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"MIRCE Science is a theory of the motion of working systems through MIRCE Space resulting from any functionability actions whatsoever, used for Management of In-service, Reliability, Cost & Effectiveness."
Dr J. Knezevic, Founder, 1999

MIRCE Science: Shark Bite as a Mechanism of Motion of Submarine Cables through MIRCE Space

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Abstract

Sharks represent a serious, but still not fully understood, threat to modern communication systems connected through submarine cables. While the vast majority of sharks do not cause any damage to cables, some shark bites have led to serious consequences to submarine cables used for the worldwide internet connection, generating high repair costs and long outages. Thus, this paper addresses shark bites from the MIRCE Science point of view, which means that it is considered as a mechanism that generates a negative functionability event that causes the motion of a system from a positive to negative functionability state. Therefore, this paper briefly examines the shark species to understand the capabilities and strength of shark bites as mechanisms that could generate undesirable negative consequences the in-service life of affected working systems. The method for predicting impacts of potential protective actions taken by design and operational decisions on in-service reliability, cost and effectiveness of submarine cables can be calculated by making use of MIRCE Functionability Equation are presented in the paper.

Key words: MIRCE Science, submarine cables, shark bites, protection actions, MIRCE Functionability Equation

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1. Introduction

Sharks have been around for over four millions years, survived five mass extinctions and recently shown an inexplicable taste for the submarine cables laid along the ocean floor, as a part of the infrastructure for provision of around 99% of all data transmission requirements. [1] The ocean floors of the world are covered by around 1 million kilometres of cables enabling human's luxuries and conveniences like Netflix or Google. Millions of people, in all types of transport, navigate the physical world using data transmitted by submarine cables, as well as WhatsApp or Signal users to make and change plans in real time. Even further, hospitals, electricity grids, emergency services, public transport, the aerospace and even international politics diplomacy are deeply depend on the internet to run safely and smoothly. [2]

Although submarine cables are a highly reliable means for information transmission, their in-service reliability is affected by external actions. They result from a variety of factors, like the impacts of fishing boats, the interactions of cable landing sites with busy harbours, waterways and associated anchorages and the length of the continental shelf and the system's routing to deep water. Also, natural occurrences such as earthquakes and landslides have damaged cables; together with the corrosive saltwater, extreme temperature fluctuations and marine life all threaten marine cables.

The first recorded shark bites of a deep-ocean fibre-optic cable occurred off the Canary Islands around 1985 to 1987. On four occasions these pioneering systems were damaged by small sharks biting through cable's polyethylene sheath. Testing by Bell Laboratory scientists [7] showed that it was the deep-dwelling, crocodile shark (Pseudocarcharias kamoharai), which occupied water depths between 1000 and 1900 meters.

As in-service reliability, cost and effectiveness of submarine cables are essential for the provisioning of the global data transmission their design process and specifications must be able to ensure delivery of these targets. Thus, the main objective of this paper is to highlight the shark bite as one of many treats that impact in-service performance of submarine cables directly and many other worldwide systems that are consequentially affected. Therefore, this paper briefly examines the shark species to understand the capabilities and strength of shark bites as mechanisms that could generate undesirable negative consequences the in-service life of affected working systems. The method for assessing the impact of potential protective actions, design and operational, on in-service reliability, cost and effectiveness of submarine cables by making use of MIRCE Functionability Equation has been presented in the paper.

2. The Philosophy of MIRCE Science

The philosophy of MIRCE Science [3] is based on the premise that the purpose of the existence of any human created working system is to do a work. The work is considered to be done when the expected measurable function is performed through time. At any instant of calendar time, a working system could be in one of the following two macro states:

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

- Negative Functionability State (NFS), a generic name for a state in which a working system is unable to deliver the expected measurable function(s).

In MIRCE Science, the work done by a working system is uniquely defined by the trajectory generated by its motion through MIRCE Space[1]. That motion is driven by functionability actions, which are classified as:

- Positive Functionability Action (PFA) that compels a system to move to a PFS,
- Negative Functionability Action (NFA) that compels a system to move to a NFS.

