as -40°C (-40°F), it gives off enough vapour to form a burnable mixture in air. Phenol is a combustible liquid. It has a flashpoint of 79°C (175°F), so it must be heated above that temperature before it can be ignited in air.

⁴¹ The flashpoint of a liquid is the lowest temperature at which the liquid gives off enough vapour to be ignited (start burning) at the surface of the liquid. Sometimes more than one flashpoint is reported for a chemical. Since testing methods and purity of the liquid tested may vary, flashpoints are intended to be used as guides only, not as fine lines between safe and unsafe.

be ignited when it is in the air at levels between 1.4 and 7.6 percent. A concentration of gasoline vapour in air below 1.4 percent is too "lean" to burn. Gasoline vapour levels above 7.6 percent are too "rich" to burn. It is necessary to stress that flammable limits, like flashpoints, are intended for guidance only, not as fine lines between safe and unsafe.

4.1 Aviation Fuel

Each aircraft engine is designed to burn a certain fuel. There are two basic types of fuel: reciprocating-engine fuel (also known as gasoline or AVGAS) and turbine-engine fuel (also known as Jet fuel).

Jet fuel is a type of aviation fuel designed for use in aircraft powered by gas-turbine engines. It is colourless to straw-coloured in appearance. The most commonly used fuels for commercial aviation are Jet A and Jet A-1, which are produced to a standardised international specification. The only other jet fuel commonly used in civilian turbine-engine powered aviation is Jet B, which is used for its enhanced cold-weather performance.

Jet fuel is a complex kerosene-based hydrocarbon mixtures consisting of up to 260 aliphatic and aromatic hydrocarbon compounds, including varying concentrations of potential toxicants such as benzene, n-hexane, toluene, xylenes, trimethylpentane, methoxyethanol, naphthalenes, including polycyclic aromatic hydrocarbons, and certain other fractions, like: n-propylbenzene, trimethylbenzene isomers. [8]

The range of molecular weights, or carbon numbers, is defined by the requirements for the product, such as the freezing or smoke point. Kerosene-type jet fuel (including Jet A and Jet A-1) has a carbon number distribution between about 8 and 16 (carbon atoms per molecule); wide-cut or naphtha-type jet fuel (including Jet B), between about 5 and 1 Table 1 gives the main characteristics of aviation turbine engine fuels Jet A and Jet A-1.[6]

Parameter	Unit	JET A	JET A-1
Density at 15°	kg/m ³	775 to 840	775 to 840
Flash point	°C	38	38
Auto-ignition temperature	°C	210	210
Freezing point	°C	-40	-47
Open air burning temperature	°C	260 - 316	260-315
Maximum burning temperature	°C	980	980
Electric conductivity	10 ⁻¹² S/m	1.0 to 2.0	1.0 to 2.0
Gravimetric energy content	MJ/kg	42.8	42.8
Volumetric energy content	MJ/kg	35.3	34.7

Table 1: Characteristics of fuels JET A and Jet A-1

4.2 Aviation Fuel Ignition

Generally speaking, ignition is considered to be a vapour-phase combustion action with the evolution of heat and emission of light that may or may not be visible to the naked eye. Such reactions are most often associated with the rapid oxidation of a combustible in air or oxygen.

Electrical ignition takes place as result of: [9, 10]:

- Brake sparks when current-carrying conductors are abruptly separated, like when an electric switch is open. The energy is $E = 0.5LI^2$, where L is the inductance;
- A thermal process, in which excessive surface heating is generated by the resistance R to current flow I in an electrical circuit during the time t . The energy generated is equal to $E = I^2Rt$;
- Electrostatic sparks that are formed when the electrical charge of a conductor is sufficient to bridge the gap to another conductor or insulator. The energy generated is $E=0.5CV^2$, where C is the capacitance of charged conductor and V is the potential difference.

There is a definite concentration range over which mixtures of each hydrocarbon in air will burn. This is called the flammable range. Not all fuel-air mixture can be ignited. The composition of the fuel-air mixture in the vapour space is dependent on the fuel type, temperature and physical state, i.e., vapour or mist [11]. Sloshing of the fuel in the tank is the mechanism that is typically associated with mist formation.

When considering the equilibrium conditions only, each fuel-to-air ratio is determined by the temperature and pressure of the system. The temperature determines the quantity of the fuel by controlling its vapour pressure and the altitude determines the quantity of air. Therefore, by a suitable combination of temperature and altitude, under equilibrium conditions, the ullage of a fuel tank can be made either flammable or non-flammable [12].

5. Sources and Causes of Fuel Explosions in Tanks

Analysis of the causes of the ignition of fuel in a commercial aircraft's fuel tanks could be attributes to following sources:

- *In-tank electrical wiring*: hot wires, short circuit, induced currents, chemical damage, mechanical damage
- *Fuel pump motor wiring*: wear of Teflon-sleeving, wear of wire insulation, short circuit, electric arcing
- *Electric motor of fuel pump*: interturn short circuit, phase-to-phase short circuit, phase-to-housing short circuit, hot spots, arcing on terminals
- Pump dry-running (fuel lubricated bearings): sparks generated due to mechanical friction
- *Adjacent systems* (electric anti-ice system and others): electric arcing external to the fuel tank, hot surface ignition explosion within the adjacent area
- *Static electricity build-up due to fuel circulation*: electrostatic discharge from fuel surface to tank walls
- *Lighting*: electrostatic discharge within the fuel tank electrical arcing between components (inadequate distance between components)

6. Mechanisms of Spark Initiations

A brief description of mechanisms of spark initiations due to electric effects is given below:

- *Short circuit (SC)*: is an electrical circuit that allows a current to travel along an unintended path with impedance tending to zero. This results in excessive current flow in the power source through the 'short'. If a fuse is in the supply circuit, it will blow out, and stop the flow of current by opening the circuit. It can produce very high temperatures due to the high power dissipation in the circuit. A short circuit may be in a direct or alternating current (DC or AC) circuit.
- *Electrostatic discharge (ESD)*: is a single-event, rapid transfer (1 ns to 1 ms) of electrostatic charge between two objects, usually resulting from their different potentials, coming into direct contact with each other. It can also occur when a high electrostatic field develops between two objects in close proximity. Electrostatic charge build-up occurs as a result of an imbalance of electrons on the surface of a material, which generates an electric field.
- *Electric arc*: is an electrical breakdown of a gas that produces a continuously moving forward plasma discharge resulting from a flow of a current through normally nonconductive media such as air. The maximum current through an arc is limited only by the external circuit, not by the arc itself. Arcing can also occur when a low resistance channel, like: foreign object, conductive dust, moisture, etc., forms between objects with different potential, as they can facilitate formation of an electric arc. The ionised air has high electrical conductivity approaching that of metals, and can conduct extremely high currents, causing a short circuit and tripping protective devices like, fuses and circuit breakers. The electric arc is recognised as a source of high level of heat. Lee reported that the temperature of metal terminals can be up to 20 000 K [12].
- *Streaming electricity and electrostatic spark ignition*: is a phenomenon generated by the transfers of electrons between contacting surfaces of flowing liquid and a pipe, as they past each other. This charge then initiates potential stems from the chemical reactions taking place at the interface between the wall material of the pipe and the aqueous solution flowing through it. The volume charge developed in the liquid is transported by the flow, resulting in a charging current being carried by the liquid. If the walls of the flow system are insulated or floating, the flow electrification process also leads to an electrostatic charge accumulation (ECA) and the generation of high electrostatic surface potential at interfaces. The lower the electric conductivity of the liquid, the stronger the ECA. Aircraft fuels have electric conductivity of 1.
- *Electrical overstress (EOS)*: is a phenomenon where electrical signals applied to a circuit or a device exceeds normal operating parameters. It is typically defined as an over-voltage or over-current event with a duration exceeding 100 to 1000 ns and nominal durations of 1 ms that occur while the device is in operation. It is typically differentiated from the ESD, which has a shorter duration (1 ns to 1 ms). Events that can lead to EOS damage

include voltage spikes, lightning strikes and any temporary and unexpected connections to power or ground. EOS events cause the transition of a functionable system into NFS due to dielectric breakdown (excessive voltage) or thermal runaway from Joule's heating (excessive current).

- *Thermal overstress*: Thermal overstress (excess heat) can be caused by electrical overstress that take place when a device is subjected to more than its rated current or voltage and it exceeds the power dissipation defined by its safe operating area. ESD can cause thermal overstress, too.

7. Post Fuel Tank Explosion Positive Functionability Actions

The life of a functionable system type, in MIRCE Science, is considered to be the sequence of transitions between the original PFS till the last NFS. [1] The transitions are the result of the corresponding functionability actions, which are of natural or human origins.

According to the research performed by the author, no commercial aircraft that experienced a fuel tank explosion has been exposed to any positive functionability action [1] in order for it to be returned to a PFS. The reason is very simple; the consequences of the explosions of the fuel tanks were of such magnitude that no plausible positive functionability action was possible, as in many cases the whole aircraft was destroyed. Thus, the fuel tank explosion is one of a few definite negative functionability actions that strengthen the claim of the 6th axiom of MIRCE Science: "*A functionable system type ends life in a negative functionability state.*" [1]

8. Design Methods for Reducing the Probability of Fuel Tank Explosions

Since the introduction of kerosene fuel for civil aircraft use in the late 1940's, the aircraft designers have been aware that the ullage would contain a mixture of fuel vapour, or mist and air, which could be ignited in the presence of a spark, flame, or hot surface.

To reduce the probability of fuel tank explosions, the design community has always assumed existence of a flammable vapour in the fuel tanks and adopted standards to preclude ignition sources from the fuel tanks. The following are some of the design measures taken to satisfy that philosophy [7]:

- Electrical energy applied to any component in the fuel tank is limited to a value that is 10 times lower than the Minimum Ignition Energy (MIE) necessary to ignite a fuel-air mixture. The MIE for hydrocarbon vapours is about 0.25 mJ.
- Electrical components and wiring within a fuel tank are designed to handle 1500 V AC that is well in excess of the voltage available on the airplane (115/200 V). It is not allowed to bundle 28 V AC wires and 28 V DC wires (automatic fuel shut off valve).
- It is not allowed to bundle 28 V AC wires and 28 V DC wires (automatic fuel shut off valve).

- The flow of a hydrocarbon type fuel through pipes, valves, filters, etc., causes the ECA in the fuel, which, if relaxed sufficiently fast, could allow the accumulation of hazardous potential levels inside a receiving tank. Therefore, it is necessary to avoid very high rates of fuel flow in the refuelling system and control distribution of the fuel in the tanks. In addition, meticulous attention is paid to electrical connection of all metallic parts to dissipate the charge. The use of special additives in the fuels to increase the fuel electrical conductivity is required in some countries.
- Power limitation devices should be incorporated to minimize power into a fuel tank to eliminate hot spots.
- Surface temperatures inside the tanks, under normal and failure conditions, are kept at least 10°C below the minimum necessary to ignite a fuel-air mixture. Pump motors are kept cool by an integral passage of circulating fuel. The motors have a temperature fuse, which cuts the electrical supply before an unsafe surface temperature is reached. In addition, the pumps and other similar equipment inside the tanks are designed and tested to explosion-proof standards. Bleed air pipes or electric heating elements in the wing leading edges are frequently routed close to fuel tank walls. In such a case, heat-sensitive detector-wires are installed to protect fuel tanks from overheating.
- As, on average, each aircraft is hit by lightning once per year [3] major consideration of fuel system safety is protection against the affects of lightning. When an aircraft is struck by lightning, a pulse of high current flows through the aircraft from the entrance to the exit points. Protection against this phenomenon is provided in a number of ways, like: sound electrically-bonded structure of the aircraft, thick wing skin panels, careful location of tank vents and so forth.

9. Conclusions

MIRCE Science perceives in-service life of functionable system types as a motion through positive and negative functionability states, governed by natural phenomena or human activities, jointly named, functionability actions. This paper set out to analyse the mechanisms of fuel tank explosions, as one of in-service phenomena that cause the motion of an aircraft through MIRCE Space, and as such it has a significant impact on the final functionability performance. The major explosions that took place in commercial aviation during last 50 years are briefly described at the beginning of the paper, under pin the purpose of this paper.

In order to reduce the probability of fuel tank explosions it is essential to understand the physical mechanisms that cause the explosions. In this paper the impacts of malfunctioning electrical equipment installed in the fuel tanks (fuel pumps, fuel probes, level sensors, wiring) and routinely operate in the fuel vapour environment or partially submerged in the fuel are recognised as potential sources of fuel tank explosions together with causes of the consequential electric sparks or arcing phenomena.

The analysis of accidents shows that central wing tank and fuselage mounted tanks experience considerably more explosions than wing tanks, since they are more vulnerable to explosions in the presence of ignition sources. The impact of the surrounded equipment with high energy heat sources, like air conditioning system,

has been analysed and it was concluded that as a result of this additional heat load around the central fuel tank they are more flammable than left or right wing fuel tanks.

Clearly the aircraft design community has recognised that flammable vapour exists in the fuel tanks it has adopted standards to preclude ignition sources from the fuel tanks. Some of the design measures taken to satisfy that emergent risk are presented at the end of the paper.

Finally, the paper illustrates the need for taking existing Engineering knowledge further; to enable prediction of "emerging in-service risk" earlier in the design process. For example, it is essential to link the impact of internal architecture of the aircraft (near air-conditioning units) and its location in the universe (sitting on a runway in Abu-Dhabi) with the increased risk of fuel tank explosion. That extension is provided through MIRCE Science, where the functionality phenomena are recognised, through MIRCE Mechanics, which requires understanding of all internal and external mechanisms that influence the motion of the functional system type through MIRCE Space, into MIRCE Engineering and MIRCE Management that look at avoiding unwanted risk through engineered solutions or managing the impact of the risk as an integral part of the business plan.

