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Citation for published version:
Tang, W, Flynn, D, Brown, KE, Robu, V & Zhao, X 2020, The Design of a Fusion Prognostic Model and Health Management System for Subsea Power Cables. in *OCEANS 2019 MTS/IEEE SEATTLE.*, 8962816, IEEE, OCEANS 2019, Seattle, Washington, United States, 27/10/19. https://doi.org/10.23919/OCEANS40490.2019.8962816

Digital Object Identifier (DOI):
10.23919/OCEANS40490.2019.8962816

Link:
Link to publication record in Heriot-Watt Research Portal

Document Version:
Peer reviewed version

Published In:
OCEANS 2019 MTS/IEEE SEATTLE

The Design of a Fusion Prognostic Model and Health Management System for Subsea Power Cables

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Abstract: **Subsea power cables are critical infrastructure for the continuity of energy supply and are a key enabler to the global growth in offshore renewable energy generation. Capital projects for long range, greater than 60km distances, for transmission networks can cost in excess of £1billion. In this paper, we have extensively reviewed the data within academia and industry with respect to the practices and challenges of subsea power cable management. With a detailed focus on 15 years of historical cable failure data from the UKs largest owner of subsea power cables, we identified that existing commercial monitoring systems do not monitor about 70% of subsea power cable failure modes. To overcome the challenges this represents to delivering cost effective and timely intervention to subsea power cables, we present a fusion prognostic model to enable predictive forecast on cable failure modes, include location and rates of degradation.**

In our model, we incorporate physical models to simulate the process where common cable failure modes lead to cable damage, such as abrasion and corrosion. In addition, we implemented multi-physics modelling techniques to model cable displacement and scouring, taking into consideration different environmental condition profiles. We also demonstrate how new sensing technologies can be integrated into this sensor agnostic model in order to enhance lifetime prediction accuracy. An operational decision support system is implemented within this work to integrate these different physical failure models, using a fusion model approach which integrates in-situ inspection data from sonar, autonomous underwater vehicle (AUV) inspection mission planning, and data analysis results into a holistic subsea cable remaining useful life prediction capability.

Keywords—subsea cable monitoring, health management system, fusion prognostic model.

I. Subsea Cable Market

In recent years, global investment in offshore renewable energy has been increasing [1]. The United Kingdom is recognized as one of global leaders in offshore renewable energy, given its 29 existing offshore windfarms of 5.1 GW installed capacity and investment of £80-160 Billion to achieve 20–40 GW by 2025 [2].

Offshore windfarms and other offshore renewable energy installations depend on subsea power cables to transmit and distribute electricity to consumers. Sustainable power supply and the economic viability of offshore windfarms is highly dependent on the reliability of these subsea cables. Revenue loss from power outages due to a fault in a subsea cable in the instance of a wind farm with 300 MW capacity stands at around £5.4 million per month [3]. Meanwhile, subsea cables can take months to be repaired, during which time asset owners may incur large revenue losses. It is also estimated that any delay in repairing and replacing subsea cables can cost tens of thousands of euros per hour [4]. According to insurance underwriter G-Cube, offshore insurance claims relating to subsea power cables equated to €60 million in 2015 alone [5]. Given the importance of subsea cable assets, it is necessary to build an integrated solution for degradation and reliability monitoring, and efficient subsea cable maintenance. According to a report by the Crown Estate [6], such an integrated and innovative solution could 'reduce operation and Maintenance spending and downtime'. In this paper, we are presenting a fusion prognostics and health management (PHM) architecture for monitoring the degradation process of subsea cables holistically and cost-effectively. Specifically, multi physical models were developed to simulate common cable failures and displacement. We also demonstrated how wideband sonar techniques and AUVs could be used to obtain real time integrity data. We then demonstrate how an operational decision support system can be designed to implement different modules for cable real time inspection, lifetime prediction and maintenance planning.

The structure of this paper is as follows: Section II provides a review of the common failures of subsea cables; Section III introduces current condition monitoring methods for subsea cables; Section IV provides the detailed methodology of our physics based model to simulate the cable sliding, scouring, degradation and cable life time prediction; Section V introduces our system design and descriptions of the main modules are provided. The primary conclusions of our research are described in Section VII.