To scientifically understand the mechanisms that generate functionability actions, positive and negative, analysis of the in-service behaviour of several thousands of items, modules, assemblies and whole systems in aerospace, nuclear, transportation, motorsport, communication, defence and other industries have been conducted at the MIRCE Akademy. The minimum sufficient "physical scale" which enables scientific understanding of relationships between physical phenomena that take place in the natural environment and the physical mechanisms that govern functionability events has to be based with the following range:

- 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 metre.
- 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 metre.

The time evolution of a working system through MIRCE Space is physically manifested through the occurrences of functionability events, which are classified as:

- Positive Functionability Event (PFE) that is a physically observable occurrence at which a working system moves a PFS,
- Negative Functionability Event (NFE) that is physically observable occurrence at which a working system moves to a NFS.

The MIRCE Functionability Equation is a mathematical description of the motion of the working systems through MIRCE Space, caused by any action whatsoever, is defined by the following expression [3]:

$$y(t) = 1 - \sum_{i=1}^{\infty} F_S^i(t) + \sum_{i=1}^{\infty} O_S^i(t), \quad t \geq 0 \qquad (1)$$

In the above equation $F_S^i(t)$ is a cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the sequential negative functionability event, $TNE_S^i(t)$ of a system considered. In MIRCE Science it is defined by a following convolution integral:

[1] MIRCE Space is a conceptual 3-dimensional coordinate system depicting a probabilistic trajectory of the motion of a working system type through MIRCE Functionability Field. Knezevic (2017)

$$F_S^i(t) = \int_0^t O_S^{i-1}(x) dF_{S,i}(t-x), \qquad i = 1, \infty \qquad (2)$$

where: $F_{S,i}(t)$ denotes a cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the i_{th} negative functionability event, $TNE_{S,i}(t)$ of a working system type considered.

In Eq.1 $O_S^i(t)$ is a convoluted form of cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the consecutive positive functionability event, $TPE_S^i(t)$ of a system considered. In MIRCE Science it is defined by the following convolution integral:

$$O_S^i(t) = \int_0^t F_S^i(x) dO_{S,i}(t-x), \qquad i = 1, \infty \qquad (3)$$

where: $O_{S,i}(t)$ is a cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the i_{th} positive functionability event, $TPE_{S,i}(t)$ of a system considered.

The remaining part of the paper focuses on the shark bite as one of many negative functionability actions generated by the natural world that directly impacts the in-service reliability, cost and effectiveness of submarine cables and associated systems, from MIRCE Science perspective.

3. Submarine Cables

Submarine cables are not one-size-fits-all solutions. Different applications require cables with unique characteristics. Particular submarine cable specifications are needed to meet their demands. Thus, the main categories of submarine cables are:

- Submarine communication cables are the backbone of global telecommunications and data transfer.
- Underwater Power Cables that transmit electrical power from offshore wind farms to tidal energy installations and oil and gas platforms to the mainland.
- Submarine research cables are used for various scientific purposes, like: collection of oceanographic data and underwater monitoring.
- Specialised submersible vehicles cables that provide power supply, control, and data transmission for remotely operated vehicles and autonomous underwater vehicles.

3.1 Submarine design driven decisions

In-service performance of submarine cables, like all other working systems, is ensured by the decision made at the initial stages of the design process. Major design concerns regarding in-service performance of submarine cables are:

- Conductor materials which determines portion of their performance and longevity.

- Insulation and jacketing materials that are responsible for protecting and maintaining signal strength.
- Armour and Sheathing that provides resistance against mechanical damage, including crushing and abrasion.
- Voltage ratings, which depends on the usage, as it must assure that the cable can safely transmit electrical power, while avoid overheating or breaking down.
- Current carrying capacity that determines the maximum amount of electrical current the cable can safely carry without overheating.
- Installation specifications that cover factors such as laying depth, burial methods, and the use of protective equipment, which is essential to prevent costly cable damage and ensure the safety of installation crews, which could be cost significant.
- Inspection and maintenance policies which are key for their inspection intervals and methods to detecting water ingress, physical damage, or insulation degradation.
- Repairs and splicing of submarine cables due to damage or faults are complex and challenging tasks, which often require specialised equipment and expertise.