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MIRCE Science Based Operational Risk Assessment

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Abstract

The philosophy of MIRCE Science is based on the premise that the purpose of existence of any functionable system⁴² is to do functionability work. The work is done when the expected measurable function is performed through time. However, experience teaches us that expected work is frequently beset by the natural environment, the general population or the businesses, some of which result in hazardous consequences. Undoubtedly, the ability to accurately and quantitatively assess the risk of occurrence of these undesirable and especially those hazardous interruptions early in the design stages would be invaluable for all decision makers. Regardless of whether engineering solutions or management methods are chosen to control the risk, they will have a direct impact on the operational plan that should deliver the expected work, within the expected budget and delivering the expected return on their investment (e.g. profit or performance). For the last sixty years, Reliability Theory has been adopted to address this need. However, the efficacy of these predictions is only valid until the time of the occurrence of the first failure of a functional system. This is seldom understood and far from satisfactory where we are working with repairable or maintainable equipment and systems over their expected life. Consequently, the main objective of this paper is to demonstrate how the body of knowledge contained in MIRCE Science can be used for the assessment of the risk of occurrences of operational interruptions during the expected life of any given functionability system type. MIRCE Science is based on the scientific understanding of the mechanisms that generates the occurrences of these interruptions, considered within a physical scale between 10^{-10} and 10^{10} of a metre. These mechanisms, together with the corresponding applied human rules, shape the pattern of the occurrences of these expected interruptions through what we will come to understand as MIRCE Space⁴³. The life-long pattern expected to be generated by each future functionability system type is predictable, from the early stages of the design, by making use of the MIRCE Functionability Equation, the mathematical formulation of which is presented in this paper. Some real life operational interruptions are analysed and presented in the paper as supporting evidence for the validity of performing risk assessment in accordance with MIRCE Science, which is quantifiable by the amount of functionability work that can be expected to be delivered through the life of each functionable system type.

⁴² **Functionable system** type is a set of mutually related physical entities and human made rules uniquely put together to do functionability work.” [1]

⁴³ **MIRCE Space:** A conceptual space that defines the combination of the MIRCE Functionability Field, which is an infinite but countable set of all possible functionability points, each representing a functionability state that a functionable system type could be found in, with the probability that the functionable system type will be in that state at each instance of calendar time. [1]

0. Dedication

This paper is dedicated to the memory of Margaret Yvonne Stringer (1938-2018), who during last fifteen years supported the creation of MIRCE Science with total commitment, endless energy and enthusiasm, from the administrative point of view.

1. Introduction

According to Einstein “*Everything that the human race has done and thought is concerned with the satisfaction of felt needs*”. Thus, human needs for transporting, communicating, defending, heating, cooling, entertaining and many other functions are satisfied by ships, airplanes, tractors, computers, radios and other functional systems. As they are functioning in accordance to the laws of science, which are independent of time, place and human impact, their designed in functional performance, like speed, acceleration, power, fuel consumption and many others, are accurately predictable. [1]

However, experience teaches us that the operational life of functional systems is frequently beset by undesirable interruptions resulting from:

- Physical and chemical processes taking place inside them, like corrosion, fatigue, creep, abrasion, wear and similar
- Environmental impacts caused by natural phenomena, like: lightning, snow, rain, sand, fog, wind, solar radiation, earthquakes, tsunami and so forth
- Human induced actions, such as lack of operational and maintenance resources (personnel, fuel, spares, facilities, tools, etc), errors in the execution of tasks (operational, maintenance, storage, transportation, and others), organisational issues, regulatory bodies and similar

Needles to say that the above-mentioned operational interruptions result in:

- Hazardous consequences to the users, the natural environment and the general population, like a few major accidents in nuclear energy production: Three Mile Island (1978 in USA), Chernobyl (1986 in USSR), Fukushima (2011 in Japan), Deepwater Horizon oil spill (2010, USA), NTPC power plant explosion (2017 in India) and numerous others.
- Business consequences due to loss of revenue, consumer or public confidence and imposed penalties (contractual/legal). For example in commercial aviation the delay of each flight generate the cost to:
 - the airline due to:
 - loss of income generated by transporting passengers and cargo, poor customer relationships,
 - increased demand for support resources (spares, tools, equipment, etc.),
 - increased numbers of maintenance facilities,
 - including skills and training of personnel required to deal with the consequences of cancellations
 - costs arising from re-routes, aircraft substitution, passenger handling (hotels, buses, meal vouchers)
 - the customer too, due to:

- disrupted plans,
- missed business appointments,
- missed “non-repeatable” family and personal events
- lost time
- potencial consequences to the cargo due to late shipments.

Undoubtedly, the ability to accurately and quantitatively assess the risk of the occurrences of operational interruptions early in the design stages would be invaluable for decision makers. Regardless whether engineering solutions or management methods are chosen to control the risk, they will have a direct impact on the operational plan that should deliver the expected functionality, within the expected budget and, delivering the expected return on investment (e.g. profit or performance). Consequently, the main objective of this paper is to demonstrate how the body of knowledge contained in MIRCE Science can be used for the assessment of the risk of occurrence of these operational interruptions, hazards and business impacts, during the life of any given system created to satisfy human need(s).

2. Reliability Theory Approach to Risk Assessment

The necessity to predict the risk of occurrences of operational interruptions started with the advanced developments within the military, aviation and nuclear power industries where the potential consequences of occurrences of unexpected operational interruptions could have huge hazardous and business impacts. In response to that, during 1950s, Reliability Theory has been “created”. It was based on mathematical theorems rather than on scientific theories. Considerable effort was expended to try and further the application of the existing mathematical and statistical methods and analysis techniques with little effort trying to understand the mechanisms that caused the occurrences of these operational interruptions, commonly known as failures.

It is necessary to stress that there seems to be a certain fundamental difficulty, especially among deterministically educated engineers and managers, in understanding and interpreting reliability functions. This is because stochastic processes (probability) cannot be seen or measured directly, like physical properties. For example, pressure, temperature, volume, weight of a component can be measured and they have clear and measurable meanings. The failure of a system/component is also clear. However, the concept of a reliability function is abstract and immeasurable. It cannot be seen on the system/component. In fact, it serves as an abstract property of a system/component that obtains a physical meaning only when a large sample of systems/components is considered.

In the 1980, with little being understood about the complexities of the mathematics required to address reliability characteristics, the practicing reliability engineers and analysts turned to what they had, which was enormous practical experience of the manners in which failures manifested them, commonly known as failure modes. Thus, a large number of “practical reliability methods” have been developed and used, all of which were based on the failure mode, effect and criticality analysis, but still without fundamentally understanding and addressing mechanism(s) that generated the failure.

2.1 Reliability Function

To illustrate the above statement the fundamental expression for reliability will be used. It is generally accepted that reliability is the probability (P) that a system will operate without failure during a stated period of time (t), thus:

$$R(t) = P(TTF > t) = \int_t^{\infty} f(t)dt, \quad t \geq 0 \quad 1$$

where: $R(t)$ is the reliability function, $f(t)$ is the probability density function of the random variable known as the Time To Failure (TTF) of a system.

The reliability of a system is quantified through the probability that it will not fail up to time t . For example, if calculated reliability for, say 500 hours of continuous operation, is 0.68, it means that, on average, out of 100 components, 68 will not fail within that interval of time, as shown in Figure 3. However, it also means that, on average, in the “physical reality”, 32 systems of this type would have failed during this period of operational time.

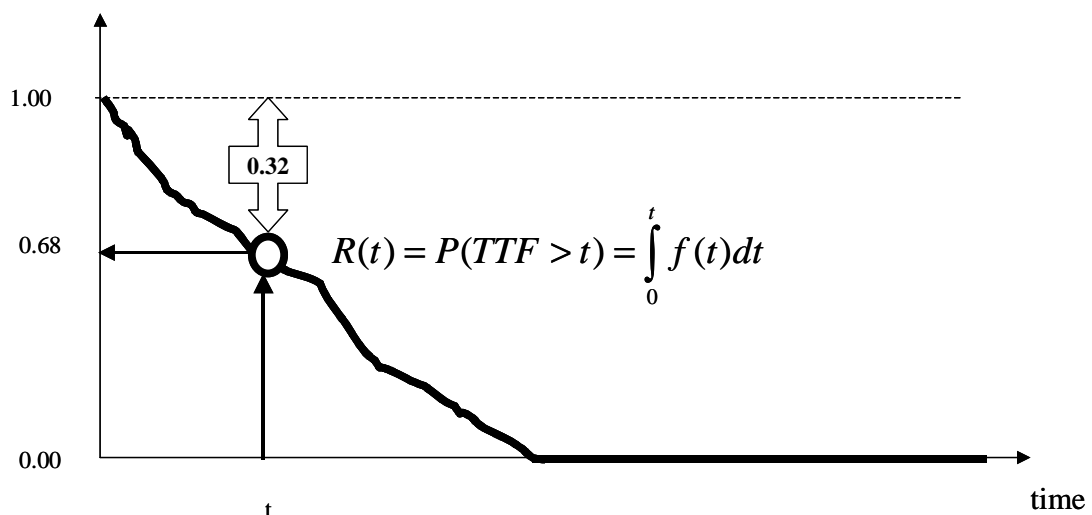


Figure 1: Reliability function of a new system

Regarding non-maintainable or non-repairable systems it is the end of their life story. As the interval of time is increasing the proportion of systems that have failed is also increasing until all of them fail, as Figure 1 clearly demonstrate.

However, if the components of a system are maintainable or repairable it is often difficult to express the reliability of a system in terms of the reliability of its components. Even further, looking at the reliability function shown in Figure 3, it is reasonable to ask what has happened with those “32 systems” that failed before time t . Clearly, some of them could be:

- still in a failed state as nobody did anything to them
- in a state of first repair/replacement
- back in operation, as the first repair/replacement has been completed
- in a failed state for the second time and waiting for repair/replacement
- in a state of second repair/replacement

A small selection of research performed by the author is presented hereinafter, through the observed undesirable interruptions that are were the physical reality of the functionable systems, that took place beyond the assigned Reliability Function and as such were never part of the risk assessments performed originally in the design office, or were performed to some extent, but in a non-representative/erroneous manner, from the operational point of view.

4.1 Design-in Performance of Boeing 747

Between 1965 and 1969 the Boeing Corporation created the Boeing 747 (B747), known as the “Jumbo Jet”. Several thousand-design engineers worked for 4 years to create an innovative, exciting and “globally life-changing” aircraft with the following measurable functionality performance:

Passengers: 3-class configuration 2-class configuration 1-class configuration	366 452 N/A
Cargo:	6,190 ft ³ = 30 LD-1 containers
Engines: maximum thrust	Pratt & Whitney JT9D-7A, 46,500 lb Rolls-Royce RB211-524B2, 50,100 lb GE CF6-45A2, 46,500 lb
Maximum Fuel Capacity:	48,445 U.S. gal (183,380 L)
Maximum Take-off Weight:	735,000 lb (333,400 kg)
Maximum Range:	6,100 statute miles (9,800 km)
Typical Cruise Speed: at 35,000 feet	Mach 0.84, 555 mph (895 km/h)
Basic Dimensions: Wing Span Overall Length Tail Height Interior Cabin Width	195 ft 8 in (59.6 m) 231 ft 10.2 in (70.6 m) 63 ft 5 in (19.3 m) 20 ft (6.1 m)

Table 1: Functionality Performance of B747

Unquestionably, the creation of the B747 was a revolutionary achievement in the history of commercial aviation. However, do airlines buy an aircraft to measure the wingspan or count the number of containers that can be fitted in the cargo department? [1] Certainly not, they purchase them to generate revenue by flying passengers and cargo to their destinations, with the expectation they will be “on time and never crash”.

4.2 In-service Performance of Boeing N747PA

Knezevic in [1] presented a part of the logbook of the very first Boeing 747 owned by Pan Am, registration number N747PA, which, during the 22 years in-service, recorded the following data:

Operational Actions	Unit	Quantity
Airborne	Hours	80,000
Flown	Miles	37,000,000
Transported	Passengers	4,000,000
Take-offs	n/a	40,000
Landings	n/a	40,000
Fuel consumed	Gallons	271,000,000

Table 2: Functionability Performances

The above information is primarily related to the revenue and cost of the flying business, which are of prime importance to Pan Am airlines. However, the most important information, relevant to this paper, is the following, maintenance-related data:

Maintenance Actions	Quantity
Number of tyres replaced	2,100
Number of brake systems replaced	350
Number of Engines replaced	125
Number of times passenger compartment replaced	4
Number of times lavatories replaced	4
Number of X-ray frames of film used for structural inspections for metal fatigue and corrosion	9,800
Number of times metal skin on superstructure, wings and belly replaced	5

Table 3: Maintenance Activities performed on N747PA

All maintenance-related actions (scheduled, conditional and unscheduled) performed on this particular aircraft amounted to 806,000 maintenance man-hours. To make this more meaningful, that equates to around 36,636 maintenance man-hours for each year in-service, or 3,053 hours each month in-service or 102 hours every week in-service or 4.24 maintenance man-hours per day of existence!

Having been academically educated through the mathematics of Reliability Theory and fully aware of the physical reality, summarised with the type of the data shown in Figures 2, the author has been puzzled for decades as to how those two fit together! For example, where are “lives” of those 125 engines used on this particular B747 captured in the reliability function of the B747 type of aircraft?

Consequently, during the last 60 years Reliability Theory made very little progress in terms of becoming a science that practitioners could rely on to make accurate predictions, which could be confirmed by practical observations. The reason is very simple: Statistics does not mandate the need to understand the cause of statistical behaviour. Furthermore Reliability Engineering and Reliability Practitioners were erroneously focused, through contract requirements, on providing some kind of “confidence” or measure of reliability that had to conform to irrelevant doctrine, but

it was simple to generate, manipulate, handle and compare. Only where safety criticality meant failure was not an acceptable option, did anyone explore the realities of how parts or systems would actually fail, usually through extensive and expensive testing or simulation. However this limited and localised understanding of how things really fail did not drive or stimulate the wider community to break free from the standardised, homogenised models and processes entrenched in contracts and apparently legitimised by many training providers and tools to support their use. It is little wonder the science and understanding necessary to underpin failure predictions was unable to find fertile ground for the development of accurate, life-long, risk assessment methods that can identify hazardous consequences and business impacts.

5. The Philosophy of MIRCE Science

Having pointed out some key inadequacy of the Reliability Theory approach to life-long risk assessment for the systems whose operational interruptions could have significant safety or business consequences, the remainder of this paper will present the new body of knowledge, developed and named MIRCE Science, by the author [1].

