

Structural integrity monitoring

Review and appraisal of current technologies
for offshore applications

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With the ageing of the North Sea fleet of platforms and semi-submersibles, the importance of maintaining structural integrity offshore is increasingly recognised and structural inspection plays a significant role in demonstrating ongoing integrity and the potential for life extension. Structural integrity (SI) monitoring can complement existing inspection techniques to provide greater confidence in structural integrity or to reduce inspection cost. It has been found that offshore experience of SI monitoring is limited to date and that current systems are for bespoke applications. This report focuses on fixed steel structures, topsides and semi-submersible hulls.

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Abbreviations and Acronyms

ACFM	Alternating Current Field Measurement
RACM	Riser and anchor chain Monitoring
AE	Acoustic emissions
AGM	Air Gap Monitoring
API	American Petroleum Institute
CFMD	Continuous Flooded Member Detection
DNV	Det Norske Veritas
DP	Digital Photography
DR	Digital Radiography
ECD	Eddy Current Detection
FG	Fatigue Gauge
GPS	Global Positioning System
HSE	Health and Safety Executive
LD	Leak Detection
MPI	Magnetic Particle Inspection
NFRM	Natural Frequency Response Monitoring
PFP	Passive Fire Protection
RAT	Rope Access Technician
SI	Structural Integrity
SIMoNet	Structural Integrity Monitoring Network
SLOFEC TM	Saturated Low Frequency Eddy Current
SM	Strain Monitoring
TOFD	Time of Flight Diffraction
UKCS	United Kingdom Continental Shelf
TR	Temporary Refuge
EER	Environmental Emergency Response
RRF	Relaxation Resonance Frequency
OLM JIP	Online Monitoring Joint Industry Project
WFD	Widespread Fatigue Damage

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EXECUTIVE SUMMARY

With the ageing of the North Sea fleet of platforms and semi-submersibles, the importance of maintaining structural integrity offshore is increasingly recognised and structural inspection plays a significant role in demonstrating ongoing integrity and the potential for life extension. Structural integrity (SI) monitoring can complement existing inspection techniques to provide greater confidence in structural integrity or to reduce inspection cost. It has been found that offshore experience of SI monitoring is limited to date and that current systems are for bespoke applications. This report focuses on fixed steel structures, topsides and semi-submersible hulls. The report is presented in two parts:

The first part (Chapter 2 - 4) includes:

- Hazard identification and consequence analysis;
- Review of relevant codes and standards and other background literature;
- Review of current and potential SI monitoring technologies applicable for use offshore;
- Identification of capabilities and limitations in current SI monitoring techniques.

The second part (Chapter 5 - 8) includes:

- A qualitative review of the current inspection and SI monitoring techniques based on the need to detect damage mechanisms effectively, cost-effectively and with a minimum safety risk;
- Based on various damage mechanisms, an assessment of the capability of SI monitoring techniques to complement current inspection techniques;
- An assessment of the potential capability of SI monitoring techniques to monitor difficult to inspect items and for application in life extension;
- Requirements for the development of SI monitoring techniques.

The general findings of this report are as follows:

- There are a number of codes and standards which make reference to SI monitoring but no standard on its application in the offshore industry exists.
- A significant number of SI monitoring techniques exist and these have been reviewed. There is significant variability in the level of development of the different SI monitoring techniques.
- A qualitative assessment has been carried out to identify where SI monitoring can complement periodic inspection methods. A number of damage mechanisms for which SI monitoring techniques can complement inspection methods have been identified.
- There is an opportunity for SI monitoring techniques to be used to inspect/monitor damage mechanisms on difficult to inspect items, particularly to support life extension. These include: welded pile sections, grouted connections, shear plates for pile sleeve-connectors, ring-stiffened joints, items in the splash zone and deep water components.
- Further development of existing SI monitoring techniques is required to meet offshore requirements. This report gives some examples of potentially useful developments.

INTRODUCTION

Background

Atkins was requested by the Health and Safety Executive (HSE) to conduct a review and appraisal of current structural integrity (SI) monitoring technologies for offshore applications.

Many of the structures in the UK sector of the North Sea are now reaching or have exceeded their original design life and this presents new challenges for the structural integrity management of these structures. SI monitoring can, in combination with other methods, be used to demonstrate continued safe operation of a structure which has exceeded its original design life. Other typical applications for SI monitoring include:

1. Monitoring of a known local defect or high risk part of a structure;
2. Justify a reduction in NDT/inspection activity;
3. Cost reduction for new build structures; and
4. Satisfying regulator requirements.

Objective

The objective of this review is to provide the reader with basic information on generally available SI monitoring techniques. A review has been carried out to identify where SI monitoring can complement existing inspection techniques. A brief section summarising common requirements for development-in order to make SI monitoring more applicable in practice-has been included for the benefit of developers of SI monitoring technologies.

Regulation and Initiatives

Maintaining structural integrity during the lifetime of an installation is a main requirement under the Design and Construction Regulations [1]. This is normally achieved for installations on the UKCS through a Structural Integrity Management Strategy, which identifies the arrangements for achieving maintenance of structural integrity through periodic assessments and carrying out any remedial work in the event of any damage or deterioration being identified. This strategy includes the inspection tools, methods of deployment, frequencies of inspection, etc. It should also incorporate an understanding of the criticality of structural elements in terms of platform redundancy among other things. The costs of offshore inspection can be significant and ways of reducing these, while still meeting safety and fitness for purpose requirements are useful.