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II. SUBSEA CABLE FAILURES

. There are four types of classification of cable failures: internal, early-stage, external failures and failures due to environmental conditions. Currently, there is a shortage in cable failure statistical data, and the literature on different cable failure modes is also limited.

A. *Internal Failure*

Internal cable failure may occur due to overvoltage and overheating and cause damage to cables' ability of electricity transmission. Strong voltage generation, for example in wind turbine generators can cause overvoltage. On the other hand, even when electric transmission is within cable design limits, overheating may still occur. For example, when seabed condition changes, or tidal flow moves, sediments on the seabed may move and resulting in cable routes being buried. Under this condition, heat from electric transmission cannot be quickly moved away from the surface of the cable, causing overheating. Another form of internal failure is the degradation of able insulation layers as a result of stress such as temperature and mechanical stresses.

B. *Early Stage Failures*

Most cables today are protected by single or double-layer armouring. However, cable failure can still occur during the early installation stage. When installing, stress on the cable may manifest immediately, or after many years of deployment [1]. In the installation stage, manufacturing faults are often detected during the early installation process when the cable is energized and are considered as the dominant reason for causing installation failures. However, evidence for these cases are anecdotal and cannot be considered as the root cause of installation failures [7]. Meanwhile, cable-laying vessels can also be responsible for causing damage to cables that are already laid on the seabed.

C. *External Failures*

According to the Scottish and Southern Energy (SSE), environmental conditions and third-party damage account for a predominant share of subsea cable failures (48% and 27% respectively). Wear-out from corrosion and abrasion due to environmental conditions can damage and fail cable armour and sheath, leading to cable failures. Random events such as anchoring and trawling of ships on the seabed are examples of third-party damage, which could inflict failure to subsea cables.

Human activities may also cause unintended and external subsea cable failures, particularly in the initial installation stages. For example, when installing a turbine, the jack-up vessel used in the process may cause damage to subsea power cables laid around the area. This damage may come from both the initial impact of the jack-up vessel, but also from pushing the buried cable deeper into seabed substrate [7].

D. *Environmental Conditions*

During the installation process, the nature and the location of installation are critical factors for cable health. The level of protective armouring, laying environment also affects cable health post-burial. For example, whether the cable is floating freely on the seabed, or buried and covered under sand and rocks can determine the level of environmental damaged experienced by the cable.

Damage may also incur due to changes in current and seawater waves, which may abrade and stress subsea cables. When cables slide from their original positions, they may abrade against the seabed or rocks [7]. Cables laid in seawater may also suffer from corrosion particularly to the outer protective layers and the steel armouring. Environmental hazards such as tsunamis, sea level rises, subsea earthquakes can also significantly damage subsea cables. For example, hurricanes such as the Katrina may create landslides underwater, leading to strong tidal and current movements. As a result, the seabed where subsea cables are buried may be eroded, leading to exposure of subsea cables to sea water [9]. Within the section III we will now review the state of the art monitoring technologies.

III. STATE OF THE ART MONITORING

Currently, commercial condition monitoring systems for subsea cables include tests by cable manufacturers that focus on the internal robustness of cables. These tests are conducted so that before being shipped to customers, subsea cables meet specific pre-set standards. The tests examine different cable behaviors such as electrical and thermal, as well as the cables' mechanical strength [8]. For example, cable abrasion tests are conducted using a mechanical rug that imposes wear to cables similar to wear experienced in the installation process. The result therefore cannot be applied to cables in operation that experience actual abrasion.

In addition, commercial condition monitoring systems center around internal failure modes when examining cables in operation. Such monitoring systems include distributed strain and temperature (DST) measurement systems and partial discharge monitoring system. For example, DST enables asset users to monitor the thermal behavior of subsea cables. At onshore substations, operators can analyze outputs from the DST printouts, therefore enabling detection and localization of internal fiber damage to the subsea cables. However, DST and partial discharge monitoring systems do not represent a precursor indicator to failure. As a result, it is still necessary for subsea cable asset owners to conduct diver inspections, or use remotely operated underwater vehicles (ROVs) to examine subsea cable health.