The philosophy of MIRCE Science is based on the premise that the purpose of the existence of any functionable system is to do functionability work. The work is done when the expected measurable function is performed through time. [1] MIRCE Science is a theory for predicting the expected functionability performance of a functionable system type. The accuracy of the predictions is governed by the degree of scientific understanding available on the physical mechanisms and human rules that govern the motion of the functionable system types through MIRCE Space.

MIRCE Science comprises axioms, laws, mathematical equations and calculation methods that enable accurate predictions of the functionability performance of a given “future” system to be calculated.

In 1993, Knezevic introduced the concept of functionability⁴⁴, which was defined as: “the ability of a functionable system type to do functionability work.” Thus, in MIRCE Science, from functionability point of view, at any instant of calendar time, a given functionable system type could be in one of the following two states:

- Positive Functionability State (PFS), a generic name for a state in which a functionable system type is able to deliver the expected measurable function(s),
- Negative Functionability State (NFS), a generic name for a state in which a functionable system type is unable to deliver the expected measurable function(s), resulting from any reason whatsoever.

The motion of a functionable system type through the functionability states, in the direction of time, is generated by functionability actions, which are classified as:

⁴⁴ Knezevic J., Reliability, Maintainability and Supportability – A Probabilistic Approach, pp.292, plus software PROBCHAR, McGraw Hill, London, 1993.

- Positive Functionability Action (PFA), a generic name for any natural process or human activity that compels a system to move to a PFS.
- Negative Functionability Action (NFA), a generic name for any natural process or human activity that compels a system to move to a NFS.

The motion of a functionable system type through the functionability states is manifested through the occurrences of functionability events, which are classified as:

- Positive Functionability Event (PFE), a generic name for any physically observable occurrence in time that signifies the transition of a functionable system type from a NFS to a PFS.
- Negative Functionability Event (NFE), a generic name for any physically observable occurrence in time that signifies the transition of a functionable system type from a PFS to a NFS.

Consequently, the concept of the motion in MIRCE Science is conceptualised as the change in the functionability state of a functionable system type through time, resulting from any functionability actions whatsoever and the actions required to produce a functionability motion, as shown in Figure 4.



Figure 4: Motion of Functionable System through Functionable states

6. Axioms of MIRCE Science

“Science deprives many from the right to have an opinion.”
Arie Dubi⁴⁵

MIRCE Science is based on the mathematical theory of probability, which is axiomatic. To establish the “structure” for the “scientific truth” within MIRCE Science the following set of axioms has been created:

Axiom 1: A functionable system type begins life in a positive functionability state.

Axiom 2: A functionable system type stays in a given functionability state until compelled to change it by an imposed natural phenomenon or human action.

Axiom 3: A functionability event is an observable occurrence, in the direction of calendar time, at which a functionable system type changes its functionability state.

Axiom 4: The probability that a functionable system type will move to a negative functionability state at any instant of time is greater than zero.

⁴⁵ Dubi, A., System Engineering g Science, Analytical Principles and Monte Carlo Methods, pp 168, MIRCE Science, Exeter, UK, 2003.

Axiom 5: The probability of human error in the execution of any functionality action is greater than zero.

Axiom 6 A functionable system type ends life in a negative functionality state.

These axioms are the bedrock for all the calculations and predictions in MIRCE Science. It is necessary to stress that there are many statements that do not result from these axioms and do not negate them. The statements “The Lancia Stratos is a beautiful car” or “Maintenance is a necessary evil” do not result from any of these axioms nor do they negate any of the axioms. Hence, the axioms of MIRCE Science divide all the statements regarding the behaviour of a functionable system type, through time, into three mutually exclusive groups:

1. True statement: which means it is in accordance with the axioms.
2. False statement: which means it contradicts any of the axioms.
3. Not related: which means that does not come from, nor contradicts, any of the axioms.

These axioms also limit the scope of the application of MIRCE Science, which is correct, as it does not cover the whole spectrum of activities and events in the life of a functionable system type, for example marketing, contracting, insurance and many others.

7. MIRCE Space is Beyond the Reliability Function

“The mathematics is not there till we put it there.”
Arthur Eddington

As mathematics is the language of the science it is necessary to describe the physically observable motion of a functionable system type through the functionality states in the language of mathematics that will enable predictions of the expected functionality performance to be made.

In the language of mathematics, an experiment is defined as: “a real or conceptual act, tasks or process leading to one and only one outcome, at a time, so that the set of all possible outcomes can be specified”. Consequently, in MIRCE Science a functionality point is each distinguishable functionality state that a functionable system type can be found in, at the end of any experiment, dependant on the duration in calendar time over which the experiment has been performed, indexed as t . Thus, the initial or zero positive functionality state at any instant of calendar time t , will be denoted as, $\{PFS_s^0(t)\}$, the first negative functionality state,

$\{NFS_s^1(t)\}$, first PFS $\{PFS_s^1(t)\}$, second NFS, $\{NFS_s^2(t)\}$,, i^{th} NFS, $\{NFS_s^i(t)\}$, and so forth. This new “conceptual entity” was named MIRCE

Functionability Field of a system (MFF_S), and is graphically presented in Figure 7, for a functionable system type. It is an infinite set of possible functionality points, each representing functionality states that a functionable system type could be found during any functionality related experiment, which is defined by the following set [1]:

$$MFF_S(t) = \{PFS_S^{i-1}(t), NFS_S^i(t), i = 1, 2, \dots, \infty, t \geq 0\} \quad 3$$

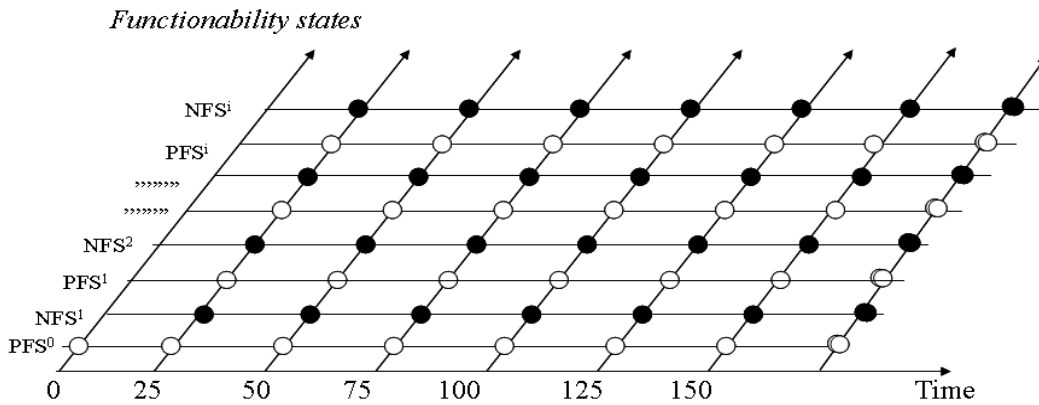


Figure 5: MIRCE Functionability Field

The fundamental functionability events, regarding the functionability state of a functionable system type are fully defined by the following two “new” events:

- {Functionable system type in PFS at a given instant of calendar time}, denoted as $\{PFS_S(t)\}$, represents a union of mutually exclusive functionability points, {functionable system type in PFSⁱ at time t}, denoted as $\{PFS_S^i(t)\}$, is fully defined by the following expression:

$$\{PFS_S(t)\} = \{PFS_S^0(t) \cup PFS_S^1(t) \cup \dots \cup PFS_S^i(t) \dots\} = \bigcup_{i=1}^{\infty} \{PFS_S^{i-1}(t)\} \quad 4$$

- {Functionable system type in NFS at a given instant of calendar time}, denoted as $\{NFS_S(t)\}$, that represents a union of mutually exclusive functionability points, {functionable system type in NFSⁱ at time t}, denoted as $\{NFS_S^i(t)\}$, is fully defined by the following expression:

$$\{NFS_S(t)\} = \{NFS_S^1(t) \cup NFS_S^2(t) \cup \dots \cup NFS_S^i(t) \dots\} = \bigcup_{i=1}^{\infty} \{NFS_S^i(t)\} \quad 5$$

The creation and definition of MIRCE Functionability Field is the foundation on which all analytical elements of the theoretical parts are based.

8. The Concept of MIRCE Space in MIRCE Science

“It is impossible to trap modern physics into predicting anything with perfect determinism because it deals with probabilities from the outset.” Arthur Eddington

Based on numerous observations of the behaviour of functionable system types in the past, it was very clear to the author that the necessary dimension of the motion, in MIRCE Science, is the probability of being in different functionability states, in respect to calendar time. This realisation gave rise to the establishment of the concept of MIRCE Space [1]. It consists of the continuous MIRCE Functionability Field and corresponding probability functions that mathematically define the

physical position of a functionable system type at any instant of calendar time, as shown in Figure 6.

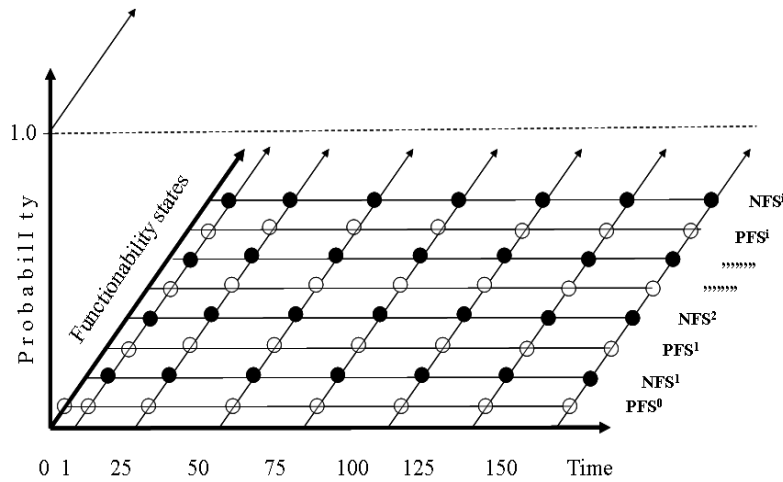


Figure 6: The Concept of MIRCE Space

The definition of a probability function, based on Kolmogorov’s axiomatic approach, applied to a MIRCE Science experiment confined to MIRCE Space is any assignment of a number to each functionability point, representing the probability of a functionable system type being in that particular state, at that instant of calendar time, say a PFS, which fulfilled the following properties:

1. $P\{PFS_s^{i-1}(t)\} \geq 0, \quad i = 1, 2, \dots, \infty, \quad t \geq 0$
2. $P\{MFF_s(t)\} = P\{PFS_s^{i-1}(t), NFS_s^i(t)\} = 1, \quad i = 1, 2, \dots, \infty, \quad t \geq 0$
3. $P\{PFS_s^i(t) \cup PFS_s^{i+1}(t)\} = P\{PFS_s^i(t)\} + P\{PFS_s^{i+1}(t)\}, \quad i = 1, 2, \dots, \infty, \quad t > 0$

This, three-dimensional relationships enabled the creation of the mathematical scheme for the calculation of the expected functionability performance of a functionable system and the associated risk assessment of the occurrences of negative functionability events, with their hazardous or business consequences, for the given functionable system type.

8.1 Probabilistic Motion through MIRCE Space

“Motion does not mean travel of the ball-type electron along some orbit around the nucleus. Motion is the change in the state of the system.”
Werner Heisenberg

The schematic representation of the motion of a functionable system type through MIRCE Space by depicting occurrences of positive and negative functionability events is shown in Figure 9. Distances between sequential events define the length of the calendar time that system spends in a corresponding functionability state. Experimental MIRCE Science has shown clearly that those intervals of calendar time are statistical variables. The sequence and origins of calendar times to the sequential occurrences of positive and negative functionability events, which in MIRCE Science are treated as random variables, are denoted as:

$$TNE_{s,i}, TPE_{s,i}, \quad i = 1, \infty. \quad [1]$$

Hence, for each NFA a probability distribution function can be used to mathematically define the probability of occurrence of the corresponding NFE in respect to calendar time. Therefore, the probability that the NFE will take place before or at a given instant of calendar time, at the system level, is defined by the following expression:

$$F_{S,i}(t) = P(TNE_{S,i} \leq t) = \int_0^t f_{S,i}(t)dt, \quad i = 1, \infty, \quad t \geq 0 \quad 6$$

where: $f_{S,i}(t)$ is a probability density function of the random variable $TNE_{S,i}$.

Correspondingly, for any positive functionability action, there is a probability distribution function that mathematically defines the probability of the occurrence of the corresponding positive functionability event during any interval of calendar time, t , which is defined by the following expression:

$$O_{S,i}(t) = P(TPE_{S,i} \leq t) = \int_0^t o_{S,i}(t)dt, \quad i = 1, \infty, \quad t \geq 0. \quad 7$$

where: $o_{S,i}(t)$ is a probability density function of the random variable $TPE_{S,i}$

8.2 Sequentiality of Functionability Events in MIRCE Science

The continuous motion of the functionable system type through the functionability states, contained in the MIRCE Functionability Field, was the foundation of the “mathematical interpretation” of the observed physical reality. It is based on a framework of the sequential nature of the occurrences of PFEs and NFEs in the direction of calendar time. However, the author has been fully aware that probability functions defined by equations 9 and 10 start from their own individual times of origin [1]. That factual truth causes additional challenge, as in the life of any functionable system type there is only one time of origin, as far as the author is concerned. It is denoted as $t=0$ and it signifies the introduction of the functionable system type into operational existence. Hence, all other functionability events must have reference to it.

Figure 7 schematically represents the sequence of occurrences of positive and negative functionability events, with both origins of calendar time, cumulative from $t=0$ and from the occurrence of the previous functionability event.