The HSE introduced an initiative Key Programme 3 (KP3) in 2004 focusing attention on installation integrity and maintenance management matters. This was because many offshore installations (and the equipment on them) had reached, or were near to the end of their design lives and the drive to reduce costs led to changes in offshore maintenance arrangements including a reduction in skilled offshore workers.

As a result of the initiative, HSE inspectors have looked closely at key maintenance/integrity issues, developing joint programmes with industry, trade unions and safety representatives/workers; sharing findings with all concerned and taking any necessary enforcement action. In 2007 this has been replaced by the Structural Integrity Management Inspection Programme (SIMIP).

SI Monitoring

SI monitoring can assist in meeting the requirement to manage lifetime structural integrity and also provide information to demonstrate the case for life extension. The use of real-time monitoring can provide both valuable structural data as well as cost savings if the technique can complement or replace offshore inspection methods.

The case for the use of SI monitoring to complement conventional inspection techniques can be assessed using the following broad comparative criteria:

1. Sensitivity/effectiveness of technique;
2. Health and safety benefits; and
3. Cost reduction.

Although there are currently no actual regulatory requirements for SI monitoring in the UK, the HSE do provide some guidance on SI monitoring, e.g. Offshore Information Sheet 8/2007 [2]. DNV [3] requires an approved leak detection system to be installed for the life extension of semi-submersibles.

In order to identify SI monitoring methods that qualify for this study, an assessment of hazards, consequences and appropriate SI monitoring techniques has been carried out. The main focus of the work is on SI monitoring of ageing structures; however, most methods can equally be applied to other applications.

In the context of this work, the definition of a SI monitoring method is a method for continuously monitoring a parameter that impacts on structural integrity. This study excludes periodic inspection of a particular component.

The relative cost of SI monitoring methods has been considered in this project. Generally, bespoke equipment is required and cost is dependent on the specific application, installation and operating requirements which can vary significantly. It has therefore not been practicable to provide reliable cost estimates.

1. SCOPE

This document includes review and appraisal of SI monitoring methods which can be applied to offshore jacket structures, steel semi-submersibles structures for drilling and/or production operations. The following methods have been reviewed:

- Acoustic emission monitoring
- Leak detection
- Air gap monitoring
- Global positioning system monitoring
- Fatigue gauge monitoring
- Continuous flooded member detection monitoring
- Natural frequency response monitoring
- Acoustic fingerprinting
- Mooring chain monitoring
- Strain monitoring

The above techniques are reviewed and compared in more detail in Section 4.

2. ASSESSMENT OF HAZARDS, CONSEQUENCES AND APPROPRIATE SI MONITORING TECHNIQUES

Typical offshore structural hazards are reviewed together with the relevant safety critical systems. The prevention, mitigation and control measures are briefly discussed. The consequences for each hazard are listed and relevant SI monitoring techniques to monitor these are identified.

2.1 HAZARD AND CONSEQUENCE IDENTIFICATION AND RELEVANT SI MONITORING TECHNIQUES

Extreme Weather

Extreme weather involves a combination of three different components: wave, current and wind. The environmental loading due to the combined action of these three factors constitutes the governing loading condition for the design of offshore jacket type structures, and hence constitutes a significant hazard in the United Kingdom Continental Shelf (UKCS).

At present, the design practice API RP 2A [4] is based on the 100-year return period wave height acting together with "associated" wind and "associated" current conditions. The majority of the North Sea structures were designed based on a 50-year return wave height combined with 50-year wind and 50-year current, which are the criteria given in the HSE/Department of Energy (DEN) Guidance Notes [5] and its previous editions.

Geological/geotechnical hazards

The geological/geotechnical hazards which could result in structural failure are due to one or more of the following:

- Pile pull-out in tension;
- Pile punch-through in compression;
- Formation of plastic hinges in piles due to bending;
- Degradation in pile capacity under cyclic loading;
- Differential settlement;
- Degradation in foundation capacity due to seabed scour; and
- Subsidence and slope instability.

Fatigue

Fatigue damage to welded structural components arises because of the cyclic nature of wave or wind loading. The North Sea wave climate is much more damaging in respect of fatigue than for example the Gulf of Mexico, and fatigue is now recognised as an important hazard for North Sea structures. Fatigue damage is in the form of cracks, usually at welded connections, which can grow to through to through-thickness stage and eventually lead to member severance.

Corrosion / material degradation

Steel immersed in seawater suffers corrosion at a significant rate unless protected, usually by a cathodic protection (CP) system. Most platforms use sacrificial anode systems, with a distribution of anodes provided to give sufficient protection over the structure. In addition it is also common practice to provide a 'corrosion allowance' for members located near the mean sea

level (often between 6-12 mm), where corrosion rates are higher. Steel exposed to sea spray is also vulnerable and in the splash zone, epoxy or similar paints are often used to provide corrosion protection, since the CP system is ineffective in this zone.

Dropped Objects

Impact by dropped objects or swinging loads during lifts by cranes and similar devices constitutes an important hazard scenario for an offshore installation. The impact could be with hydrocarbon containing equipment or directly onto a structurally sensitive part of the installation.

Ship Collisions

Ship collisions can be classified as either “powered collisions” from passing vessels or “in-field collisions” from supply and standby vessels operating in the field. Jacket structures have generally been designed to withstand kinetic impact energies of the order of 11-14 MJ.