To date, limited knowledge on abrasion and corrosion wear-out mechanisms exists. For example, a localized abrasion wear model was developed by Larsen-Basse et al. [10], but is not applicable the entire cable route, meanwhile, it does not account for scouring and corrosion. Another abrasion and corrosion model by Wu [11] require cable movement to serve input for the model. Furthermore, although Booth and Sandwith [12] showed that Taber abrasion tests can be used to obtain the abrasion wear coefficient for the polyethylene outer-serving of subsea cables. Data obtained from the Taber tests were never used in a model-based analysis framework to assess cable health.

Thus far, not many options exist for cable users to effectively monitor and predict subsea cable RUL. Although failures related to mechanical, chemical and electrical behavior of cables are well-documented, the most common subsea cable failure modes: environmental and third-party damages, are not thoroughly studied and incorporated in the current condition monitoring systems. As a result, there is a need for a comprehensive cable health management system that considers environmental parameters and third-party damage information, to prevent nearly 80% of subsea cable failures [8].

IV. Cable Modeling and Lifetime Prediction

A. *Cable Sliding Modeling*

We first find sliding distance with a mathematical model on the mechanical forces acting on cables. Two dominant mechanical forces act on subsea cables: F_{Drag} is the drag force resulting from tidal flow; $F_{Friction}$ is the frictional force from the opposite direction (see Figure 1)

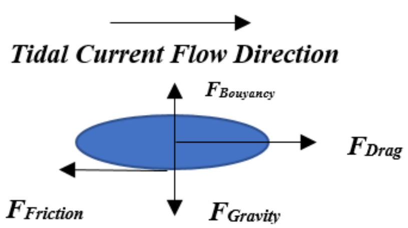

Figure 1. Current flow and forces on cable

F_{Drag} is calculated using equation (1), ρ represent seawater density, v is cable velocity with respect to seawater, A is the reference area. In this study, we adopt a value 1.2 for C (drag coefficient) as in [13]. The frictional force can be calculated with (2) using $F_{Buoyancy}$ (buoyancy force), $F_{Gravity}$ (gravitational force), and μ (friction coefficient, typically between 0.2 and 0.4) [14].

$$F_{Drag} = 0.5\rho v^2 AC \tag{1}$$

$$F_{Friction} = (F_{Gravity} - F_{Buoyancy})\mu \tag{2}$$

For a specific tidal flow profile, we predict sliding distance (S) along the cable route with a catenary model. Figure 2 illustrates the four different forces (A_x, A_y, B_x, B_y) experienced by the cable when fixed at both its ends (A, B). Using moment equilibrium equation from [15], cable sliding distance Y_{n-1} at each zone, forces A_y and B_y can be predicted using forces on each cable segment as well as cable zone lengths.

In equilibrium, the horizontal forces equate, $A_x = B_x$. It is therefore possible to use the moment equilibrium at each loading point, we can obtain a common derivation for sliding distance Y_i as follows:

$$Y_i = \frac{A_y \sum_{j=1}^{i} X_j - \sum_{k=1}^{i-1} F_k \sum_{l=k+1}^{i} X_l}{A_x} \tag{3}$$

B. *Cable corrosion and abrasion modeling*

Subsea cables can also be subject to tidal current that causes scouring when laid on seabed. $V_{BedFriction}$ is needed to calculate the timeframe of scouring process. We calculate $V_{BedFriction}$ need to be calculated as in [16] and [17], taking into account water depth and seabed roughness. Using equation (4), T_{Scour} is obtained.