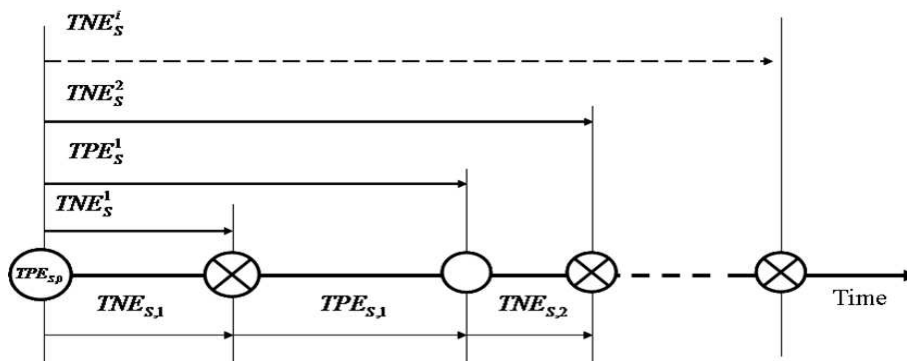


Figure 7: Individual and Cumulative Times to Positive and Negative Functionability Events in MIRCE Science

At this point it is necessary to clearly understand the difference between the measuring and predicting processes. Experimental MIRCE Science, given sufficient time, would be able to measure numerical values of $TNE_s^i, TPE_s^i, i = 1, \infty$ and then use adequate statistical methods to determine the probability distribution functions for all of them. These functions, in generic form are described in the following manner:

$$O_s^i(t) = P(TPE_s^i \leq t) = \int_0^t o_s^i(t)dt, \quad i = 1, \infty, t \geq 0 \quad 8$$

$$F_s^i(t) = P(TNE_s^i \leq t) = \int_0^t f_s^i(t)dt, \quad i = 1, \infty, t \geq 0 \quad 9$$

Needles to say that any solution to the quest for the risk assessment would have no practical application if an infinite period of testing time is spent testing each feasible design solution of the new functionable system type. Consequently, the main challenge during the creation of MIRCE Science was the creation of a theoretical scheme that would mathematically calculate the sequential occurrences of the functionability events in the direction of the calendar time, for each feasible variation of a functionable system type being considered [1].

Thus, the sequential positive functionability function, $O_s^i(t)$, which defines the probability that the PFE_s^i in the life of a functionable system type, will take place before or at the instant of calendar time t , is defined by the following convolution integrals:

$$\begin{aligned} O_s^i(t) &= P(TPE_s^i \leq t) = P(TNE_s^i + TPE_{s,i} \leq t) \\ &= P(TNE_s^i \leq x \cap TPE_{s,i} \leq t - x) \\ &= \int_0^t F_s^i(x) o_{s,i}(t - x)dx = \int_0^t F_s^i(x) dO_{s,i}(t - x), \quad i = 1, 2, \dots, \infty, t \geq 0 \end{aligned} \quad 10$$

The above mathematical interpretation has the following physical meaning: in order for the i^{th} sequential positive functionability event, PFE^i , to take place before, or at the instant of calendar time t , it is necessary that the previous functionability event, which in this case is NFE^i , takes place sometime before time t , denoted by x in the above expression. Then, the sequential PFE_i has to take place during the remaining interval of calendar time, which in this case is denoted with $(t-x)$, where the value of x , goes from zero to t [1].

The process of defining the negative sequential distribution Function, $F_s^i(t)$, which defines the probability that the i^{th} sequential NFE of the functionable system type will take place before or at an instant of calendar time t , follows the same mathematical principle. Thus, the sequential negative functionability function is fully defined by the following equation [1]:

$$\begin{aligned}
 F_s^i(t) &= P(TNE_s^i \leq t) = P(TPE_s^{i-1} + TNE_{s,i} \leq t) \\
 &= P(TPE_s^{i-1} \leq x \cap TNE_{s,i} \leq t - x) \\
 &= \int_0^t O_s^{i-1}(x) f_{s,i}(t-x) dx = \int_0^t O_s^{i-1}(x) dF_{s,i}(t-x), \quad i=1,2,..,\infty, t \geq 0
 \end{aligned}
 \tag{11}$$

The above two generic functions, defined in the form of convolution integrals, are the foundation of subsection of the operational behaviour of a functionable system type to the methods of science and the development of the theory for the quantitative prediction of functionability performance of any functionable system type [1].

Theoretically speaking, with these multidimensional integrals it became possible to “move through” MIRCE Space, by passing through each sequential functionability state in the direction of calendar time, and thus generating a trajectory unique to each functionable system type, as illustrated, for a hypothetical system, in Figure 8 (Negative Functionability Functions are represented by the broken lines). The reason for that was the fact that the same set of generic equations, when applied to different design solutions, will generate different trajectories of the motion through MIRCE Space, which means different exposure to the associated risks. Hence, a generic platform had been created on which each feasible design solution will generate its own future “trajectory”.

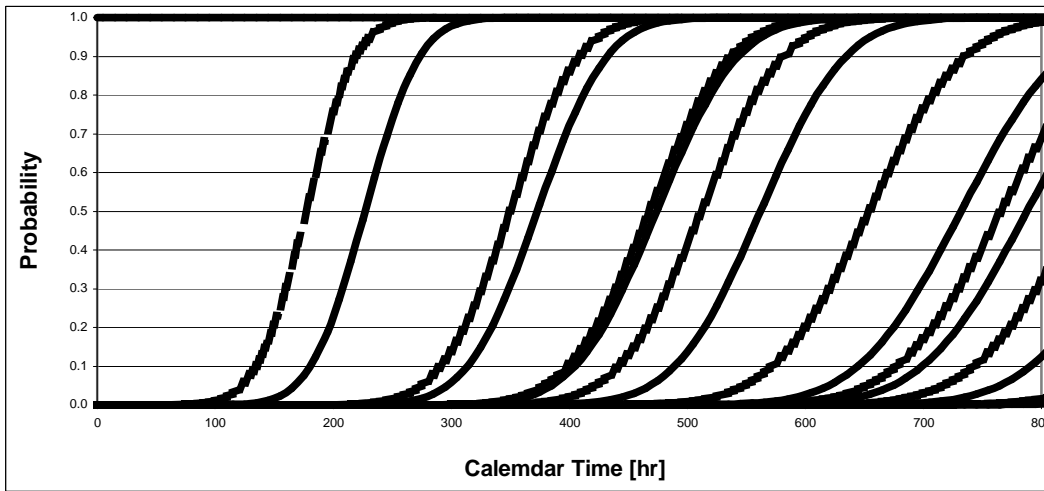


Figure 8: Sequential Occurrences of Positive and Negative Functionability Functions

Those futures “trajectories” can be compared, improved or modified, until the final configuration of a system is chosen. Naturally, each trajectory is associated with its own corresponding risks and their consequences. However, this predicted “future trajectory” for a functionable system type includes concerns of both interested sides, producers and users, or planners and managers.

9. MIRCE Functionability Equation

The trajectory of functionability is uniquely defined by the sequence of functionability events, from the birth of the system to its decommissioning. Thus,

the fundamental equation of MIRCE Science, the functionability equation $y(t)$, that defines the probability of a system being functionable at a given instant of time t is defined as:

$$y_s(t) = P\{PFS_s(t)\} = \sum_{i=1}^{\infty} y_s^i(t) = \sum_{i=1}^{\infty} [O_s^{i-1}(t) - F_s^i(t)], \quad t \geq 0 \quad 12$$

Equation 12 defines the expected trajectory of the motion of functionable system type through positive functionability states of MIRCE Space, while doing positive functionability work. As the above expression was developed by the author at the MIRCE Academy, it was named the MIRCE Functionability Equation⁴⁶.

Figure 9 shows the MIRCE Functionability Function for a hypothetical functionability system. The “classical” reliability function (Eq. 1) for this system is represented by a broken line.

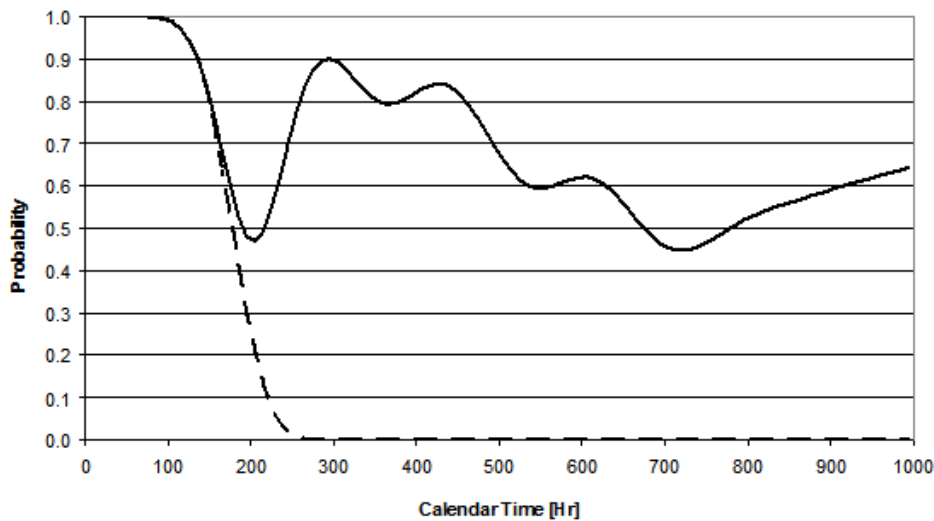


Figure 9: MIRCE Functionability Function for a Hypothetical System

It is obvious that the reliability function is a special case of the functionability function (Eq. 12), when $i=1$, $y_s(t) = P\{PFS_s(t)\} = O_s^0(t) - F_s^1(t) = 1 - F_s^1(t) = R_s^1(t)$.

10. MIRCE Functionability Work Equations

“All truths are easy to understand once they are discovered. The point is to discover them.” Galileo Galilei (1564-1642)

According to MIRCE Science philosophy the positive functionability work is done when a functionable system type is delivering functionality performance (See Table 1 for the Boeing 747), which means that it must be in positive functionability state. The area under the trajectory of the motion of a functionable system type through MIRCE Space, defined by the MIRCE Functionability Equation, is equivalent to the positive functionability work done by the system in the interval of calendar time T .
[1]

⁴⁶ Dr Jezdimir KNEZEVIC Int. Journal of Engineering Research and Applications www.ijera.com ISSN: 2248-9622, Vol. 4, Issue 8(Version 7), August 2014, pp.93-100

The expected positive functionality work to be done by a functionable system type during a given interval of calendar time T , $PFW'_s(T)$, measured in calendar hours, Hr, can be calculated by making use of the following equation:

$$PFW'_s(T) = \int_0^T y_s(t) dt \quad [Hr] \quad 13$$

By making use of the above equation it is possible to calculate, during the design stages, the expected functionality work that would be done by a given functionable system type, for each of feasible options of the future system. This is a huge advantage, compared to current practices where the work done in the past is measured during the operational life of a functionable system type and then the necessary statistics produced for the sample size only.

Consequently, the life of a functionable system could be considered as the motion of the system through the functionality states. The pattern generated by the motion of functionality through the functionality states, in respect to the passage of time, forms the functionality trajectory. Clear examples of this fact are the motions of F1 cars during the Monaco Grand Prix 2018 through the PFSs (see Table 5) and the NFS (see Table 4), in their MIRCE Space.

11. MIRCE Mechanics

Based on several decades of experiencing and researching the operational behaviour of functionable system types, the author was convinced that in order to understand them and even more to predict their behaviour, it is necessary to understand the physical mechanisms that govern the occurrences of functionality events. Without a scientific understanding of these mechanisms it would be impossible to determine the most appropriate probability distribution functions that accurately describe the motion of functionable system types through MIRCE Space and ultimately quantify the functionality work done and corresponding functionality costs. For that to happen, it is essential for the generic random variables in Equations 6 and 7 to be “physicalised”, for each functionable system. It is required by a science based understanding of the physical processes and human rules that determine them and only then used them in: engineering, technological, business and economical contexts. It is necessary to stress that “Mathematics does not teach us how to think correctly.”⁴⁷

To facilitate a higher level of accuracy between observable physical processes and human actions and their mathematical descriptions through probability distribution functions the author has created MIRCE Mechanics. It is a part of MIRCE Science that is exclusively focused on the science based understanding and description of the physical mechanisms that govern the behaviour of functionable system types and consequently their functionality performance.

⁴⁷ Pasternak, J., *Indefinability, An Essay on the Philosophy of Cognition*, Page 118, edited by Arne F. Petersen, pp. 144, Published by Museum Tusulanum Press, University of Copenhagen, Denmark, 1993. ISBN 10: 877289531

11.1 Negative Functionability Events Generating Mechanisms

According to the second axiom of MIRCE Science the motion of functionable systems through MIRCE Space is a result of imposed natural phenomena or human actions, which are jointly called functionability actions. It could be regarded as analogous to force in Newtonian mechanics. Numerous observational studies and experiments conducted have shown that just counting the occurrences of functionability events that signify transitions from PFS to NFS is sufficient enough for the statistical analysis of the data, but not for understanding the physical mechanisms that cause their occurrences⁴⁸, the reason why it happened.

To scientifically understand the mechanisms that generate negative functionability events, analysis of the operational behaviour of several thousands of components, modules and assemblies of functionable systems in defence, aerospace, nuclear, transportation, motorsport, communication and other industries have been conducted at MIRCE Academy.

In MIRCE Science all negative functionability actions are categorised as following [1]:

- **Component-internal actions:** that consist of:
 - Inherent actions that are introduced into components prior to their introduction into operational life through the activities associated with the design, manufacturing, handling, transportation, maintenance, storage and similar processes.
 - Cumulative continuous actions that are an inevitable part of the components operational life resulting from natural decay processes such as: corrosion, fatigue, creep, wear and similar.
- **Component-external actions:** which are originated by:
 - Environmental phenomena that cause discrete overload, like foreign object damage; birds strike (domestic and wild animals), weather (hail, rain, snow, lightning, solar radiation, etc..) and so forth.
 - Human activities:
 - Errors that are related to phenomena that cause overload, for example use and abuse by operators, (pilots, driver and other users), maintainers (maintenance induced errors) and logistics support personnel (bogus parts, shelf life, etc.)
 - Rules that are related to organisational policies, legal requirements, national and international, best practices or any other human imposed functionability related actions (scheduled and condition based maintenance tasks).
- **System-internal actions:** resulting from processes that are taking place within a system, like a change from passive to active state for certain components and modules, a change in functionability states of some of its constituent components that impact the functionability of the system.
- **System-external actions:** which are generated by:

⁴⁸ Knezevic, J., *Inherent and Avoidable Ambiguities in Data Analysis*, SRD Assoc. Member's Technical Symposium, "Data, Information Decision Making", pp 31,39, AEA Conference, Risley, U.K., 28th February 1996.

