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Structural and System Monitoring for Enhanced Oil and Gas Recovery in the Danish North Sea

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Introduction

The Danish Hydrocarbon Research & Technology Centre (DHRTC) has defined four core scientific themes within which scientific research activities related to enhanced oil and gas recovery in the Danish North Sea will be funded. As made clear by the centre's document "Scientific Framework for the Danish Hydrocarbon Research & Technology Centre", the success of the DHRTC will be dependent on it's ability to derive technological answers which span across the scientific themes. Therefore, the objective of this document is to outline a general cross-disciplinary framework for the research and development of structural and system monitoring schemes, with the intention of improving the efficiency and extending the lifetime of offshore oil and gas recovery systems.

R&D objectives

DHRTC has defined six areas of application in which research and development (R&D) should lead to substantial increases in oil and gas production. These include:

- Improved sweep efficiency
- Reduced residual hydrocarbon saturations
- Detect and produce by-pass hydrocarbons
- Enable development of marginal and tight oil and gas discoveries
- Extend well integrity and well life
- Extend life of surface installations

It can be understood that a multi-faceted R&D approach covering all themes will be required to achieve the significant advances in these areas (Fig 1). No one group or entity will be able to cover all required facets. Therefore, a multi-party, cross-disciplinary approach should be pursued for each facet.

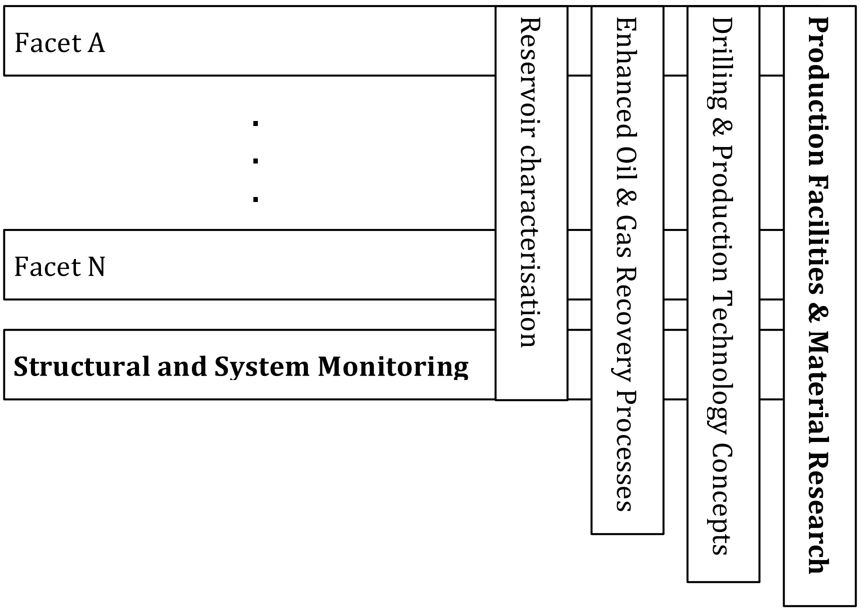

Figure 1. Multi-faceted R&D approach covering DHRTC scientific themes

Structural and system monitoring (SSM) comprises a key facet, without which R&D efforts will lead to limited success. Structural and system monitoring broadly involves the acquisition of structural and operational parameters, which when evaluated allows for the optimisation of oil and gas production in a safe and sustainable manner within this context. Simply, without measurements, the desired safety and efficiency will not be achieved.

Broadly, the R&D objectives related to SSM will involve the improved data recovery from and usage of existing monitoring systems, the optimal application of new technologies and the evaluation of the cost-benefits and feasibility of emerging technological developments.

Cross-disciplinary framework

Developments in SSM will be needed to address the challenges in all four defined scientific themes (Fig. 1). To emphasise the cross-disciplinary nature of this facet, the theme of Production Facilities & Material Research & Design is chosen for expansion of the framework.

The cross-disciplinary framework for R&D can be viewed in terms of a discipline matrix, as shown in Table 1. Although not comprehensive in nature, it shows the multiple items under each discipline that need to be addressed within this theme, so as to lead to improved oil and gas extraction.

Table 1. Discipline matrix relating to Production Facilities & Material Research & Design

Assessment	Causes	Effects	Mitigation	Repair
Design verification OMA Risk Reliability Codes	Loading Ageing Imperfections Wear	Fatigue Degradation Corrosion Creep/Relaxation Blockage	Retrofit Adaptation Inspection Maintenance	Welding Replacement Structural reinforcement

The purpose of SSM strategies is to collect the necessary data to be able to add value to each of the aforementioned disciplines and sub-items. As an example, SSM should be employed full-scale and the data acquired from it should be used to improve design verifications though back calculations of induced stresses and/or load coefficients. It can be used to assess corrosion and to evaluate the quality of welds during repair. It can be used in the implementation of control strategies for adaptive technologies and/or for the measurement of fatigue amplitudes and cycles.