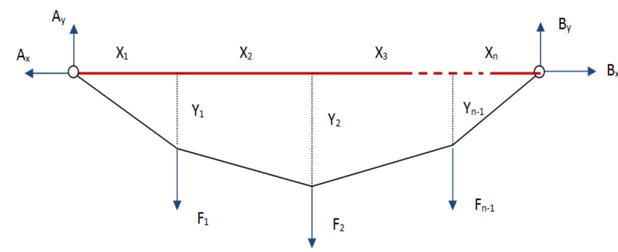

Figure 2. Catenary model with fixed cable and concentrated loadings

$$t_{scour} = \frac{d_{Cable}^2}{(g(SG-1)d_{50}^3)}\left(\frac{1}{50}\right)\left(\frac{V_{BedFriction}^2}{g(SG-1)d_{50}}\right)^{-\frac{5}{3}} \tag{4}$$

In addition to scouring damage, abrasion and corrosion may also cause subsea cable failures. In this study, we adopt the Archard [18] abrasion wear model. As (5) shows, $V_{Abrasion}$ is calculated using cable weight in water (F_{Cable}), sliding distance ($d_{Sliding}$), is the hardness (H), and the wear coefficient (k).

$$V_{Abrasion} = k\frac{F_{Cable} d_{Sliding}}{H} \tag{5}$$

In equation (5), k is the wear coefficient which depends on material and its interaction with a particular seabed. In this paper, we conducted Taber experiment on armor samples with different materials (shown in Table I.) on flat sheet form provided by the cable manufacturer. In the experiment, we used three types of abrasive wheels. The wear coefficient k of all the corresponding wheel types and cable layer materials are shown in Table I.

TABLE I. Taber Experiement and Estimated Wear Coefficients

Wheel Type	Polypropylene	Bitumen	Stainless steel
H10	6.548×10-4	4.21×10-5	6.628×10-4
H18	8.8308 ×10-4	1.703×10-5	2.773×10-2
H38	8.35×10-5	1.078×10-5	1.974×10-3

Equation (6) is used here to calculate $V_{Corrosion}$ (corrosion wear volume) as in [19], where c_1 represent the corrosion penetration rate, c_2 a constant taking value of 1/3 or 1, $A_{Exposed}$

the area of cable material exposed to seawater, t the time passed from when initial cable burial, $T_{Coating}$ the time taken for cable coating to deteriorate.

$$V_{Corrosion} = c_1 A_{Exposed}\left(t - T_{Coating}\right)^{c_2} \tag{6}$$

V. Cable Lifetime Prediction

Thus far, we have shown that, under a pre-defined tidal flow profile, sliding distance, abrasion and corrosion wear volume can be predicted. Using these information, a model can be developed to predict the health status of subsea cable. Environmental factor input, such as tidal flow pattern at each local section of cable can also be incorporated into the existing model. Typically, tidal flow pattern will move the cable to extreme sliding distance eight times from its original position in one lunar day. Total sliding distance can then be obtained by multiplying the sliding distance predicted from (3) by eight.

The overall mean time to failure (MTTF) can be obtained from Equation (7), where V_{Total} represents the total volume any cable can lost to its protective layer before failure occurs. $V^{day}_{Abrasion}$ is the abrasion wear rate per day, and $V^{day}_{Corrosion}$ is the corrosion wear rate per day.

$$\frac{V_{Total}}{\left(V^{day}_{Abrasion} + V^{day}_{Corrosion}\right)} \tag{7}$$

Finally, Figure 3 shows the structure of protective layers that should be accounted for in predicting volume losses. We use the maximum volume lost for each layer to predict the lifetime of the cable as follows:

$$V_{33} = (r - h_1 - h_2)^2 \frac{(\theta_3 - \sin(\theta_3))}{2}$$

Equation (8) defines the time to maximum volume loss to the third layer:

$$\frac{V_{33}}{\frac{k_3 F_{Cable} c d^{day}_{Sliding}}{H_3} + c_{31} L_3 \left(t - T_3^{Coating}\right)^{c_{32}}} \tag{8}$$

where $c = \frac{L_3}{L_1 + L_2 + L_3}$ and t is the elapsed time (days) after laid.

Similarly, failure time can be derived for the other protective layers on each stage of cable degradation. When the armoring layer of the subsea cable has lost all volume, the cable is considered as incurring complete failure.