- Discrete environmental phenomena related to weather (hail, rain, snow, lightening, volcanic eruptions, strong wind, solar radiation, etc.) and other causes that impact on the functionality of a functional system type.
- Human activities:
 - Errors, which are related to the phenomena of use and abuse by: operators, maintainers or supply chain personnel.
 - Rules, which are related to organisational policies, legal requirements, national and international, best practices or any other human imposed functionality actions that cause the occurrence of NFEs for the functional systems.

During the last 40 years of research in reliability the author has learned and proven that the time to occurrence of negative functionality event, denoted as TNE, is a random variable that is defined by the appropriate probability distribution⁴⁹. Thus, each negative functionality event must be associated with a single physical mechanism or human action that generated it.

11.2 Positive Functionability Actions

To scientifically understand the mechanisms that generate positive functionality events, analysis of the motion of several thousands of components, modules and assemblies of functional systems in defence, aerospace, nuclear, transportation, motorsport, communication and other industries through NFS state have been conducted at MIRCE Academy. Consequently, in MIRCE Science all positive functionality actions are categorised as following [1]:

- **System-Internal actions:** commonly known as maintenance tasks, are further categorised as following⁵⁰:
 - Servicing: replenishment of consumable fluids, cleaning, washing and similar.
 - Lubrication: installing or replenishing lubricant.
 - Inspection of a component against a defined physical standard.
 - General visual inspection: performed to detect obvious unsatisfactory conditions.
 - Detailed visual inspection: consists of intensive visual search for evidence of any irregularity, usually assisted by inspection aids.
 - Special visual inspection: an intensive examination of a specific area using special inspection equipment such as radiography, thermography, dye penetrant, eddy current, high power magnification or other Non-Destructive Testing (NDT).
 - Examination: a quantitative assessment of one/more functions on a component to determine whether it performs within acceptable limits.

⁴⁹ Knezevic, J., *Modelling System Reliability - Way Ahead*, CODERM Newsletter, Vol. 12, No. 2, pp 8-9, MOD, UK, June 1995.

⁵⁰ Ben-Daya, Duffuaa., Raouf, Knezevic and Ait-Kadi, D. (2009), *Handbook of Maintenance Management and Engineering*, Springer, Dordrecht, Heidelberg, London and New York, NY, USA.

- Restoration: perform to return a component to a specific standard. This may involve cleaning, repair, replacement or overhaul.
- Discard: removal of from operational life.
- **System-External actions:** related to activities that are affecting the whole functionable system and they are grouped in the following manner:
 - Environmental positive actions: fog lifting, thawing, decontamination, washing and so forth.
 - Legal positive actions: related to all activities that are required to be performed due to health and safety regulations at national and international level of jurisdictions and restrictions.
 - Organisational positive actions those are specific to a user or group of users of functionable systems, which could relate to marketing, operational, political, economical and other functions.

11.3 Physical Scale of MIRCE Mechanics

A full understanding of the mechanisms of the motion of functionability phenomena that drive the occurrence of functionability events is essential, as statistical methods used to analyse and quantify reliability do not study the causes of statistical behaviour. Consequently, systematic studies must be applied to understand the phenomena that cause the occurrence of:

- **Positive Functionability Events:** such as: birth (beginning of operational life), servicing, lubrication, visual inspection, repair, replacement, final repair, examination, partial restoration, trouble shooting, storage, modification, transportation, sparing, cannibalisation, refurbishment, health monitoring, restoration, packaging, diagnostics and similar.
- **Negative Functionability Events,** such as: thermal ageing, actinic degradation, fatigue, pitting, acid reaction, bird strike, warping, abrasive wear, suncups formation on the blue ice runway, thermal buckling, photo-oxidation, production errors, strong wind, maintenance error, hail damage, lightning strike, hard landing, quality problems, sand storm and so forth;

In order to understand the motion of functionability it is necessary to understand the mechanisms of the motion. That represented a real challenge. Answers to the questions “what is the real cause of say, fatigue, the wind direction change, suncups formation on the blue ice runway, faulty weld, bird strike, perished rubber, maintenance induced error, carburettor icing”, to name just a few, have to be provided. Without accurate answers to those questions the prediction of their future occurrences is not possible, and without ability to predict the future, the use of the word science becomes inappropriate.

For years, research studies, international conferences, summer schools and other events have been organised in order to understand just the physical scale at which functionability phenomena needs to be studied and understood. Resulting from these numerous discussions, studies and trials, it has been concluded that any serious studies in this domain, from Mirce Mechanics point of view, have to be informed by the following two boundaries:

- the “bottom end” of the physical world, which is at the level of the atoms and molecules that exists in the region of 10^{-10} of a metre⁵¹ ;
- the ”top end” of the physical world, which is at the level of the solar system that stretches in the physical scale around 10^{+10} of a metre⁵².

This range is the minimum sufficient “physical scale” which enables a scientific understanding of relationships between system operational processes and system operational events. In other words, this is the physical range within which, the system operational processes mentioned above (fatigue, the wind direction change, suncups formation on the blue ice runway, bird strike, perished rubber, carburettor icing) take place and as such can be understood and predicted.

12. The Role of MIRCE Science in Life Cycle Engineering and Management

Although science has to be truthful, rather than useful, MIRCE Science is essential for scientists, mathematicians, engineers, managers, technicians and analysts in industry, government and academia who have an interest in predicting the functionability performance of a given functional system type in order to maximise the benefit, in accordance with their chosen criterion⁵³. For that to happen, MIRCE Science equations are required. These equations are different in many ways from those used in classical sciences that are based on the deterministic equations; independent of time and human influences and used for predicting the functionality performance of functional system types.

The main task of any "component/product design" engineer and manager is to make decisions regarding the individual components/products allocated to them. For a component/product of their concern they have to decide on the single solution among all possible alternative solutions. For example, certain decisions might benefit reliability performance, but at the same time increase production and/or maintenance cost. Others might reduce the development cost but increase Not-Fault-Found rate or Turn-Around-Cycle. Hence, engineers and managers constantly conflict and compromise as they strive to do their best regarding their own component/product.

The main job of a functional system type designer is to understand the decisions made by the “component” engineers and to incorporate them into the "best functional system type option" in response to the given functionality and functionability performance requirements, in the time available and within the budget allocated. In order for that to happen, multi dimensional trade-offs have to be made, at the system type level. For example, Jack Hessburg’s job, as a Chief

⁵¹ Knezevic, J., “Atoms and Molecules in Mirce Mechanics Approach to Reliability”, SRESA’s International Journal of Life Cycle Reliability and Safety Engineering, vol. 1, no. 1, pp. 15-25. Mumbai, India, 2012.

⁵² Knezevic, J., Papic, Lj., “Space Weather as a Mechanism of the Motion of Functionability through Life of Industrial Systems”, Advances in Industrial Engineering and Management, Vol. 4, No. 1 (2015), 1-8, American Scientific Publishers, Printed in the United States of America.

⁵³ Knezevic, J., Impact of Correctness of Reliability Analysis on Effectiveness of Logistic Support Analysis, CODERM, News Letter, MOD, U.K. Vol. 12, No. 1, pp 8-9, January 1995.

Mechanic of Boeing 777⁵⁴ (B777), was to design the B777 so that it will “fly on time and never crash”, not a landing gear, engine, air-conditioning system or any other part in isolation. To this end, Hessburg nurtured the desire to have the ability to normalise these extremely complex trade-offs between the “functional B777”, as perceived by the Boeing Corporation, and “functionable B777”, as perceived by United Airlines. This has now materialised in the creation of the axioms, methods and mathematical scheme of MIRCE Science.

With the continuous increase in the complexity of the new technologies used in modern systems, relying solely on the “personal experiences and gut feelings” of system engineers and project managers to make critical decisions is no longer viable or in fact possible. Perhaps the main reason for that is the corresponding increase in uncertainty regarding the consequences of each decision made on the future operational behaviour of a system. Hence, the main concern of the functionable system type decision makers is the ability to quantify and normalise the future consequences of their decisions, across the feasible options. This is not possible to perform accurately and dependably without the body of knowledge encapsulated in MIRCE Science

The most important feature of MIRCE Science is that all decisions are based on the total quantification of the measures of functionability performance for each design option, with full visibility of all the rules and assumptions made, rather than on intuition, “gut feelings” or seniority of the engineers and managers within the design team. This epitomises the phenomenon phrased by Professor Dubi, “The more complex the problem the less one needs to learn in order to have an opinion.”⁵⁵

13. Conclusions

The main objective of this paper was to present the MIRCE Science approach to risk assessment, one that is based on the laws of science, which denies the existence of parallel universes where the laws are either ignored or bent to accommodate administrative or contractual requirements. Within this paper we have seen a prime example of the later in the well accepted model of system reliability that requires the acceptance of this concept of an “alternative universes” that is based on the argument that components and consequently systems possess a constant, time independent, failure rate, while totally ignoring the physical existence of operational, maintenance and support processes which generate observable undesirable interruptions into the operational life of functionable systems. This approach stems from neither science nor observation, but from a lack of consequence in using models and processes that did not accurately reflect the future reality of the products and systems delivered to the end users. This acceptance of inaccurate predictions that led to: erroneous spares procurement; inability to forecast or schedule repair: loss of operational capability (at inopportune moments) and unhappy Customers, had little impact on those proponents who actively defended the cause and simply allowed all laws of science to be suspended. As a

⁵⁴ Knezevic, J., Chief Mechanic: the New Approach to Aircraft Maintenance by Boeing, Journal of Quality in Maintenance Engineering, Volume: 5 Issue: 4, 1999

⁵⁵ Dubi, A., System Engineering g Science, Analytical Principles and Monte Carlo Methods, pp 164, MIRCE Science, Exeter, UK, 2003

professional community we must accept this doctrine is in direct opposition to the observed physical phenomena like corrosion, fatigue, creep, wear and similar undesirable interruptions resulting from accumulation of “damage” and human dependent physical processes that generate; production, transportation, operation, maintenance and storage related risk events, which clearly demonstrate the inadequacy of system reliability function (Eq. 1 and 2) to predict with any degree of confidence the life-long behaviour of functionable systems and especially as a basis for any risk assessment tasks.

Finally, it is essential to re-state the distinction between the scientific formulation of the motion of functionable systems through functionability states, contained in MIRCE Science and Mechanics and presented in this paper, from the administrative approach that is based on reliability models of systems that are created to demonstrate the contractual compliance of a legally binding acquisition processes, as it is the case in many industries today. It must be stressed that science is the proved model of reality that is confirmed through observation, so in closing, the author wishes to encourage all reliability professionals to move from the universe of convenience, in which the laws of science are suspended, to this universe that is based on the laws of science, as only then can true risks assessments and reliability predictions reflect future realities. It is the author’s believe that all of those professionals, who wish to embrace accurate and operationally confirmed risk assessment tasks, will welcome the body of knowledge contained in MIRCE Science as the proven foundation for their future professional endeavours.

14 Acknowledgements

I wish to acknowledge the hard work of my students during last 35 years, without naming any individual one, at Exeter University and MIRCE Akademy, for hours of research regarding the operational behaviour of functionable systems that I continually conducted with total dedication to learn the physical mechanisms of the motion as the pre-requisite for their mathematical formulation.

Also, my huge thank you goes to the Fellows and Members of the MIRCE Akademy, past and current, whose professional experience accelerated the process of the creation of MIRCE Science in each individual way and I hope will also facilitate its applications.

Last but not least, I wish to thank Dr Varde from Bhabha Atomic Research Centre, Mumbai, for keeping our professional collaboration healthy and pleasurable, since its beginning, almost 10 years ago.

15. References

[1] Knezevic, J., The Origin of MIRCE Science, pp. 232. MIRCE Science, Exeter, UK, 2017, ISBN 978-1-904848-06-6

Appendix A: Worldwide Observed MIRCE Science Functionability Events

As a part of the continuous process of collecting information on the observed behaviours of functionable system types through operational processes, in June

2014, the author started collecting the worldwide functionability events⁵⁶ that are relevant to MIRCE Science.

Full text of the relevant events and processes, together with our additional research, is kept in the archive of the MIRCE Akademy, while short descriptions of them are posted on the Akademy's website⁵⁷ for all interested parties, of course, free of charge.