Fire and Blast

Fire and blast are now recognised as one of the most important hazards offshore. Fires and explosions arise mainly from hydrocarbon leaks. The management of these leaks is a high priority topic. Management of the hazards is primarily through process design, provision of blast and firewalls and passive fire protection on members. The consequences of fire and blast depend on the nature of the incident. Jet fires can cause very considerable structural damage, and it is normal design practice to protect members vulnerable to such fires. Explosions can also cause serious structural damage, either through the initial blast or through damage from projectiles. Fire and explosion can reduce the availability of the emergency response systems and the temporary refuge (TR), which are a necessary part of the offshore emergency management system.

Loss of Station Keeping

Accurate station keeping is essential to ensure integrity of the riser/conductor systems and other connections to the seabed or nearby installations. Station keeping generally relies on the integrity of the mooring system, which can be affected by fatigue/corrosion and other degradation mechanisms.

Change of Use

This topic has received little attention to date, relevant to structural integrity. However the main hazards in this area are weight management, and enhanced risks for fire and explosion arising from change of process requirements, etc.

Table 1 SI Monitoring Techniques Used to Monitor Damage Parameters

Hazard	Safety critical structural systems	Prevention, mitigation, control measures	Consequences	Relevant SI monitoring techniques (to hazard)
Extreme Weather	Jacket, Foundation, Risers/Appurtenances and their supports	Adequate air gap, design using adequate design wave height, redundancy in design	Loss of stability Loss of airgap (Member buckling Pile failure Member severance)	AGM GPS SM NFRM
Geotechnical Hazards	Foundation	Sea-bed surveys, adequate foundation design, scour allowance, scour inspection, measurement of settlement/subsidence	Loss of airgap Platform tilt Pile failure Pile pull out	GPS AGM NFRM
Fatigue	Jacket, Risers/Appurtenances and their supports, topsides	Design for adequate fatigue life and inspectability, IMR, remote monitoring	Crack initiation Through-thickness cracks Member severance Widespread fatigue damage (Breach of water-tight integrity Loss of stability)	AE CFMD LD NFRM FG SM
Corrosion / materials degradation	Jacket, Topside structures, Risers/Appurtenances and their supports	Corrosion protection, corrosion allowance, CP monitoring, IMR	Loss of wall thickness Cracking Embrittlement Wear Erosion Member buckling Connection to SCE lost (Breach of watertight integrity Loss of stability)	AE NFRM FG
Dropped Object	Jacket, Risers/Appurtenances and their supports, topsides	Design of key members for bow and dent damage, management of crane operations	Member denting / buckling / severance Crack initiation (Breach of water-tight integrity Loss of stability)	NFRM
Ship Collision	Jacket	Design for adequate energy absorption, control on vessel operation, warning systems	Member denting / buckling / severance Crack initiation Breach of water-tight integrity Loss of stability	NFRM
Fire & Blast	MSF, Accommodation module, TR, EER structures, Fire/Blast walls, caissons, exposed jacket legs, risers	Fire/blast walls, PFP, detection and warning systems, deluge system, reduce leaks sources	Loss of structural stiffness Structural overload Blast damage to steelwork	Not generally monitored with SI monitoring methods
Loss of Station Keeping	Moorings, dynamic positioning system	Load measurement		GPS RACM
Change of Use	Jacket, Foundation and Topside structures	Weight management, strengthening/modification	Pile failure Loss of airgap Structural overload	AGM

AGM = Air Gap Monitoring

GPS = Global Positioning System

SM = Strain Monitoring

NFRM = Natural Frequency Response Monitoring

AE = Acoustic Emission Monitoring

LD = Leak Detection

CFMD = Continuous Flooded Member Detection

FG = Fatigue Gauge

RACM = Riser and Anchor Chain Monitoring

2.2 CAPABILITY OF SI MONITORING TECHNIQUES

The previous section identified relevant SI monitoring techniques with respect to offshore structural hazards and consequences. Table 2 below summarises the applicability of each SI monitoring technique in terms of its capability to monitor a parameter that impacts on structural integrity.

Table 2 Monitoring Capability of SI Monitoring Techniques

SI monitoring technique	Monitoring capability
Air Gap Monitoring	Loss of Air gap
Global Positioning System	Loss of station keeping Loss of air gap
Acoustic Emission	Fatigue crack initiation Fatigue crack growth Corrosion
Continuous Flooded Member Detection	Member leak detection Through-thickness cracks Through-thickness corrosion
Leak Detection	Breach of water-tight integrity Through-thickness cracks Through-thickness corrosion
Natural Frequency Response Monitoring	Member severance Significant damage to member and joints
Riser and Anchor Chain Monitoring	Loss of mooring line tension
Fatigue Gauge	Fatigue cracking
Acoustic Fingerprinting	Through-thickness cracks (fully-severed members)
Strain Monitoring	Local stress and loading regime

3. REVIEW OF RELEVANT CODES AND STANDARDS AND PUBLISHED DOCUMENTS

This section presents a brief overview of relevant codes and standards and other published documents with respect to SI monitoring.

3.1 RELEVANT CODES AND STANDARDS

A number of offshore codes and standards make reference to SI monitoring. These include:

1) ISO 19902 – Petroleum and Natural Gas Industries — Fixed Steel Offshore Structures, Section 24 [6].