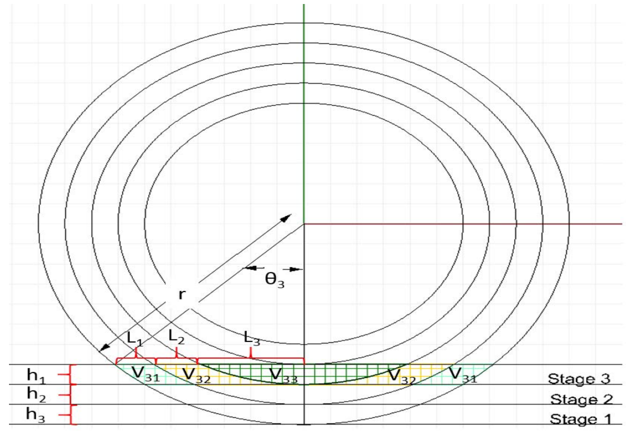

Figure 3. Schematic view of layer volumes in stage three

VI. System Design and Archetechture

In this section, a fusion prognostic health management system is illustrated for subsea cable lifetime estimation, real time inspection and maintenance planning. The overall working flow between modules is detailed in Figure 4. Specifically, 4 main modules are embedded into an operational decision support platform.

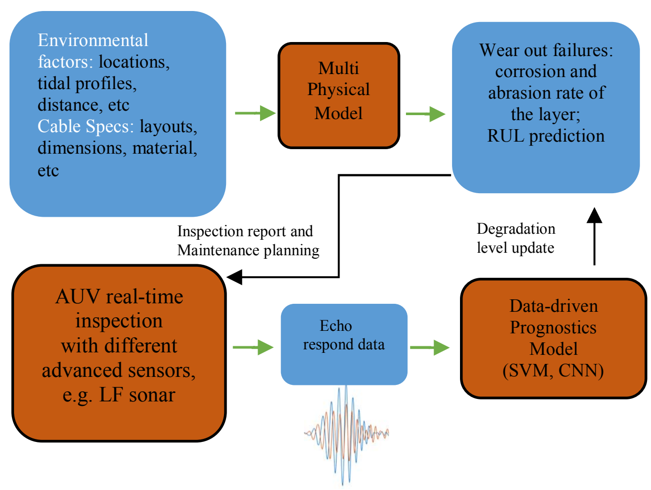

Figure 4. Workflow of main modules in the system

A. Cable RUL Prediction

This module is the implementation of the physics model described in Section 5, which is used to predict remaining useful life (RUL) of subsea cables. The methodology has been coded with and is linked to a database containing different cable designs, layouts and cable properties

For a defined cable layout on different seabed conditions and tidal flow inputs, this module will simulate cable movement, the process of scouring, and predicts the loss of cable wear that will occur over time due to both abrasion and corrosion.

Figure 5 shows the process of deploying a new subsea power cable route in our system. Users can select different types of cables and input the environmental profiles like seabed type and tidal flow. Figure 6 shows how the simulated model is presented in our system. After the deployment of the cable route, the user could apply the cable RUL prediction module on any cable segment of the whole route.

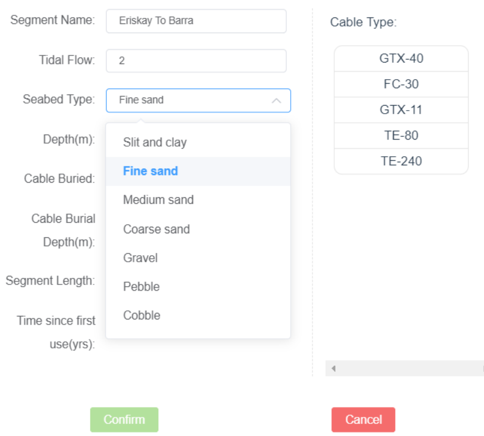

Figure 5. UI of Deploying Cable

This module also provides a valuable capability in prognostics and asset health management for optimization of the cable installation planning, i.e. verification of varying cable products and installation routes. The users could see a comparable presentation of cable RUL when choosing different types of cables at the beginning of cable deployment.