- 12th June 2014: Unfavourable Winds Delay Test Flight of NASA's Low-Density Supersonic Demonstrator
- 23rd June 2014: Fire on Board of F-35A
- 14th July 2014: Cause of Fire on Board of F-35A
- 15th July 2014: Oil Leak Stopped Test for C Series Engine
- 17th July 2014: Malaysia Airlines Flight MH17 Shot Down
- 25th July 2014: MD-83 Wreckage Found in Mali
- 16th October 2014: Solar Power Channel Repair of the International Space Station
- 17th October 2014: Spaceplane X-37B landed after 675 days in orbit
- 22nd October 2014: 218 minutes of Functionability Actions on the International Space Station
- 23rd October 2014: SpaceX Dragon capsule's return delayed due to heavy seas
- 29th October 2014: Orbital Sciences Antares Rocket Blew up 10 Seconds After Liftoff
- 31st October 2014: Virgin Galactic's Accident
- 8th December 2014: Light Jet Crashed Near the Airport in Washington D.C. Area
- 28th December 2014: Air Asia Airbus A320 crashes in the Java Sea:
- 5th January 2015: Technical Problem Scrubbed a Launch of SpaceX to ISS:
- 12th January 2015: SpaceX Dragon Resupply Capsule Grappled by ISS Astronauts
- 14th January 2015: Astronauts Forced to Abandon Part of ISS:
- 15th January 2015: False Alarm Caused Evacuation of Astronauts in ISS:
- 26th January 2015: Airlines Cancelled 1,900 U.S. Flights as Storm Hits Northeast
- 19th February 2015: NASA Delays Space Station Space Walk because of suit Issue
- 1st March 2015: ISS Docking Port Antenna Installations Completed:
- 2nd March 2015: USAF Weather Satellite Explodes After Thermal Spike
- 4th March 2015: Turkish Airline jet skidded in Nepal
- 4th March 2015: ESA experts assess risk from exploded USAF weather satellite

⁵⁶ Vast majority of the information presented below comes from the Journal "Aviation Weekly and Space Technology", which has been providing fast and up to date information through their daily Aviation Weekly Bulletin service

⁵⁷ <http://www.mirceakademy.com/index.php?mact=News,cntnt01,detail,0&cntnt01articleid=15&cntnt01returnid=15> (accessed on 13 August 2018)

- 19th March 2015: Lufthansa Technik's Robot-based Inspection of Engine Components
- 23rd March 2015: Engineering Judgment Key in 757 Forced Landing In Antarctica
- 24th March 2015: Germanwings A320 Reached Ugly State in French Alps
- 24th March 2015: Near Loss of U.K. A330 due to Positioning of Captain's Personal Camera
- 29th March 2015: Air Canada A320 skidded upon Landing at Halifax:
- 6th April 2015: First Great Western train driver takes wrong train & goes wrong way
- 16th April 2015: Throttle Valve Checks after Flawed Falcon 9 Recovery Attempt
- 29th April 2015: Failure of Russian Space Station Resupply Mission:
- 30th April 2015: Bird Strike During Flight-test of Airbus A320neo
- 9th May 2015: Airbus A400M Crashes during Test Flight in Spain
- 10th May 2015: MA60 Wing Detaches in Runway Excursion
- 12th May 2015: 4 hour delay due Transportation Security Administration agents having gone home
- 25th May 2015: Double Engine Failure of Airbus A330
- 29th May 2015: Falsified Records for Used CFM56 Engine Blades
- 29th May 2015: A400M Crashed by Incorrectly Installed Engine Software
- 1st June 2015: Airbus A310 Prototype Retires After 33 Years
- 15th June 2015: Heavy Fumes in Cabin Force Passengers out on Wing
- 28th June 2015: Space X Falcon 9 exploded after the Launch
- 8th July 2015: United Airlines experienced Nation-wide Grounding
- 29th July 2015: Hail Damaged Boeing 787 returns back to China
- 30th July 2015: Dubai Airport Planning Camera-based Debris Detection:
- 12th August 2015: American Airlines Repaired Hailstorm-damaged B787:
- 16th August 2015: Indonesia's Trigana Air, ATR 42 Crashed
- 19th August 2015: Investigators Found Cause of Ethiopian B787 Fire
- 8th September 2015: British Airways Boeing 777 Fire Incident in Las Vegas:
- 1st October 2015: Airbus Replaces First A320neo Test-Aircraft Engine
- 7th November 2015: Airbus A321 In-flight Break-Up in Egypt
- 30th November 2015: Boeing Ends C-17 Production in California
- 1st December 2015: AirAsia Flight QZ850 Crash Partly due to Faulty Equipment
- 2nd December 2015: Boeing Completed 5 year Fatigue Tests on 787 Airframe
- 14th December 2015: A member of Air India's ground crew "sucked" into an Aircraft Engine
- 31st December 2015: Rat on Plane Forces Air India Flight to Return to Mumbai
- 12th January 2016: Philae Lander Fails to Respond to last-efforts to wake it up
- 17th January 2016: Falcon 9 Launches Jason-3 Satellite, but Fails the Landing Attempt
- 29th January 2016: Two Incidents by South Korean Low-Cost-Carriers:

- 22nd February 2016: Prohibition of Transport of Lithium-ion Batteries on Passenger Aircraft
- 28th February 2016: SpaceX aborts SES-9 Launch
- 1st March 2016: Airbus Fixes for A320neo False Alarms & PW1100G:
- 19th March 2016: Fly Dubai Flight FZ981 Crash Landing Killing 62 People on the Board
- 7th April 2016: Unseen Blast Injuries to the Brain Trauma
- 17th April 2016: Smoke and fumes event involving Boeing 787, N36962
- 15th May 2016: Smoke event involving Airbus A380
- 18th May 2016: Disappearance of the Airbus A320 over Mediterranean Sea
- 10th June 2016 No 'Common Thread' In F-18 Weapons Mishaps
- 7th July 2016: Oil System Flaw Caused PW1524G Engine Uncontained Failure
- 3rd August 2016: Emirates B777 at Dubai landed with Gear Retracted
- 8th August 2016: Passengers Stranded after Delta Flights Grounded Worldwide:
- 15th August 2016: RAF Pilot Who Sent A330 Into Plunge With Camera To Be Court-Martialed
- 27th August 2016: Power plant's inlet cowl detached in midair of Boeing 737-700
- 28th August 2016: 6 Boeing 787 Grounded for Rolls Royce Engines Inspections:
- 1st September 2016: ANA to Replace Turbine Blades On RR Trent 1000 Engines on 787s:
- 1st September 2016: SpaceX Pad Explosion
- 6th September 2016: Confusion Over Power Setting Key Factor In Emirates Crash
- 13th September 2016: metal Fatigue Caused the Uncontained Left Engine Failure
- 1st October 2016: Difficulties With Fume Investigations of Ryanair's Boeing 737
- 4th October 2016: Human Error Behind Air Asia X Diversion:
- 4th October 2016: Failed Airbus A320 Actuator Incident Debated By Safety Agencies
- 1st November 2016: USAF KC-10 Tanker Loses Refuelling Boom In Flight
- 2nd November 2016: Uncertain American CF6 Failure Cause
- 2nd November 2016: Weather scrubs SpaceShipTwo glide flight test
- 25th December 2016: Hard Landing of Wings Air ATR 72-600 in Indonesia
- 9th January 2017: SpaceX delays Launch due to Weather
- 14th January 2017: SpaceX Returns To Flight by Deploying Iridium Satellites
- 16th January 2017: Turkish Boeing 747-400 freighter crashed into a village near Manas airport in Kyrgyzstan
- 24th January 2017: Lights-Out Error Instigated Southwest Accident at the Nashville International Airport.
- 22nd February 2017: GPS Sensors Data For Forecasting Dangerous Solar Storms
- 19th February 2017: SpaceX Launches Tenth ISS Resupply Mission

- 8th March 2017: Elevator Malfunctions In MD-83's Rejected Takeoff
- 29th May 2017: British Airways' IT Meltdown
- 1st June 2017: United Faces Penalty for operating an airworthy B787
- 18th June 2017: Malfunction of a Chinese Satellite
- 18th June 2017: SpaceX Postponed the Launch of a Bulgarian Communications Satellite
- 15th August 2017: Tracking a solar eruption through the Solar System
- 18 September 2017: Golf Ball Sized Hailstones force EasyJet Flight into Emergency Landing
- 31 October 2017: Broken F-35 Parts Take Six Months To Fix, Government Accountability Office Finds
- 13 November 2017: First Singapore Airlines Airbus A380 Now In Storage
- 20 November 2017: SpaceX Classified Zuma Launch Delayed Until At Least December
- 29 November 2017: USAF Grounds T-6 Trainers after Hypoxia-Like Events
- 30 November 2017: Mobile App For Light Maintenance
- 7 January 2018: Delayed SpaceX Falcon Sends Payload into Orbit
- 18 January 2018: USAF's Attempt To Solve Hypoxia Headache
- 23 January 2018: Google Lunar X Prize to End Without Winner
- 29 January 2018: Putting Everyday Computer Parts to Cspace Radiation Test
- 6 February 2018: Successful SpaceX Falcon Debut Test Flight
- 6 February 2018: Boeing 777X Engine Flight Test Facing Delay
- 7 February 2018: MRJ Flight Testing Retires Main Risks
- 16 February 2018: Space Radiation on Earth
- 18 February 2018: First Commercial Astronaut Training Program
- 6 March 2018: Second ex Singapore Airlines A380 Stored
- 9 March 2018: 10,00th Boeing 737 Produced
- 12 March 2018: At least 49 Dead in Nepal after Plane Crashes on Landing
- 25 March 2018: Plastic Sandwich Bag Caused Retirement of Williams F1 Car in Melbourne
- 9 April 2018: Potential Link between Long Term Heart Health and Galactic Cosmic Radiation
- 10 April 2018: Airbus Develop Drone for Inspecting Aircraft in Hangars
- 17 April 2018: Boeing 737-700 Engine Exploded on Southwest 1380 Flight
- 17th April 2018: Rolls-Royce Powered Boeing 787 Operators Brace for Disruption
- 19 April 2018: Delta Airlines Reduction in Cancelled Flights
- 23 April 2018: Emergency Airworthiness Directive for CFM56-7B Inspections
- 27 April 2018: No Fleet-Wide Issues Found as CFM56 Inspections Progressing
- 2 May 2018: Boeing 737-700 Safely Landed After Window Cracks In-flight
- 5 May 2018: Airbus 319 Safely Landed After Windscreen Burst
- 6 May 2018 Inspection on CFM56 Probe Targets Blade Fatigue Cracks and Damage Pattern
- 12 May 2018: Lesson From Cold Weather Operations
- 15 May 2018: New Method for Carbon Fibber Health Monitoring
- 16 May 2018: SpaceX Eyeing 300 Missions for Next Five Years

- 18 May 2018: In Cuba Over 100 Died in B737 Crash Shortly After Takeoff
- 21 May 2018: Boeing Showed No Initiative To Fix F/A-18 Hypoxia Concluded NASA
- 28 May 2018: Serge Dassault Dies Aged 93
- 27 June 2018: Japan's Hayabusa2 spacecraft arrived at asteroid Asteroid 162173 Ryugu
- 28 June 2018: Fatigue Crack Led To BA Boeing 777 Engine Fire (2015)
- 30 June 2018: Second Failure of Japanese Rocket Start-up
- 27 June 2018: Sterilising an Antenna for Mars
- 4 July 2018: The Toxic Side of the Moon
- 31 July 2018: Lufthansa Technik Develops Waterless Engine Wash Product

Ice Crystal Icing as a Mechanism of Motion of Aircraft through MIRCE Space

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Abstract

MIRCE Mechanics is a part of MIRCE Science that focuses on the scientific understanding and description of the phenomena that govern the motion of functionable system types through the functionability states of MIRCE Space [1]. A full understanding of the mechanisms that generate the motion is essential for the accurate predictions of the functionability performance of functionable system types using MIRCE Science. According to the 2nd Axiom of MIRCE Science the motion of functionable system type through MIRCE Space is a result of imposed natural phenomena or human activities, which are jointly called functionability actions. Thus, the main objective of this paper is to address ice crystal formation (icing) in aircraft engines, as physical phenomena that are experienced by aircraft after prolonged exposure to an area where ice crystal concentrations are present. These are methodological conditions where strong convective weather activity lifts high concentrations of ice crystals to high altitude. The crystals can partly melt and stick to internal engine surfaces causing power loss and/or surge/stall to occur. Available data indicates that there have been at least 100 events of jet engine power loss due to core-icing during the last 30 years

1. Introduction

MIRCE Mechanics is a part of MIRCE Science that focuses on the scientific understanding and description of the physical phenomena and human rules that govern the motion of functionable system types through the functionability states of MIRCE Space [1]. A full understanding of the mechanisms that generate this motion is essential for the accurate predictions of the functionability performance of functionable system types using the mathematical scheme of MIRCE Science.

On 25 August 2010, a Boeing 757-200 on a passenger flight from Freetown Sierra Leone to London Heathrow was cruising at night in Instrument Meteorological Condition (IMC) at 37,000 feet, when vibration levels on both engines increased. Having observed light icing on the windscreen by torchlight, the flight crew carried out the Quick Reference Handbook⁵⁸ procedure for ice shedding on the left engine. As engine thrust was reduced, the vibration level increased rapidly to the maximum

⁵⁸ The Quick Reference Handbook (QRH) contains all the procedures applicable for abnormal and emergency conditions in an easy-to-use format.

Engine-Indicating and Crew-Alerting System (EICAS)⁵⁹ reading. An attempt to restore normal function was not successful and engine malfunction followed. Vibration on the other remained abnormally high and so a MAYDAY was declared and aircraft diverted to Nouakchott (Mauritania) and landed safely. None of the 103 passengers were injured and there was no engine damage. The Final Report submitted by UK Air Accident Investigation Board⁶⁰ concluded that the icing environment led to the event.

Thus the main objective of this paper is to address the high altitude ice crystal formation (known as Icing) as a physical mechanism that generates the motion of an aircraft to functionability states of MIRCE Space⁶¹, together with the positive functionability actions taken by flight crew to cause the transition to the positive functionability states.

2. MIRCE Science Fundamentals

MIRCE Science comprises axioms, laws, mathematical equations and calculation methods that enable accurate predictions of the functionability performance of a given “future” system to be calculated.

According to the 2nd Axiom of MIRCE Science the motion of functionable system types through MIRCE Space is a result of imposed natural phenomena or human activities, which are jointly called functionability actions [1]. At any instant of calendar time, a given functionable system type could be in one of the following two functionability states:

- Positive Functionability State (PFS), a generic name for a state in which a functionable system type is able to deliver the expected measurable function(s),
- Negative Functionability State (NFS), a generic name for a state in which a functionable system type is unable to deliver the expected measurable function(s), resulting from any reason whatsoever.

The motion of a functionable system type through the functionability states, in the direction of calendar time, is generated by functionability actions, which are classified as:

- Positive Functionability Action (PFA), a generic name for any natural process or human activity that compels a system to move to a PFS.
- Negative Functionability Action (NFA), a generic name for any natural process or human activity that compels a system to move to a NFS.

⁵⁹ An engine-indicating and crew-alerting system (EICAS) is an integrated system that provides aircraft crew with aircraft engines and other systems instrumentation and crew annunciations.

⁶⁰ The **Final Report**: [AAIB Bulletin: 6/2011 EW/C2010/08/15](#) of the Investigation was published on 9 June 2011.

⁶¹ MIRCE Space is an analytical concept used in MIRCE Science to describe the motion of functionable system through functionability states in respect to calendar time. Mathematically, it is three-dimensional space whose coordinates are; calendar time, functionability states of a functional system type and a probability of system being in any of these functionable states.

To scientifically understand the mechanisms that generate negative functionability events, analysis of the in-service behaviour of several thousands of components, modules and assemblies of functionable systems types in defence, aerospace, nuclear, transportation, motorsport, communication and other industries have been conducted at the MIRCE Academy.