This recently published ISO standard on fixed offshore installations [6] includes a section on in-service inspection and structural integrity management. In the commentary to the main section Table A.24.4-3 lists a range of inspection methods. An extract from [6] comments on measuring the air gap viz:

“Where air gap measurement devices are correctly set up, calibrated and maintained, continuous records of wave heights and tide can provide very useful information on environmental conditions. Where this can be combined with directionality data and ideally some method of estimating actions (e.g. strain gauges), the data can be used in analyses and assessment of defects and of remaining life, possibly reducing conservatism. Satellite surveying techniques can often be used to determine levels.”

2) API “Recommended Practice for the Structural Integrity Management of Fixed Offshore Structures” [4]. This document is a draft.

Section 5.8.9 on “Non-Destructive Examination” includes a statement that the monitoring of fatigue sensitive joints and/or reported crack-like indications may be an acceptable alternative to analytical verification.

3) NORSOK “Condition Monitoring of Load-Bearing Structures” N-005, 1997 [7].

Annex A of this document includes in-service inspection methods. In the section on/selection of methods it is stated that:

“For certain purposes, Instrumentation Based Condition Monitoring, IBCM, can be used as a cost effective alternative to conventional inspection methods, particularly for monitoring areas with limited accessibility, as a supplementary mean to e.g. verify novel design solutions. Typical applications of IBCM can be strain monitoring of jacket structures, foundation behaviour during extreme storms etc.”

Strain and deflection monitoring are also included in the list of techniques.

4) ISO 16587:2004 [8] describes the performance parameters for assessing the condition of structures including types of measurement, factors for setting acceptable performance limits, data acquisition parameters for constructing uniform databases, and internationally accepted measurement guidance (e.g. terminology, transducer calibration, transducer mounting and approved transfer function techniques).

3.2 REVIEW OF PUBLISHED DOCUMENTS

Over the last several years, a number of papers and reports have been published on the topic of SI monitoring, covering a range of different techniques. The key reports have been reviewed and a detailed review summary is provided in Appendix 4. Specific topics on which papers and reports have been written include:

- General approach to SI monitoring;
- Development of new techniques;
- Natural frequency response monitoring; and
- Acoustic emission monitoring.

This review provides useful background to the previous and future development of SI monitoring techniques.

3.3 INSPECTION REQUIREMENTS

Several standards and recommended practices list a detailed set of inspection requirements for the underwater, splash zone and topsides structures. These serve to highlight areas where SI monitoring techniques might be useful.

Underwater and splash zone

ISO 19902 [6] lists the following as inspection priorities:

- primary structural framing;
- leg/pile connections;
- external inspection of pipeline risers and supports;
- external inspection of J-tubes and supports;
- conductor guide framing;
- service caissons and supports;
- riser guards;
- boat landings and fenders;
- other secondary framing and appurtenances;
- underwater cathodic protection system; and
- any special corrosion coatings of components located in the splash zone.

The draft API Recommended Practice document - based on ISO 19902 [6] provides more details of some of the inspection requirements, namely:

- Primary structural framing: detection of excessive corrosion of welds and members, weld/joint damage (including overload and fatigue damage) and mechanical damage in the form of dents, holes, bows and gouges. Other features to be inspected for include ineffective corrosion protection systems, scour, seafloor instability, excessive or hazardous debris and excessive marine growth.
- Conductors: overall condition from the splash zone area and upwards. The conductors should be inspected for coating condition, extent of corrosion, damage, presence of shims and movement.

- Risers: overall condition from the splash zone area and upwards. The risers should be inspected for breakdown of coatings and/or the extent of corrosion and the integrity of supporting steelwork and clamps.
- Appurtenances: damage or deterioration.

Topsides

ISO 19901-3 [9] lists the main structural items for topsides inspection. These include:

- Main deck girders and highly stiffened panels;
- Leg transitions to sub-structures (fatigue and fabrication defects);
- Module trusses and module support points;
- Accommodation module, anti-vibration mountings and support points;
- Bridges (e.g. bearing fatigue);
- Flare booms and vent stacks (supports to the main structure, strength reduction due to heat, fatigue cracks);
- Cranes including pedestals and attachments to main deck structure (e.g. fatigue);
- Drilling rigs;
- Lifeboats and other EER equipment e.g. davits;
- Helideck;
- Fire protection systems, coatings (e.g. PFP);
- Corrosion protection systems (paint and coatings);
- Access routes, floors and gratings; and
- Supports for equipment particularly any safety critical systems.

4. REVIEW OF SI MONITORING TECHNIQUES

This section summarises the basic information available on the SI monitoring techniques identified in Section 2.2.

Due to the bespoke nature of the systems, it has not been possible to include cost estimates for the different technologies in this report.