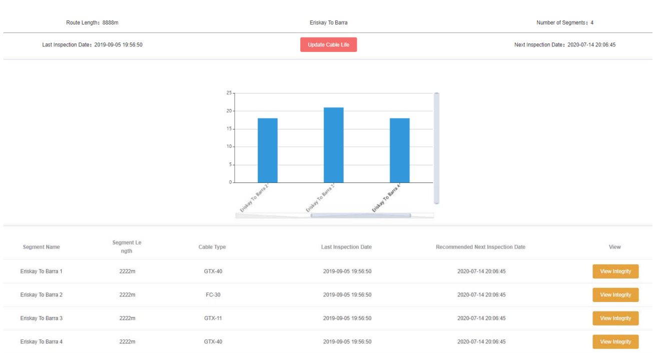

Figure 6. RUL prediction of a selected route

B. Cable Integrity Verification and data driven prognostics

Currently there are no technologies available to undertake a detailed and in-situ assessment of subsea cable integrity. Restrictive inspection methods such as diver inspection have multiple limitations, for example, requiring good visibility, challenges in locating and accessing the cable, while data collected with these methods remain observational. Previous work by [20] has shown that using advanced bio-sonar technology, it is possible to obtain cable integrity data that corresponds to different degradation stages.

This module is a demonstration of how we could apply AUV and bio-sonar techniques to obtain real time cable integrity data (Fig.7). The cable RUL prediction module could provide us an insight of where and when the faults may be, also when a real time verification is needed (Fig.6). Then the user could deploy an AUV embedded with bio-sonar to conduct underwater scanning missions on the suggested cable segments based on the prediction results. Moreover, the AUV will be more efficient, accurate and safe in verifying sections that are more severely damaged than others or not by the embedded bio-sonar. Previous work [21] has shown the feasibility of wideband sonar and machine-learning techniques to conduct accurate cable integrity analysis. In our work, we employ this methodology and feed cable echo response data into our data-driven prognostics model, providing updates of more accurate cable degradation feedback.

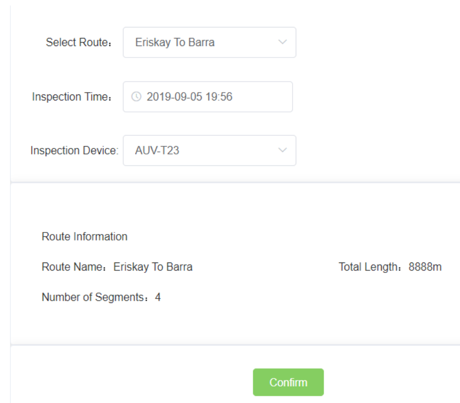

Figure 7. New inspection mission initiation

C. Cable Integrity Update and maintenance Planning

For subsea cable asset owners, delay in repairing or replacing cables can cause substantial economic losses, it is thus essential for offline operators to conduct careful planning to maintain cable integrity [6].

In our system, the output from the prognostics model are sent back to the off-line RUL prediction model, where updated predictions are made on potential future failure modes, failure time, failure locations or segments. These predictions therefore enable optimized decision making and planning to conduct future AUV inspection mission.

VII. CONCLUSION

In this paper, we developed a modelling methodology and associated operational decision support platform to predict cable lifetime. The cable prediction model incorporates abrasion and corrosion and sliding. It also enables the user to predict cable movement (including the effects of scouring) under various tidal flow patterns. In our model, data from Taber test on protective layer wear coefficients are also integrated for more accurate lifetime predictions.

The operational decision support tool can be used to predict the RUL of existing subsea cable installations and can support optimal route and cable type selection for a given installation. A benefit of our open reference architecture, is that this supports a sensor agnostic approach, supporting the integration of new data inputs. This has been used to demonstrate how utilizing advanced bio-sonar technologies, subsea robotics and the cable RUL prediction model, we can advance current practice in the health management of these critical assets.

ACKNOWLEDGMENT

The authors from Heriot-Watt University acknowledge the funding support from the EPSRC project on HOME-Offshore (grant EP/P009743/1) as well as the EPSRC Offshore Robotics for Certification of Assets hub (grant EP/R026173/1). The authors also want to acknowledge the technical support of Hydrason Ltd.

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