In MIRCE Science all negative functionability actions are categorised as following [1]:

- Component-internal actions that consist of:
 - Inherent actions that are introduced into components prior to their introduction into service through the activities associated with the design, manufacturing, handling, transportation, maintenance, storage and similar processes.
 - Cumulative continuous actions that are an inevitable part of the components in-service life resulting from natural decay processes such as: corrosion, fatigue, creep, wear and similar.
- Component-external actions, which are originated by:
 - Environmental phenomena that cause discrete overload, like foreign object damage; birds strike (domestic and wild animals), weather (hail, rain, snow, lightening, solar radiation, etc..) and so forth.
 - Human activities:
 - Errors that are related to phenomena that cause overload, for example use and abuse by operators, (pilots, driver and other users), maintainers (maintenance induced errors) and logistics support personnel (bogus parts, shelf life, etc.)
 - Rules that are related to organisational policies, legal requirements, national and international, best practices or any other human imposed functionability related actions (scheduled and condition based maintenance tasks).
- System-internal actions: resulting from processes that are taking place within a system, like a change from passive to active state for certain components and modules, a change in functionability states of some of its constituent components that impact the functionability of the system.
- System-external actions: which are generated by:
 - Discrete environmental phenomena related to weather (hail, rain, snow, lightening, volcanic eruptions, strong wind, solar radiation, etc.) and other causes that impact on the functionability of a functionable system type.
 - Human activities:
 - Errors, which are related to the phenomena of use and abuse by: operators, maintainers or supply chain personnel.
 - Rules, which are related to organisational policies, legal requirements, national and international, best practices or any other human imposed functionability actions that cause the occurrence of NFEs for the functionable systems.

This paper discusses one of many system-external actions, namely a discrete environmental phenomenon whose mechanism causes a jet engine to lose power and transition to a NFS due to the ingestion of ice particles. In the mid-90s several

commercial airplane jet engines experienced more frequent powerloss in ice particle conditions, resulting in a focused investigation, and a greater awareness that led to the recognition of similar events on other aircraft. As the number of occurrences of these events increased the necessity for their scientific understanding arose. These events were predominately associated with flight at high altitude near deep convective systems, often in tropical regions. [2]

Data collected pointed out that the events are caused by ingestion of high concentrations of ice particles and that supercooled liquid water is either of secondary importance or not required. [3] The brief description of the basic theory of how ice accretes in the engine by this process is described in the paper.

3.0 The Atmosphere

“We live submerged at the bottom of an ocean of the element air, which by unquestioned experiments is known to have weight, and so much, indeed, that near the surface of the Earth where it is most dense,.....” *E. Torricelli (1608-47)*

The atmosphere of the earth is a thin spherical shroud composed of a mixture of gases and retained by gravitational attraction. It extends to a great height, but conventional flight is possible only in its denser layers. However, around 90% of the total mass of the air is found below 40km (25 miles). This thin layer of air makes life on earth possible.

The lowest layer of the atmosphere, the one in which humans live, is called the troposphere⁶², which hosts much of what is called weather. The temperature drops linearly in the troposphere-that is, the decrease in temperature with altitude follows a straight line. The cooling of the air with increasing distance from sea level is about -6.5° Celsius per kilometre (known as the lapse rate). The troposphere extends to about 11 km, and at its upper edge (known as tropopause) there is a shift in the behaviour of the temperature. Beyond the troposphere is the cold stratosphere where the temperature remains a constant -56° Celsius for about 9 km.

The troposphere undergoes vertical air movement, for example, convection, an upward motion of air due to heating. This effect may alter the lapse rate and cause instability. The rising air gets colder. Once the moisture in the air reaches saturation at the dew-point temperature, it condenses on the huge number of aerosols (dust particles, salts, ions, and so forth) present in the air. The resulting movements of clouds, thunderstorms, and precipitation are part of the origin of local weather. The difficulty inherent in the meteorological prediction of local weather is all too apparent. Global circulation, however, concerns a more constant meteorological pattern, driven by the overall effects of sun’s radiation. Local weather, in a larger geographical area, results from a perturbation – or disturbances – superposed on the basic global pattern. Because of the higher position of the sun in the sky, more energy is delivered by radiation to the equatorial regions. In complicated

⁶² The Greek word *tropos* means turning; turbulent air motion results in continual mixing

interactions of pressure and radiation differences occurring at all latitudes, air rises near the equator and flows at high altitudes toward the poles. [5]

3.1 Aviation portion of the atmosphere

The composition of the air in the aviation portion of the atmosphere comprises of gases that include nitrogen, oxygen, argon, carbon dioxide and water vapour, together with solid particles such as dust, sand and carbon (smoke). There are also traces of other gases such as helium, hydrogen and neon.

The density of gases and solid particles that we know as “the air” is the greatest near the surface of the earth’s surface because of the greater weight of the air above. This density decreases with increase of the height. This reduction in density affects the amount of water vapour present in the air and as it decreases with increasing height, the lower stratosphere is almost dry. The water vapour can condense out as droplets to form clouds, or mist. It can also form dew or frost on the ground. The solid particles and other impurities in the atmosphere provide the nuclei around which condensation of water vapour occurs. The solids can also restrict visibility as smoke haze, dust haze or sand storm. [5]

The most important single property of the atmosphere is its variability. It is continuously variable both horizontally and vertically in:

- Pressure is defined as the weight of air in the column above a unit area of the earth’s surface. It is expressed in millibars, which are equal to 100 Newtons per square metre.
- Temperature is the controlling factor in meteorology. Change in temperature leads to density changes that cause vertical air movement in one hand, and changes in pressure leading to horizontal air movements and winds.
- Humidity represents the amount of water in the air. As the water vapour is completely transparent it has to be measured. The amount of water vapour in unit of air is called the absolute humidity. Water vapour can change to water droplets, liquid water and to ice. When and how this occurs, and the processes involved is germane to the formation of cloud and fog and to precipitation.
- Clouds are a collection of water droplets or ice crystals or a combination of both in particular formations. All clouds form by air being lifted and cooled adiabatically to below dewpoint temperature. The water vapour then condenses out as droplets or directly as ice crystals by sublimation. Some of the water droplets can exist at temperatures well below zero and becomes supercooled. These droplets are important in the formation of ice on an airframe. They appear white when the sun is able to reflect from the water or ice and gray or dark gray when hidden from sunlight. The average life of a cloud is 15 to 20 minutes. By the end of this time, the contents have evaporated, or alternatively there has been precipitation.
- Wind is the sustained movements of air from one place to another. The wind velocity reflects its speed and direction. In aviation wind speed is given in knots.
- Visibility is defined as the furthest horizontal distance that a dark object can be seen by an observer with normal eyesight. It is measured in meters at eye

level (5 feet above the ground). Thus visibility reflects the clarity of air, or how obscured it is. Reasons for obscurity are in two categories; water and ice crystals in the air and solid particles such as dust, sand and smoke.

3.2 Aviation Hazards

Meteorological aviation hazards now vie in importance with those based on engineering and therefore their significance cannot be overplayed. The hazards include:

- Wake turbulence
- Mountain Waves
- Rotor Streaming
- Low level windshear
- Clear air turbulence
- Cumulonimbus-thunderstorms
- Tornadoes
- Tropical cyclones

Further information about aviation hazards can be found in the literature [6].

3.3 Airframe Icing

Water in its liquid state is necessary for ice to form on an airframe. The ambient temperature needs to be below zero for ice to form and the same condition should apply to the aircraft itself.

Airframe icing can cause a serious loss of performance, control and safety. The effects include the following:

- Aerodynamic: ice tends to form in the greatest depth, on the leading edges of wings and tail planes thereby spoiling airfoil shapes. The result is reduced lift and increased drag, weight, stalling speed and fuel consumption.
- Weight of ice: in its severest form ice can adhere at a rate of 1 inch in 2 minutes. The weight plus the rate of formation will not be constant over an aircraft. This will cause a wandering of the centre of gravity, instability and subsequent control difficulties.
- Ice on the propeller will inevitably form unevenly causing a weight differential on the blades. This leads to the engine rocking on its mountings and producing severe vibration.
- Pitot/static icing: ice can block pitot and static inlets causing readings of pressure instruments to be grossly in error.
- General: a thin film of ice or ice crystals can cause skin friction resulting in a need for longer take-off run. Windscreens and canopies can be obscured.
- Aircraft with undercarriage may experience delay in gear deployment as doors can be “iced up” in the closed position.

3.4 Engine Icing in Internal Combustion Engines

There is impact icing that occurs in the intake area and is akin to airframe icing. This can restrict air to an engine. There is fuel icing that is caused by water in the fuel freezing in pipe bends thus reducing fuel flow to an engine.

Carburettor icing is caused by lowering of the temperature inside the carburettors so that ice can form. The reduction of temperature can be caused by: the evaporation of fuel which causes absorption of latent heat from metal internal parts or the cooling of air by adiabatic expansion as it passes through the venturi in the carburettor.

Thus the inside of the carburettor can become very cold and any water droplets from cloud or fog in the inducted air can quickly form ice. The total reduction in temperature can be in excess of 30° C and therefore icing can occur even in clear air at high temperatures if the relative humidity is 30 percent or more. Carburettor icing is most severe from -2 to +15 degrees Celsius in cloud, fog or precipitation at any power setting and also in clear air with a high relative humidity. [6]

3.5 Icing in Gas Turbine Engines

During last two decades, it became apparent that the detail design of some gas turbine engines has made them vulnerable to the risk of sudden loss of engine thrust if high densities of small ice crystals are encountered in very cold air. This Ice Crystal Icing (ICI) hazard does not usually result in complete engine malfunction (although there have been such instances) but more than one engine may be affected simultaneously. The risk occurs outside of the flight conditions which are currently defined by the regulatory authorities as "icing conditions" and therefore defined as such in the applicable Aircraft Flight Manual (AFM). In light of evidence found during investigations of in-service occurrences of the phenomenon by engine manufacturers and the relative success of design modifications, which have resolved problems with particular engine types, the main regulatory agencies have been considering how to respond to this situation for a number of years now and have, at various points, issued interim operational guidance.

4. Ice Crystal Icing Phenomenon as a Negative Functionability Action

The main risk of encountering high crystal concentrations appears to be downwind from the tops of large areas of convective cloud, which is the area where the visible anvil shape is seen when viewed from a distance. Overshooting tops (dome-like protrusions from the top of an anvil cloud) are an indicator that significant convection is occurring and that ICI may be a possibility.

A clear distinction should be drawn between the high concentrations of very small ice crystals which have caused engine malfunction and the entirely different collections of larger crystals at lower densities that give rise to high level Cirrus, Cirrostratus and Cirrocumulus cloud, which are not hazardous.

4.1 Ice Crystal Icing Effects

The microphysics which underlies the potential hazard, in respect of engine malfunction, is extremely complex and has tended to manifest itself in slightly

different ways in different incidents. This is because any undesirable effect caused by the ingestion of very small ice crystals at high densities has usually been shown to have been a function of details in engine design not originally perceived as relevant. [7]

According to Masson [8] the common feature of most investigated incidents appears to be the initial accretion and aggregation of the ice crystals on relatively warm surfaces within the forward part of an engine followed by their subsequent detachment and partial melting as they progress through the engine core. Un-commanded thrust reduction may occur because of either direct or indirect effects of this passage and, even without any effect on engine function discernable to the flight crew, engine damage can result. The sign that a significant ICI encounter is in progress has usually been seen in a gradual reduction in engine revolutions and a simultaneous rise in Exhaust Gas Temperature (EGT). As thrust lever movement becomes ineffective and engine 'rollback' may continue until a sub-idle condition is reached. Other incidents attributed to ICI have arisen when disrupted intake airflow has created an abnormal pressure gradient in the engine core which has led to a sudden airflow reversal.

The majority of recorded events of engine malfunction attributed to this cause have occurred during the early stages of descent from high altitude with thrust reduced to Fight Idle. Recorded events in the cruise have usually followed a progressive build up of ice during a much longer period of exposure to high crystal densities than has appeared to be required to cause effects in the flight idle/descent case. However, it has sometimes been challenging to identify where the ice accretion actually occurred since any effects will not necessarily occur whilst the accretion is still continuing and it appears that the glaciated conditions at an intensity to cause problems occur in relatively small "pockets". [9]

It is currently being suggested that such localised areas of high ice crystal density have up to 8 gr/m³ of Ice Water Content (IWC) compared to the current engine design standard for super cooled liquid water which is only 2 gr/m³. In this respect, the effect which these ice encounters appear to have had on engine function represents a new challenge rather than a failure to meet existing reliability standards.

This type of icing does not appear on radar due to its low reflectivity. Neither airplane ice detectors nor visual indications reliably indicate the presence of ice crystal icing conditions. It is often undetected by the flight crew and has caused many high-altitude engine failures

A number of clues to the presence of ice crystals at densities with the potential to affect engine function have been deduced from past events and include [9]:

- An air temperature significantly in excess of the corresponding International Standard Atmosphere (ISA) temperature
- The presence of some turbulence but rarely more than at light-to-moderate intensity
- Areas of heavy rain detected on weather radar below the freezing level

- The appearance of St Elmo's Fire⁶³ on the flight deck windscreens.
- The appearance of small droplets of moisture on the flight deck windscreens - the result of impacting ice crystals being melted on contact with heated screens
- Transient failure of the TAT annunciation due to ice crystal accretion within the pitot probe /head which exceed the capacity of the heating system
- The absence of airframe icing

4.2 Negative Functionability Events

Many of the incidents involving engine malfunction attributed to high level ICI have been investigated, primarily by engine manufacturers, in order to find out whether the redesign of some detail feature of their engine is required to prevent repetition.

According to Addy and Veres [2] “The complex, aero-thermodynamics involved that permit ice to accrete inside the core of an engine in flight are not understood to a level that allows effective analysis and prevention or mitigation techniques to be employed in a robust manner.” Thus it took immense engineering and investigatory research to discover it was possible for ice to accumulate on the second stage stator inside the engine core passage without the presence of significant supercooled liquid water in the air.