4.1 ACOUSTIC EMISSIONS MONITORING

SI monitoring method:	Acoustic Emissions Monitoring
OVERVIEW	
Brief description:	
Acoustic emission (AE) monitoring is the transient acoustic stress-wave which results from changes in materials. The principle of AE techniques is to use an arrangement of sensors to detect characteristic sound patterns that might signal the presence of structural anomalies locally in the structure. AE has numerous applications, although the most relevant to offshore platforms is structural monitoring of damage mechanisms such as cracks. The system has been used in areas that are known to be at a high risk of fatigue cracking and where inspection is difficult, unreliable and/or costly. The system can effectively monitor for crack initiation and growth, and can be used in conjunction with strain gauges to correlate AE signals to structural stress levels. AE provides real time information on fatigue crack initiation and crack growth, and can be used to detect fatigue cracks at early stages before conventional NDT methods would detect them. Raw data is analysed and put into a user-friendly format by the bespoke software. Due to attenuation of the AE signal, this method is suitable for local monitoring over several metres in the structure. AE sensors can be located externally or internally to the structure (e.g. in dry semi-submersible hull members).	
Purpose:	
Detection of anomalies in materials. In the offshore industry, the technique is primarily used for the detection of fatigue crack initiation and the monitoring of crack growth.	
Maturity in offshore industry:	
AE systems have been used for over a decade in the offshore industry and the technique is generally regarded as being suitable for the structural monitoring of safety critical members. Due to the need for intensive interrogation and associated costs, AE has been used only for specific high criticality applications and not as a general SI monitoring technique.	
Limitations:	
Data can be difficult to interpret and needs to be analysed by an engineer. The system can be prone to background noise which can affect its accuracy and reduce the probability of detection. The system can be partially sensitive to any activity such as maintenance works in the local vicinity because of the associated acoustic emissions created.	

OPERATIONAL REQUIREMENTS

Ease of Installation:

The system requires specialist installation. It requires that all sensors are hardwired back to a central control unit which may be some distance away, particularly for subsea installation or installation in inaccessible / remote areas.

For subsea applications, cabling through splash zone may be required.

Localised positioning of sensors external to structure requires divers.

Interrogation Method:

The raw data needs to be processed by specialist software which is usually owned by the supplier of the system. Data is presented in a user-friendly format. Due to the level of noise that can be picked up by an AE system, regular data review is required to identify foreign sources of AE noise.

Reliability / Probability of detection:

AE systems are generally considered reliable with a high probability of detection. Problems arise when there is a large amount of background noise that cannot be effectively filtered out, because this can mask the presence of activity due to defects. The system relies on operator interpretation of the data to detect the structural anomaly, and this needs to be managed to maximise detection of significant events.

Accuracy:

Modern AE systems are accurate and can detect crack initiation and early stages of propagation.

Maintenance:

The system requires periodic specialist maintenance and calibration.

4.2 LEAK DETECTION

SI monitoring method:	Leak Detection
OVERVIEW Brief description: In its simplest form, this monitoring system uses a sensor to detect water and then raises an alarm via an audible/visual unit. The technology in the system can vary significantly from early inundation alarms (fluid level switches) to more advanced systems such as field effect detector cells which produce a micro-electrical field that detects slight disruptions caused by water. Purpose: Detection of water ingress in dry areas typically in semi-submersibles. A secondary system such as a CCTV system is usually required to identify the cause of the water ingress e.g. breach of hull integrity or pipe failure. Maturity in offshore industry: Simple alarm systems have been used for a number of decades in the offshore industry to warn of high bilge water in ship hulls. Semi-submersible offshore platforms have also employed leak detectors, although these systems appear to have been bespoke designs and are often fairly dated. A number of companies offer advanced leak detection systems, but their primary business is not the offshore industry. These systems combine sensors from numerous zones (up to 32 typical) and raise an alarm from a central monitoring system. The monitoring system indicates in which zone the water leak has been detected. This system is accurate in identifying the leakage area and is also more sensitive to leakage than the simple alarm systems. Limitations: – some systems / sensor options rely on a clean environment; – may be affected by condensation or humid environment; – extensive cabling may be required as wireless systems are not well suited to typical semi-submersible environments. Regulatory requirement: HSE Information Sheet – Offshore Information Sheet 8/2007 [2] recommends that owners and operator of monohull FPSO and FSU installations review their risk assessments for the flooding of machinery spaces below water level, and ensure that effective means are provided for the detection and control of flooding. It also suggests that, if these areas are unmanned for any length of time, it is good practice to install CCTV that displays in the continuously-manned control room. DNV [1] requires an approved leak detection system for semi-submersibles and jack-ups when the fatigue utilisation index exceeds unity.	

OPERATIONAL REQUIREMENTS

Ease of Installation:

It is likely that the system would require all sensors to be wired back to the monitoring system positioned in the manned control room. Wireless systems are available but the suitability of the structure has to be assessed on an individual basis, and it is likely that the steelwork in an offshore structure would significantly reduce the range of these systems and increase the interference.

Interrogation Method:

A typical system would raise an alarm when water is detected and will indicate in which zone this occurs.

Reliability / Probability of detection:

The technology appears to be relatively mature and there appears to be no significant reliability issues with latest systems.

Accuracy:

There are a number of different sensor options, some of which can detect water levels of 3mm (measured from the floor level).

Maintenance:

Modern water sensors have no moving parts. Consequently, they require little or no maintenance. The system should however be tested in line with the relevant codes of practice [1].