Furthermore, each of the aforementioned disciplines can be researched and developed within three distinct technological timeframes. These are tried and tested existing technologies, new technologies and emerging technologies. To understand this, the discipline of assessment can be chosen and it immediately becomes apparent that it is important that the field of Operational Modal Analysis has a tried and tested set of algorithms and sensor configurations that give a limited amount of information on structural assessment, predominately in the linear domain. New techniques are examining ways to obtain e.g. stress and back-calculated hydrodynamic structural load coefficients. Emerging and future techniques will move in the direction of non-linear load and structural assessment.

The proposed framework will work across all timeframes and disciplines. The allowable benefits will be extracted from R&D in each of these disciplines and for each timeframe.

Specific technologies

DHRTC has specified a series of challenges within the theme of Production Facilities & Material Research & Design. These are the evaluation of corrosion mechanisms, scale formation and gas-hydrates, risk-based decision making and planning, sensor technology and sensor systems, fatigue and damage estimation, model predictive control, new platform concepts, new pipeline concepts, and handling of produced water. Using the example of the application of the SSM framework within this theme, specific technologies and/or methods/studies can be described that cover all three aforementioned timeframes.

As one example, sensor technology and sensor systems will have to be researched and developed extensively. Existing relevant tried and tested sensors include accelerometers, strain gauges, fibre-optic sensors, geophones, GPS, acoustic emission detectors, electrodes, wave radars, wave scanners, anemometers, PIV cameras and pressure gauges. Although most of these sensors have been available for years, their use is often not optimal, i.e. the placement of the sensors or the type of sensor for each application has not been optimised. Problems with noise and loss of data are common.

Newer technologies include wireless solutions and smart sensors that can be embedded into Intelligent Sensor Networks (ISN). This has allowed for improved sensor and data logger performances, but similar problems exist. Wireless technologies often lead to loss of data through hung transmissions. Although sensor accuracy and resolution has increased markedly over the last few decades, issues with sensor intrusions and noise are also common. Emerging technologies that look to address these issues predominantly include non-contact measurement systems and techniques. For example, Digital Image Correlation (DIC) involves the processing of remotely acquired images to create accurate high-resolution strain maps and for crack development and growth detections. The technology is an emerging one and will require further R&D so that it may be used in harsh low-light conditions on unstable platforms.

Other emerging technologies include environmental load monitoring and scanning in real time for 3D sea states including breaking waves, using advanced wave scanners, LIDAR and SODAR. Indirect measurement techniques and non-destructive technologies (NDT) are emerging for the evaluation of scour, corrosion and marine growth.

It should be apparent that a successful R&D strategy for the proposed framework will involve work in all three timeframes.

R&D Activities

In addition to sensors technologies and systems, the discipline matrix of Table 1 justifies a broad spectrum of R&D activities. A non-exhaustive list of these in no particular order include:

- <u>Sensor technologies and systems</u>: (as described above)

- Norms, codes, standards and met-ocean data:
  Updating/corrections/amendments to/of existing norms, codes and standards and basis met-ocean data statistics (e.g. sea state description, wave spectrum description, etc.) for design and re-assessment analyses of offshore structures to allow for the implementation of more advanced methods, in relation to what is currently being used.

- Historical data processing: Exploitation of existing structural health monitoring (SHM) data (e.g.: Siri platform – 4 years of SHM data, Valdemar Platform – 3.5 year of SHM data, South Arne Platform - 2 year of SHM data and the newer Hejre Platform SHM data). Establish and maintain a worldwide information database containing all processed SHM data, observations and experiences, providing a unique possibility for the utilization of data mining techniques in combination with probabilistic methods and models for extracting valuable information from already existing data.

- Laboratory tests for Verification & Validation (V&V): Tests under controlled environments for the assessment of the effects of Environmental and Operational Variability (EOV) – temperature, pressure, tidal-level, corrosion, marine growth, scour, subsidence, changes in soil conditions, operation conditions, (see also topics under Fatigue Damage Prediction & Monitoring).

- Full-scale testing and monitoring on new and existing platforms: Measurement of actual loads, structural response and aging (including corrosion rates, system fatigue and blockage rates)

- System identification: Linear & non-linear system identification (NLSID) using a combination of traditional and emerging techniques, including OMA, machine learning, Statistical Pattern Recognition (SPR), Data Mining, Wavelet Transform (WT) and predictive modelling.

- Finite element model (FEM) updating: Evaluation of Bayesian FE model updating against modal parameters, including uncertainty assessments involving the concepts of risk and reliability. Examination of the effects of non-stationarity and non-linearities affecting structural response.