Understanding submarine cable specifications, characteristics and maintenance policies is important for successfully deploying and operating undersea communication and power transmission systems, as safety of the global society is reliant on these cables. As technology advances and our reliance on undersea infrastructure grow, the importance of rigorous cable specifications becomes the norm.

3.2 Copper cables vs. fibber-optics cables

American Telephone & Telegraph Company had laid thousands and thousands of miles of copper made undersea cable all over the world with no problem. There had not been a single case of a shark biting one of the old cables, although they have found shark teeth mark[2]. They took the teeth marks from the cables surrounding to a shark dentist for identification. However, experts disagree on which type of shark was responsible for the attack.

Modern, fibber-optic cables look essentially the same as copper cables, except that they are around 2 cm in diameter, while the older ones are over 10 cm thick. Inside each of the new cables, however, are six hair-like strands of glass that can carry as many as 40,000 separate conversations traveling as staccato pulses of laser light. In contrast, the first trans-Atlantic telephone cable, whereas a “fat” copper line laid between Newfoundland and Scotland in 1956, could carry only 36 conversations. Even the newest copper cable, laid in 1983, has a maximum capacity of only 9,000 calls.

National and international regulatory bodies often mandate submarine cable specifications together with various industry standards organizations. Compliance with these specifications is essential for obtaining necessary approvals and certifications for design and operation of submarine projects.

[2] https://www.nytimes.com/1987/06/11/us/phone-company-finds-sharks-cutting-in.html

4. Shark species (Selachimorpha)

Sharks have been in the sea waters on the Earth for more than 400 million years, which means they evolved nearly 200 million years earlier than the first dinosaurs. During all this time, sharks have either shared or solely owned the position of the top predators in the marine food chain. Scientist identified more than 400 different shark species, the vast majority of which can be found in every ocean of the world, with some species also inhabiting rivers.

Sharks are a remarkably diverse group of fish. The largest species, the whale shark, can grow up to 12 m in length, whereas the smallest species, the dwarf lantern-shark, reaches a size of 17 cm only.

Sharks have seven senses, the five that they share with humans, plus an electrical sense (small pores detect minute electrical currents in the water) and a lateral line (pressure sensitive cells beneath their skin) both of which help them detect prey and avoid predators. A shark's brain shows the importance of smell to sharks, due to the fact that over 60% of their brain's total weight is taken up with processing the olfactory sense.

Sharks belong to a group of creatures known as cartilaginous fishes, because most of their skeleton is made from cartilage rather than bone. The only part of their skeleton not made from this soft, flexible tissue is their teeth. As they are made from a material known as dentin that is harder and denser even than bone, sharks have a powerful bite. Even further, rather than having just a few sets of teeth that last all their life, sharks are continually producing new teeth. As an older one breaks or wears down, it simply falls out of the front of the mouth and onto the sea floor, as a new tooth takes its place. Depending on species and diet, a shark can produce between 20,000 and 40,000 teeth, over its entire lifetime. This means that there is a much greater chance that a shark tooth will be preserved and turned into a fossil. Not only are the teeth the most common part of sharks to be found, they're one of the most common fossils of any organism.

Measuring the bite force of a shark is no easy task, while some of these numbers have been recorded in scientific studies; others are estimates or have only been recorded once. To investigate the power of the shark, scientist built a custom the "bite-meter" attached to the end of a long rod that measures the force. This was the first time that such a measurement had ever been attempted for this shark. When one specimen spotted the device the bites were relatively weak, but they quickly grew in strength and final measurement was staggering 13 kN. On the same test the bull shark has a bite force of 6,000 N, the white shark has 10 kN bite force. The strongest bite force ever measured for any animal on earth is the saltwater crocodile at 17 kN. [4]

According to scientists there is no single reason for sharks survival of all five major extinction events on Earth, all of which had different causes and different groups of sharks pulled through each one. [5] However, the shark diversity may also have played an important role, as they are able to exploit different parts of the water column, from deep dark oceans to shallow seas, and even river systems. The wide variety of food, such as plankton, fish, crabs, seals and whales enabled sharks as a group to survive all changes in the oceans during hundreds of millions of years. Perhaps, that led them to develop the taste submarine cables!