4.3 AIR GAP MONITORING

SI monitoring method:	Air Gap Monitoring
OVERVIEW Brief description: The air gap is defined as the positive difference between the lowest point of the underside of the cellar deck and the crest height of an extreme wave for a given return period (often 100 years). The purpose for monitoring the air gap is to establish whether the platform foundations are suffering from subsidence, and also to establish if a positive air gap exists. The methodology for calculating the air gap has changed considerably over the past decade. Simple methods such as a tape measure from the cellar deck have been used, which in time have been replaced by radar measurement. Measured values are recorded and averaged over a given time period. A value for the air gap can then be calculated. These methods can yield ambiguous results in practice whilst also suffering from poor repeatability (due to ocean surges, tidal changes etc.), and this complicates detection of trends over a long period of time. Modern methods use GPS to monitor the air gap. The first time the absolute level height is measured, a reference point is established that will be used for all repeat readings. This increases the repeatability and reduces inaccuracies between surveys. The GPS measurement from the reference point to the underside of the cellar deck is also measured using GPS on the first visit. This is to give an exact as-built measurement, which is important because dimensions can sometimes vary considerably from detailed drawings. Purpose: The primary application of this technique is to measure the air gap at specified intervals, for example, every 3 years. The results are then compared and any issues with reduced air gap raised. Some companies offer near real-time continuous monitoring services. These systems are important for seismically active regions or platforms that are known to be at a continuous risk due to local conditions. In general a periodic survey is sufficient. Maturity in offshore industry: Airgap monitoring has been carried out for over a decade, but the methods used have changed significantly over time. This is however a standard monitoring procedure now, and is widely applied in the offshore industry. Limitations: Requires specialist contractor to carry out measurements	
OPERATIONAL REQUIREMENTS Ease of Installation: Periodic monitoring methods do not require installation of hardware.	

Interrogation Method:

The contractor should provide the survey results in a post processed format and minimal interpretation should be required.

Reliability / Probability of detection:

Standard equipment is used for the survey and reliability is not considered problematic.

Accuracy:

To determine a reliable GPS reading the equipment is usually in place for 24hrs. Once the GPS value for the reference point above mean sea level has been determined there are various analytical methods for calculating the true air gap that are beyond the scope of this report. As mentioned in Section 4.4 the real time / instantaneous accuracy of a system using the standard GPS network is only approximately 10m which is insufficient for this purpose.

Because real-time accuracy is less important for this application, the corrections can be calculated at a later date after data has been collected. Using this method an accuracy of up to 50mm can be achieved.

Maintenance:

Any maintenance required to the measurement system would be carried out by the specialist contractor.

4.4 GLOBAL POSITIONING SYSTEM MONITORING

SI monitoring method:	Global Positioning System Monitoring
OVERVIEW	
Brief description:	
The position of a floating structure can be monitored using a Global Positioning System (GPS). The basic GPS technology is not new and is well proven. The US DoD's GPS network, available to all, has real-time accuracy in the region of 10m horizontally. Such systems require hardware in the form of a GPS receiver and a user interface. Software is then required that can be tailored to meet user requirements. The basic accuracy of the system can be improved using a number of different techniques.	
Purpose:	
The technology is especially useful to any floating structure where exact positioning is important. Two applications are as follows: – Semi-submersibles – the structure's location can be monitored and an alarm raised if it exceeds a predefined allowable deviation from a reference point. This arrangement would alert the operator to any significant issues with the mooring. – FPSOs – to continuously monitor the position of the vessel relative to a reference point. The relative position can then be used, for example, to ensure that the stresses in the risers are not excessive.	
Maturity in offshore industry:	
GPS is widely used in the offshore industry and is generally a mature technology.	
Limitations:	
Ongoing subscription required for live corrections, which increase accuracy.	
OPERATIONAL REQUIREMENTS	
Ease of Installation:	
Topsides installation of permanent equipment is required.	
Interrogation Method:	
A number of companies offer complete bespoke packages that will monitor the position of a structure and log the data, using enhanced GPS services. The system will also raise alarms based on user defined parameters. The maintenance, installation, operation guide and continuous support of the system can all be provided by the manufacturer. Correction data is delivered real-time to the receiver via communication satellites. The correction data enhances the accuracy, reliability and integrity of the standard GPS system.	

Reliability / Probability of detection:

This is a mature technology and there are no problems with reliability or probability detection envisaged.

Accuracy:

The accuracy for premium services can be improved to approximately 10cm horizontally, with more basic packages offering accuracies in the order of 1m. It should be noted that the real-time accuracy of GPS in Europe is increasing with systems such as the European Geostationary Navigation Overlay (EGNOS) being developed.

Maintenance:

Maintenance requirements for GPS systems are generally minimal.

4.5 FATIGUE GAUGE

SI monitoring method:	Fatigue Gauge
OVERVIEW	
Brief description:	
CrackFirst™ is a fatigue damage sensor system specifically designed for welded steel structures and was patented in 1990. It was developed within a DTI funded collaborative project managed by TWI and is currently available from Straininstall. The CrackFirst™ sensor itself consists of a thin steel shim, 0.25mm thick which can be attached to the target structure, close to a critical joint (up to 10mm from the toe). Under the action of cyclic loading in the structure, a fatigue pre-crack at the centre of the shim (introduced during manufacture) extends by fatigue growth.	
Purpose:	
The sensor design is such that the extent of crack growth in the shim is proportional to the cumulative fatigue damage for a welded joint subjected to the same loading. This could provide a representative record of cumulative fatigue damage occurring on a structure (assuming the sensor can be located close to the weld toe). In addition, remote operation is possible, and data can be downloaded via a wireless link. The availability of fatigue data could improve maintenance scheduling and setting of inspection intervals.	
Maturity in offshore industry:	
Limited development in the offshore industry.	
Limitations:	
– Attachment to the structure may be difficult depending on conditions, particularly underwater; – Installation of the sensor sufficiently close to the weld toe for it to respond to the fatigue loads causing damage in the structure may prove difficult; – Sensors may prove vulnerable to offshore environmental conditions; – Failure to detect loss of adhesion may lead to false negatives in measurements; – Sensors cannot be replaced when damaged.	
OPERATIONAL REQUIREMENTS	
Ease of Installation:	
Attachment of the sensor is by either a combination of threaded studs or by adhesive bonding. To protect the sensor from mechanical damage and corrosion, a sealed enclosure is fitted over the whole unit. The sensor is pre-tensioned after installation using a specially designed rig to ensure that it responds to both tensile and compressive applied load cycles, in the same way as a welded joint containing tensile residual stress.	