As each jet engine has its own unique design characteristics the actual mechanism for engine power loss may vary from type to type. Thus, each engine's overall stability is a balance between compressor stability, combustor stability and the fuel available for acceleration. The component with the least margin to cope with ice ingestion will be the weakest link. The common feature appears to be the initial accumulation of ice crystals on relatively warm surfaces in the forward part of the engine, followed by detachment into the airstream flowing through the engine core. In general, the types of engine power losses caused by ice crystal icing are categorised as engine surges and stalls, flameouts and engine damage. [2]

Ice shed into the compressor can drive the engine into stall due to the interactions between several mechanisms, like lost inertial and heat energy to the ice combined with the inefficiency of airfoils with ice on them. The chain of events begins with a sudden flow reversal, caused by compressor surge, which is followed by engine rotor speed decay as airflow is reduced due to the presence of airflow separation in compressor stages. The combustor remains lit; however, due to lack of airflow, the Exhaust Gas Temperature (EGT) typically rises quickly. Flameout occurs due to

⁶³ A visible luminous electrical discharge observed around parts of an aircraft when the electrical charge on the aircraft becomes sufficiently intense. Similar in nature to the glow from a neon tube, and often observed as brush like fiery jets extending from the tip of an aerial, a wing, propeller, windscreen or other part of an aircraft. St. Elmo's Fire occurs when the atmosphere becomes charged and an electrical potential strong enough to cause a discharge (plasma) is created between an object and the air around it. This can happen to an aircraft flying through heavily charged skies. St Elmo's Fire is usually bluish or violet in colour but can also have a greenish tinge. While not a hazard in itself, St Elmo's Fire is an indication of Thunderstorm activity and may be a precursor to a Lightning strike.

quenching of the combustor following the ingestion of ice. Engine damage happens when engine blades and vanes are impacted by shed ice. Minor blade-tip curl has occurred. Rare instances of blade release have occurred.

Generally the NFE occurred when aircraft were in the vicinity of convective clouds/thunderstorms, although flight crews reported no flight-radar echoes at the altitude of the event. Precipitation in the form of “rain” was noted on the windscreen, which at first perplexed investigators because the events occurred at altitudes far higher than where supercooled raindrops would exist. No airframe icing was noted. It has since been determined that the “rain on the windscreen” was actually the melting of the high-altitude ice particles.

Events commonly occurred while diverting around a flight-level high reflectivity region associated with an isolated thunderstorm core, as well as in the broad anvil outflow regions from clouds associated with convective storm complexes and tropical storms. Overshooting tops (dome-like protrusions from the top of an anvil cloud) are an indicator that significant convection is occurring and that ice crystal icing may be possible. Downwind from the tops of large areas of convective clouds, which are often signified by the visible anvil shape, is the main risk area for encountering high crystal concentrations.

Satellite data confirm the existence of high concentrations of very small ice crystals in the vicinity of convective weather systems. Convective storms in the tropical latitudes contain much more moisture due to the warmer air in these storms. This event is more likely to exist in the tropical latitudes because warmer air can “hold” much more moisture. In fact, these strong convective systems produce cloud tops that have been observed to burst through the tropopause.

These particles are in the order of roughly 40 microns in diameter, and even in high concentrations, these are not visually detectable even in daytime conditions. Regrettably due to limitations inherent with radar returns this phenomenon is not detectable. The temperatures at the altitudes of these events are far too cold for supercooled liquid water to exist. With a radar reflectivity of only 5% of average size raindrops, there may be little radar reflectivity at flight altitude above the minimum threshold of the pilot’s onboard weather radar. Also, radar returns are highly skewed to the large particles in the distribution, not necessarily where the mass (of ice particles) is concentrated.

5. Positive Functionability Actions Available to the Crew

Apart from following guidance provided in AFM/Operations Manual, the best way of way to avoid high concentrations of very small ice crystals is the effective use of the aircraft weather radar to ensure that significant convective activity at altitudes below typical jet aircraft cruise levels is detected and the assumption then made that at the levels above this should be avoided. When particular susceptibility to ICI is known, deviation by more margin than the typically-recommended 20 nautical-miles from all areas where large convective cells are present is advisable. Where particular engine types have been identified as at risk pending modification, a distance of 50 nautical-miles from such areas is usually recommended.

This tactical strategy can be supported by considering the ICI risk when reviewing meteorological forecasts at the pre flight planning stage. Since there will not be any forecast of areas to avoid specifically because of an ICI risk, the probability that it is likely to be a feature of all large convective systems in tropical latitudes, especially those over oceanic or coastal areas, should be the assumption. Operationally, the best advice should be provided in the AFM/Operations Manual. However, subject to any specifically applicable requirements or guidance, it is currently considered that the use of a thrust setting above Flight Idle during initial descent from high cruise altitudes in the tropics is a sensible precaution.

The last action that a crew can do is to try to restart the engine and lower levels where the atmospheric conditions are less harsh. There numerous examples where this positive functionability actions were successful and returned the aircraft into PFS.

6. Conclusions

The main objective of this paper was to address ice crystal icing of aircraft engines, as physical phenomena that are experienced by aircraft after prolonged exposure to an area where ice crystal concentrations are present. These are methodological conditions where strong convective weather activity lifts high concentrations of ice crystals to high altitude. The crystals can partly melt and stick to internal engine surfaces causing power loss and/or surge/stall to occur. Available data indicates that there have been at least 100 events of jet engine power loss due to core-icing during the last 30 years.

It is necessary to stress that occurrences of these negative functionability events could develop very quickly into a hazardous situation due to losses of pressurisation, thrust, electrics, hydraulics, and being basically down to just the avionics powered by the battery bus, while the crew is keeping control of the aircraft and making important decisions on where to point the aircraft for the “safest” landing option! The paper clearly illustrated why it is necessary to consider the impact of environmental conditions when discussing the motion of an aircraft through functionability states, as imbedded in the philosophy of MIRCE Science. It is in the direct contrast to current reliability engineering practices that address the behaviour of the components contained within a functionable system type (the aircraft) while totally ignoring the impact of changes in the atmosphere and meteorological conditions.

Hazardous events such as these will continue to occur until some solutions are found in the design offices. Of course, it requires new technology areas to be developed in order for the engine core icing hazard to be eliminated. Today’s existing engine core icing test facilities consist primarily of outdoor, ground-based facilities that are limited in their range of ambient air temperatures and pressures. Very few engine core icing test facilities have the altitude capability for this type of testing. [2]

The probability of reduction of occurrence of ice crystal icing of aircraft engines, as physical phenomena that are experienced by aircraft after a prolonged exposure to an area where ice crystal concentrations are present could be achieved by designing

better engines and more suitable test facilities, which in turn requires a fuller understanding of the physical mechanism that generate this phenomenon. The author hopes that this paper will make a contribution to those efforts.

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How Reliable is Reliability Function?

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Abstract

According to Knezevic [1] the purpose of existence of any functionable system⁶⁴ is to do functionability work, which is considered to be done when the expected measurable function is performed through time. However, experience teaches us that in-service life of functionable systems is frequently beset by undesirable negative functionability events, resulting from a variety of negative functionability actions (overstress, wearout, natural events, and human interventions), some of which result in hazardous consequences to: the users; the natural environment; the general population and businesses. During the last sixty years, Reliability Theory has been used to predict occurrences of negative functionability events. However, mathematically and scientifically speaking, the accuracy of these predictions, at best, were only ever valid to the time of occurrence of the first failure, which is far from satisfactory in the respect of its expected life. Consequently, the main objective of this paper is to raise the question how reliable are reliability predictions based on the Reliability Function.

1.0 Introduction

The necessity for the reduction in occurrences of operational failures started with the advanced developments of military, aviation and nuclear power industries, where the potential consequences could be significant. And so, during 1950s, Reliability Theory was “created”. It was based on mathematical theorems rather than on scientific theories. Massive attempts were made to further the applications of the existing mathematical, statistical and analytical methods without a real understand of the mechanisms that caused the occurrences of in-service/operational failures.

Not surprisingly, deterministically educated engineers and managers experienced fundamental difficulties in understanding Reliability Theory. The reason for that is very simple. Probability, unlike numerous measurable physical properties and as a main concept of reliability, cannot be seen or measured directly. For example: pressure: temperature: volume: weight of a component can be measured directly and by using appropriate mathematical manipulations, accurate predictions of the corresponding properties of a system constructed of these parts can be obtained. Moreover, the occurrence of a component failure is also clearly manifested and physically observed phenomena. And yet, the concept of reliability is abstract and immeasurable. It cannot be seen on the component/system. In fact, it serves as an abstract property of a component/system that obtains a physical meaning only when a large sample of components/systems is considered.

⁶⁴ Functionable system is a set of physical elements and human made rules put together to perform functionable work.

2. Reliability Function

To support the above presented conclusions regarding Reliability Theory, the fundamental definition of reliability will be used and analysed. It is widely accepted that Reliability is defined as the probability (P) that a considered entity (component, product, system) will operate without failure during a stated period of time (t), when operated in accordance with defined parameters. Mathematically, this statement is fully defined by the Reliability Function, $R(t)$.

2.1 Reliability Function of a Component

For any component considered, the reliability function is defined in the following manner:

$$R(t) = P(TTF > t) = \int_t^{\infty} f(t)dt, \quad t \geq 0 \quad 1$$

where: $R(t)$ is the reliability function, $f(t)$ is the probability density function of the random variable known as the Time To Failure (TTF) of a component.

Reliability data regarding components can be fully defined through the numerous well-known probability distributions. However, in the vast majority of cases, current industry practices are premised on the reliability of components being defined by their manufacturers through a constant failure rate, λ , which forces all interested parties to express the reliability function in the form, $R(t) = e^{-\lambda t}$!

2.2 Reliability Function of a System

The Reliability function for a system, $R_s(t)$, is determined by the reliability functions of the constituent components and the way they impact the failure of the system. For example the reliability function for the system, whose reliability block diagram is presented in Figure 1, is fully defined by the following mathematical expression:

$$R_s(t) = P(TTF_s > t) = R_A(t) \times \{1 - [1 - R_B(t)][1 - R_C(t)]\}, \quad t \geq 0 \quad 2$$

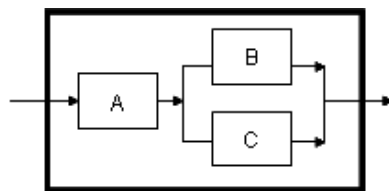


Figure 1: Reliability Block Diagram for a Hypothetical System whose failure will occur if a component A fails, or if components B and C fail

The above two equations briefly summarise the essence of the reliability function when the main concern is a prediction of the behaviour of the system until the first failure.

3. Mathematical Reality of a Reliability Function

Being educated to use mathematical expressions for all engineering predictions, which always have a single numerical outcome, the author has spent over a decade understanding the fundamental physical meanings of the mathematical definitions for the reliability of systems by the system reliability function. Thus, the realisation was that reliability mathematics dictates the following physical reality of the systems considered:

- One Hundred percent quality of components production and installation
- Zero percent of transportation, storage and installation tasks
- One Hundred percent of components are mutually independent
- No maintenance activities (inspections, repair, cleaning, etc.)
- Continuous operation of the system (24/7)
- First observable failure is a failure of the system
- Time counts from the “birth” of the system
- Fixed operational scenario (load, stress, temperature, pressure, etc.)
- Operational behavior is independent of the location in space (GPS or stellar coordinates)
- Reliability is independent of humans (operators, users, maintainers, managers, general public, law makers, etc.)
- Reliability is independent of calendar time (seasons do not exist)

4. Physical Reality of Reliability Function

Systematic research performed by the author during several decades of the observable physical realities of in-service/operational life of aerospace, military and nuclear power industries have clearly shown that the flowing physical reality determines the reliability of systems [1]:

- Quality of produced components and assemblies is less than 100%
- There are huge interactions between “independent” components
- Maintenance activities like: inspections, repair, cleaning, etc., have significant impact on the life of a system and impact reliability
- Neither all systems nor all components operate continuously (24/7)
- First observable failure is not necessary the failure of a system (failure of components B or C alone, in the Figure 1, does not cause system failure)
- Components and a system have different “times”
- Variable operation scenarios (load, stress, temperature, pressure, etc.)
- Reliability is dependent of the location in space defined by GPS coordinates
- Reliability is dependent of humans, like: users, maintainers, general public
- Reliability is dependent of calendar time

5. Closing Question

The above list of physically observed and undeniable facts seriously impact the accuracy of the reliability predictions currently provided through reliability theory. Because, the first failure event and all subsequent ones generate physically observable changes in the reliability of a system that are impossible to embrace by the existing concepts used in the formulation of the Reliability Function.

The closing question for all reliability professionals is, “How can predictions of functional system reliability be “reliable” when lifelong physically observable events and associated human rules are totally excluded from the predictions?”

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New Book: MIRCE Science by Jezdimir Knezevic



This book is about the journey over the road that the author has travelled since birth till today, but it is not a book about him; it is a book about the quest for the new body of knowledge that he named MIRCE Science, the theory for predicting functionability performance of functionable system types. This long and demanding journey consisted of three paths:

The first started with his childhood obsession with cars and autosport, progressing to building one by hand, using parts obtained from scrap yards, in a neighbour's garden. Two years later driving that car he earned one point in the National Rally Championship, while experiencing the physical phenomena of operation, maintenance and support processes (Part 1 of the book).

The second took the author to universities, libraries, institutes, companies and other organisations worldwide, in the quest for the scientific understanding of the mechanisms that lead to the occurrence of functionability events, resulting from physical, environmental and human actions. (Part 2 of the book).

The third culminated in the creation of MIRCE: Functionability, Operability, Maintainability, Supportability and Profitability Equations, the mathematical derivation of which has been fully described in this book, based on MIRCE: Functionability Field and Space. (Part 3 of the book).

MIRCE Science comprises axioms, laws, mathematical equations and calculation methods that enable quantitative predictions of the impact of the physical world and in-service rules on the functionability performance of each feasible option of the future functionable system type to be made. The complexity of this undertaking, according to Jack Hessburg (1934-2013), the World's first Chief Mechanic (Boeing 777), requires the intellectual effort equal to winning a Nobel Prize!

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