- Expansion processes: Optimisation of minimum sensor layout using FE modelling. Expansions in both dynamic FE and the more difficult quasi-static FE modes, tying in the concepts of risk and reliability.

- Fatigue damage prediction and monitoring: SHM-based fatigue monitoring and re-assessment analyses. More advanced Fracture Mechanics (FM) models need to be developed (critical crack dimension, first through thickness failure, etc.) together with consequence of failure modelling.

- Reliability and Risk: Improvements for probability of failure (PoF) estimates, through the integration of SHM data. Interesting aspects of this include the integration of SHM data and NDT methods, leading to a "live" probabilistic planning format, allowing for continuous updating and risk/damage/PoF monitoring.

- Damage detection, warning systems and evacuation timing: Improvements here will look at the evaluation of changing non-linearities and reliability analysis for damage prognosis and decision-making. Important aspects to this are post-damage/post-storm system identification and analysis.

- Control system engineering, smart structures: Structural and system monitoring will be relevant for adaptive structural systems, i.e. smart structures. Control systems engineering is needed for all aspect of extraction operation, from platform integrity to oil pumping and processing.

- Decision making and planning**:** Reliability- and risk-based decision making accounting for cost-benefits and considering Value of Information (VoI) evaluations. Means of integrated this into most of the aforementioned activities will require further investigation.

Recommended initial R&D work-packages

Modal Based Full-field Stress/Strain Assessment on Offshore Structures

The design lifetime of an offshore platform is often governed by accumulated fatigue given by the stress/strain history the structure is expected to undergo. Current design codes provide a safety margin but do not take into account the possibility of monitoring the stress/strain history of the building.

This project proposes a framework for estimating the stress/strain history in the entire structure using only a limited number of sensors. Combining results from operational modal analysis with a well-correlated FE model enables the expansion of the measured response, which for linear structures can be transformed to strains using finite element theory.

In the project both existing and new expansion processes will be investigated. An important topic will be the prediction of the quasi-static response caused by the waves acting on the structure, where it is proposed that operating deflection shapes should be used to decompose the measured response.

To validate the proposed framework laboratory tests will be performed on scaled models of offshore structures excited by shakers or placed in wave flumes under different conditions. Further validation will be performed by processing already existing data from offshore structures in the North Sea.

Damage detection / Prognosis

A project with the scope of constructing a robust and reliable structural integrity monitoring system, is a large work-package featuring many of the R&D activities listed above. The input to the damage detection paradigm consists of physical parameters (e.g. modal data) extracted by the sensors fitted to the structure and model data from an updated FE model of the structure.

Over the recent years there has been a shift within the field of vibration-based damage detection, from direct methods towards methods based on statistical measures or pattern recognition paradigms. It has become more or less apparent that the methods based on the classical relations between frequency, mode shapes and the system matrices are sensitive to noise, which has shifted the focus towards more noise-insensitive techniques. However, the output from the vibration-based techniques can be used as the input to a pattern recognition algorithm. In this case the input can be regarded as further condensed features containing both modal parameters and model data.

The most important activities in this project involve the development of a reliable measuring system and robust identification of the aforementioned physical parameters, coupled with the updating of the FE model. Once these activities are completed the output of the detection algorithms can be fed into pattern recognition paradigms to improve robustness.

Use of non-destructive non-contact methods for system and damage identification
Traditional sensors are often intrusive and only provide point information on a structure. Therefore, cracks and damage often evade detection, strains only get measured locally and the structural response picture often remains incomplete. New non-destructive non-contact measurement techniques such as digital image correlation (DIC) and laser mapping, offer new potential for the real-time mapping of strains, deformations, crack, corrosion, expansions and other forms of structural and system response and damage. Furthermore, the new measurement techniques can prove to be extremely empowering for system identification techniques that currently reply on spar point measurements for their output.

This project would look at developing the non-destructive non-contact techniques to the level that they could be applied full-scale on an offshore platform for the identification of the aforementioned response parameters over whole areas, in contrast to point-by-point measurements. Furthermore, the possibility of including these in automated systems, such as drones and small moving robotic platforms will be explored. Challenges that need to be overcome include calibration and resolution issues, the effects of platform stability on measurements and measurement in harsh conditions with low light.

R&D Collaboration
The current document has been developed in a collaborative manner between Aarhus University, the Technical University of Denmark and Rambøll Oil & Gas, Esbjerg. Although the SSM expertise with these three institutions is significant, the extent of the research and development needed, coupled with the aforementioned cross-disciplinary nature of the framework, will require substantial levels of collaboration in the form of academic and industrial partners and access to expert groups and networks. The partners herewith have access to and regularly collaborate with all of the relevant academic and industrial experts within the field. An exhaustive list of partners will be provided upon request.