Interrogation Method:

An on-board electronics unit can check the sensor status regularly and record the data in a memory which can be downloaded to a laptop PC via a wireless link or to a data logger. The unit can be powered from an on-board battery.

Reliability / Probability of detection:

Limited information to date.

Accuracy:

Claims to bound a class F detail; however, there is a significant inherent scatter in fatigue data and this should be considered in making comparison with the joint under investigation.

Maintenance:

Limited information available for offshore applications.

4.6 CONTINUOUS FLOODED MEMBER DETECTION: INTERNAL

SI monitoring method: Continuous Flooded Member Detection: Internal

OVERVIEW

Brief description:

A device is placed inside a nominally dry tubular member. If the member becomes flooded the salinity of the solution activates a galvanic cell (which remains completely passive when dry). The power of the current is used to generate an acoustic signal which is transmitted and received at the topsides. Each tubular member will contain a device that will generate a unique signal and therefore upon reception of a signal, the location of the damage will be immediately identifiable.

This method would be very realisable for new builds employing through-water telemetry. Whilst this is not as elegant a solution as the through-steel telemetry (because it requires the use of a hydrophone) it is a very practical solution.

Demonstration of the device's reliability would add considerably to the overall cost of setting up a business and may be an obstacle that would require significant investment. Therefore, a significant opportunity across a number of installations would probably be needed to make the business economically viable.

Purpose:

Continuous detection for through wall defects. Similar to flooded member detection but is continuous and therefore the lack of knowledge of asset integrity in the periods between inspections is avoided.

Maturity in offshore industry:

None. Untried and untested at full scale.

Limitations:

Only suitable for new build.

Limitations on signal attenuation (due to losses into the water) can be avoided by using lower frequencies. However, in going to lower frequencies there is a trade off on power (power required to generate lower frequencies is higher). Higher power may be required at lower frequencies as they tend to be competing with the background noise. However, a pure sinusoid may well be identifiable through high levels of background noise.

Lower frequency signals tend to require transducers that are more expensive and possibly less reliable. Magnetic loop transducers may avoid this issue but this has not been tested.

Higher frequency signals can be easily transmitted through the water. This would require detection by the use of a hydrophone.

The downside of transmitting through the water is that installing a hydrophone introduces additional design, maintenance and operational burdens which may be viewed unfavourably at the FEED and design stages at which the correct implementation would need to be built in to any new build incorporating this technology.

Can only be used in saline waters.

Members in the splash zone are difficult to monitor.

Regulatory requirement:

None

OPERATIONAL REQUIREMENTS

Ease of Installation:

Can only be installed during the construction phase. Devices have to be placed inside tubular members such that they will remain in a position to guarantee good acoustic contact during load out and installation phase (including piling). They would have to be positioned such that they did not become damaged by fabrication welds.

Interrogation Method:

The receiving device listens continuously. Upon hearing a signal an alarm is raised.

Reliability / Probability of detection:

Unproven and difficult to prove in practice.

A major concern is clearly the reliability of the device itself. As one is unable to access the device once it is installed, it is difficult to claim that the device's PFD (Probability of Failure on Demand) is very low. Discussions took place on ways to counter this problem and a brief summary of the points raised are as follows:

- Device is entirely passive - no current flows until the cell becomes wetted;
- Can use high integrity, military standard type components to withstand vibration loads during piling;
- Can design an arrangement such that any slippage during piling will either not happen or if it does it will not compromise acoustic contact;
- Device could be shipped with a battery that would enable a self-test every several weeks. This would counter concerns over not being able to identify whether the device was operational at the start of life and may provide some assurance into the life of the product; but the duration of this assurance cannot be guaranteed beyond probably 10 years.
- Redundancy – the cost of the hardware is low and their weight also low so it may be possible to install two (or more) identical devices into each member;
- Reliability proving programme - a set of devices installed inside dry tubular members would be kept under controlled conditions for a long period of time. Periodically, a number of tubulars would be flooded and their performance recorded over time. This would enable the building of an operating history. Evidently this would create a cost burden to the programme.

Accuracy:

If the devices are reliable and installed correctly the accuracy could be high.

Maintenance:

Maintenance of subsea device not possible once installed.

Illustrations

The device was tested for high frequencies using the specimen shown below. This was designed to maximise the possible submerged depth and to demand the signal to pass through two nodes with a change in direction at each.



Mid-scale specimen used for experiments



Bidston Dry Dock – 8m depth used for submerged mid-scale tests.