A recent significant discovery in marine science [2] led to the conclusion that there are some properties of the electrical current in the fiber-optic lines that attracts sharks, which may trigger an automatic feeding reflex. They are supersensitive to electrical signals, and are able to detect electric fields as faint as a few millionths of a volt per centimeter in water. Thus, a faint field near the cable activates their natural instinct, programmed in their genes, and they attack.

5. Shark bite as a Negative Functionability Action

Submarine cables are an integral part of the internet's physical infrastructure, with many funded in recent years by internet giants like Microsoft, Google, Amazon and Facebook parent Meta. Damage to these subsea networks can cause widespread internet outages and all other dependent working systems worldwide.

According to the International Cable Protection Committee (ICPC), the world's leading organisation promoting submarine cable protection and resilience, negative functionability actions related to submarine cables are proportional as following:

- 65-75 % are caused by ships' anchoring and fishing activities.
- 10% are generated by natural phenomena, such as subsea landslides and ocean currents, are responsible for up to 10 per cent of faults.
- 5% of NFEs are caused by cable component failure.
- 10-20 % of in-service failures cannot be determined.
- 1 % is attributable to shark bites, which leave evidence in the form of teeth imprints or actual teeth embedded in a cable's sheathing.

Evidence shows that between 1901 and 1957, which is a period dominated by subsea telegraphic cables, at least 28 cables were damaged by fish bites, including sharks.
Sharks do have a history of dining on ocean cables, but although they have bitten fibre-optic cables, they do not appear to have developed a taste for them.
There were around 11 cables that needed repair caused by shark bites during 1959 to 2006, the period that encompasses coaxial cables, which were replaced by fibre-optic systems in 1988.

The latest analysis, covering 2007 to 2014, recorded no cable faults attributable to sharks. Due to increased shipping and fishing activities on the continental shelf, fibre-optic cables are now protected by the addition of steel wire "armour" to the cable's exterior, as well as burial up to 3m below the seabed.

6. Positive Functionability Action

Although submarine cables are very reliable regarding their own design and manufacturing processes there are occasions when a repair to a cable becomes necessary due to the any of the above mentioned, human or natural, negative functionability actions.

Generally speaking, each repair process could be considered as unique, but the following sequence of tasks could be presented as generalised process, thus:

- Fault detection of undersea cable from the one or even both shore ends, which could be include a signal injector, that could help in locating the actual cable fault location.
- Determination of maintenance resources (people, material, equipment, tools, etc,).
- Travel to damage the cable several miles before the fault to lift its working end up to the surface and cut it off.
- Then go several miles to the other side of the damaged cable to cut and lift that end.
- Splice a new cable section in, and then lower the cable in a loop, so that it does not kink going down.

Personnel involved with submarine cable repairs express feeling uneasy regarding swimming around them.

7. Placing shark bite in MIRCE Functionability Equation

To benefit from the ability to predict expected work done by underwater cable types in respect to the frequencies and durations of outage of submarine cables caused by shark bites through in-service lives, it is necessary to place it in MIRCE Functionability Equation.

A cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the i_{th} negative functionability event, $TNE_{S,i}(t)$ of a working system considered is generically defined by Eq.2. Hence, in the case that this random variable is governed by the impact of a shark bite, it is denoted as, $TNE_{S,i,SBite}$, and it is defined by the following expression:

$$F_{S,i=SBite}(t) = P(TNE_{S,i=SBite} \le t) = \int_0^t f_{S,i=SBite}(t)dt \qquad (4)$$

where: $f_{S,i=SBite}(t)$ is a probability density function of the random variable that defines the time to the occurrence of i_{th} negative functionability event, which in this specific example is a shark bite. The above equation is in the most generic form and as such covers all possible variations and impacts of shark bite, which means each specific manifestation will have its own, most appropriate, mathematical expression. However, based on author's experience, the most likely the exponential probability distribution will be applicable to represent the shark bite which caused a NFE.

A cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the consecutive positive functionability event, $TPE_S^i(t)$ of a system considered is defined by Eq.3. In MIRCE Science it is defined by the following convolution integral

$$O_S^i(t) = \int_0^t F_S^i(x)dO_{S,i}(t-x), \qquad i = 1,\infty \qquad (5)$$

where: $O_{S,i}(t)$ is a cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the i_{th} positive functionability event,

$TPE_{S,i}(t)$ of a working system type considered. The number of these functions is equal to the number of NFAs that generate NFEs occurring during the in-service life of working systems. In the case that this random variable is governed by the impact of a positive functionability action taken in response to the occurred shark bite it is denoted as $TPE_{S,i,SBite}$, and it is defined by the following expression:

$$O_{S,i,SBite}(t) = P(TPE_{S,i,SBite} \leq t) = \int_0^t o_{S,i,SBite}(t)dt \qquad (6)$$

where: $o_{S,i,SBite}(t)$ is a probability density function of the random variable that defines the time to the occurrence of i_{th} positive functionability event, which in this specific example is a shark bite action. The above equation is in the most generic form and as such covers all possible variations and impacts PFA that could be taken to return a system to PFS after impacts of any generated NFA, which means that each shark bite related action, has its own mathematical expressions. In general, Eq. 4 could be represented as a sum of all positive functionability actions, denoted as *npa*, which should be completed to return a submarine cable to PFS, as speedily and efficiently as possible, thus

$$O_{S,i,SBite}(t) = P(TPE_{S,i,SBite} \leq t) = P\left(\sum_{j=1}^{npa} TPT_{SBite,j} \leq t\right) = \int_0^t O_{SBite}^{j-1}(x)dO_{SBite,j}(t-x), \quad j = 1, npa$$

The above expression is a sum of several independent convolution integrals, which could be very challenging task for the provision of the analytical solution, unless all of the maintenance tasks are modelled by the normal probability distribution.

8. Mitigations of the impacts of shark bites on the functionability of submarine cables

The main objective of this paper was to draw the attention of design engineers of submarine cables to the impact of shark bites on their in-service reliability and safety. These impacts have been determined by applying the principles of MIRCE Science to the process of the motion of submarine cables through MIRCE Space. Having concluded that a shark bite is detected and observed mechanism that impacts in-service reliability, cost and effectiveness of submarine cables, the obvious question is – What could be done to reduce the frequencies and consequences of these functionability events?

According to [6] the global digital giant Google makes great efforts to protect their fibber-optic cables against shark attacks. They are made of fragile fiber glass that is covered in a plastic coating of in different colours, so that maintainers can follow the path of each strand and finally all is enclosed by an outer polyurethane jacket, a protective layer (made from a material like Kevlar),

By making use of the MIRCE Functionability Equation, it is possible to assess the impact of each feasible design decision on in-service reliability, cost and effectiveness of the future working system, on a life time scale. It means that each category of functionability driven design decisions, presented in part 3.1, could be numerically evaluated and then made the final and justifiable decision in accordance to the criteria chosen.

9. Conclusion

Since sharks and submarine cables share the same physical space it is inevitable that interactions between them are possible. Using principles of MIRCE Science, in this paper a shark bite is considered as a mechanism that generate sufficient mechanical energy to cause the occurrence of a negative functionability event that cause the transition of submarine cables from a positive to a negative functionability state.

The results of the research conducted by the author, at the MIRCE Akademy, has shown that there are physical evidences of the sharks damaging submarine cables by biting them with very powerful jaws. These bites negatively affected the performance of cables, which had to be restored by the execution of adequate repair actions. These repair actions take a long time and required specific resources and complex logistics support, as the cables are deep into water and often far from the shores.

To benefit from the ability to predict expected frequencies and durations of outage of submarine cables caused by shark bites through in-service lives, by making use of MIRCE Functionability Equation, it is necessary to “translate” physical reality of related negative and positive functionability actions into their “mathematical reality”. However, mathematics does not teach the user how to select the most appropriate distributions, but requires that to be done. It means that engineers and managers need to use their experience, knowledge and assumptions made to describe those mechanisms accurately before they apply mathematics to make expected predictions. Descriptions of mechanisms of functionability actions present a huge challenge, but not for mathematicians, it is a challenge for MIRCE Science users.

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