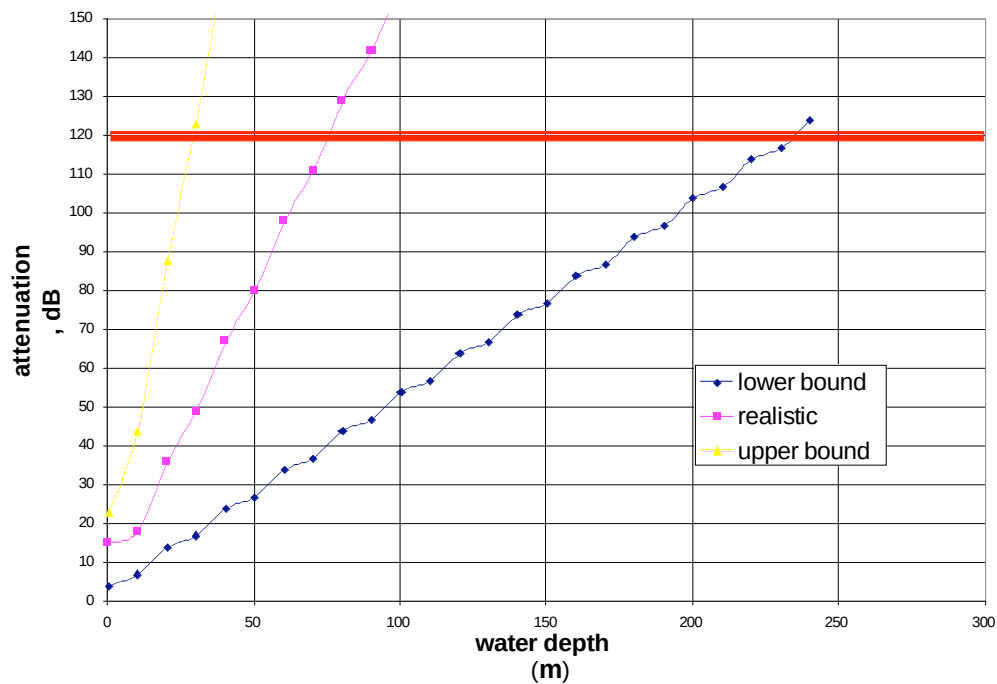
The findings of these experiments at high frequencies are as follows

Signal attenuations

	Lower Bound	Realistic	Upper Bound
L_{wet}	0.3dB/m	1.3dB/m	3.5dB/m
L_{dry}	0.0dB/m	0.5dB/m	0.7dB/m
L_J	4dB per joint	5dB per joint	9dB per joint

Where L_{wet} is the attenuation per metre in wet conditions, L_{dry} the same for dry conditions and L_J is the attenuation on passing through a joint.

Given that a signal loss of 120dB is the maximum loss at which one could realistically detect a signal, the following graph shows the limits of potentially applying through-steel telemetry.



Limits of applying through-steel telemetry using high frequencies.

It can be seen that with current technology in through steel telemetry, this method is realistically applicable at 75m water depth.

By using through-water telemetry however, these limitations would not apply.

4.7 CONTINUOUS FLOODED MEMBER DETECTION: EXTERNAL

SI monitoring method: Continuous Flooded Member Detection: External

OVERVIEW

Brief description:

A device is clamped to the outside of a nominally dry tubular member. The device transmits a high frequency acoustic signal through the member and detects attenuation of the signal at regular intervals. A highly attenuated signal would indicate the presence of water inside the member. Upon detecting a change, the device would send an alarm signal through the steel or the water which would be indicated in the control room.

Purpose:

- Continuous detection for through-wall defects;
- Essentially flooded member detection but is nearly continuous and therefore the lack of knowledge of asset integrity in the periods between inspections is avoided.

Maturity in offshore industry:

None. Untried. Untested. This was mooted at various industry forums (eg NESTA) but received no financial support. Major concerns were raised over reliability.

Limitations:

- Battery life – it is possible to reduce the power requirements by only using the system periodically (e.g. every week) as opposed to continuously. However, battery manufacturers seem to have a limit of ten years on battery reliability. This would infer the requirement for a battery change out programme which would therefore require a diver or ROV intervention. The advantage over a normal FMD programme, is that the monitoring is continuous with associated increased claims on platform reliability.
- Members in the splash zone are difficult to monitor;
- If the devices are too bulky they will introduce extra load into the structure.

Regulatory requirement:

None

OPERATIONAL REQUIREMENTS

Ease of Installation:

One of the obstacles to this being realisable is the issue of designing and installing a clamp that will maintain the position of the transducer through the life. Consideration of the large loads in the wave action zone would need to be given and it will be difficult to demonstrate high reliability given the difficulty of this problem.

The overall hydrodynamic profile of the device should minimise the attraction of any extra drag forces that could be transmitted into the jacket structure.

Interrogation Method:

The continuous FMD device detects changes to the reflected signal periodically. Upon detecting a change an alarm signal is transmitted to the control room.

Reliability / Probability of detection:

Unproven.

It might be possible to argue that the probability of detection would be similar to that for FMD applied in the field. However, the electronics in this device would be performing the interpretation of the signal and would therefore need to be high integrity with associated cost implications.

Accuracy:

If the device was reliable and the devices installed correctly the accuracy could be potentially as high as that for FMD – approx 90%. However, concerns over signal drift, clamp robustness and the electronic processing and interpretation of the signal could significantly erode this limit if these points were not addressed appropriately.

Maintenance:

Possible by ROV and diver only. Battery change-out may be required.

4.8 NATURAL FREQUENCY RESPONSE MONITORING

SI monitoring method: Natural Frequency Monitoring (NFRM)

OVERVIEW

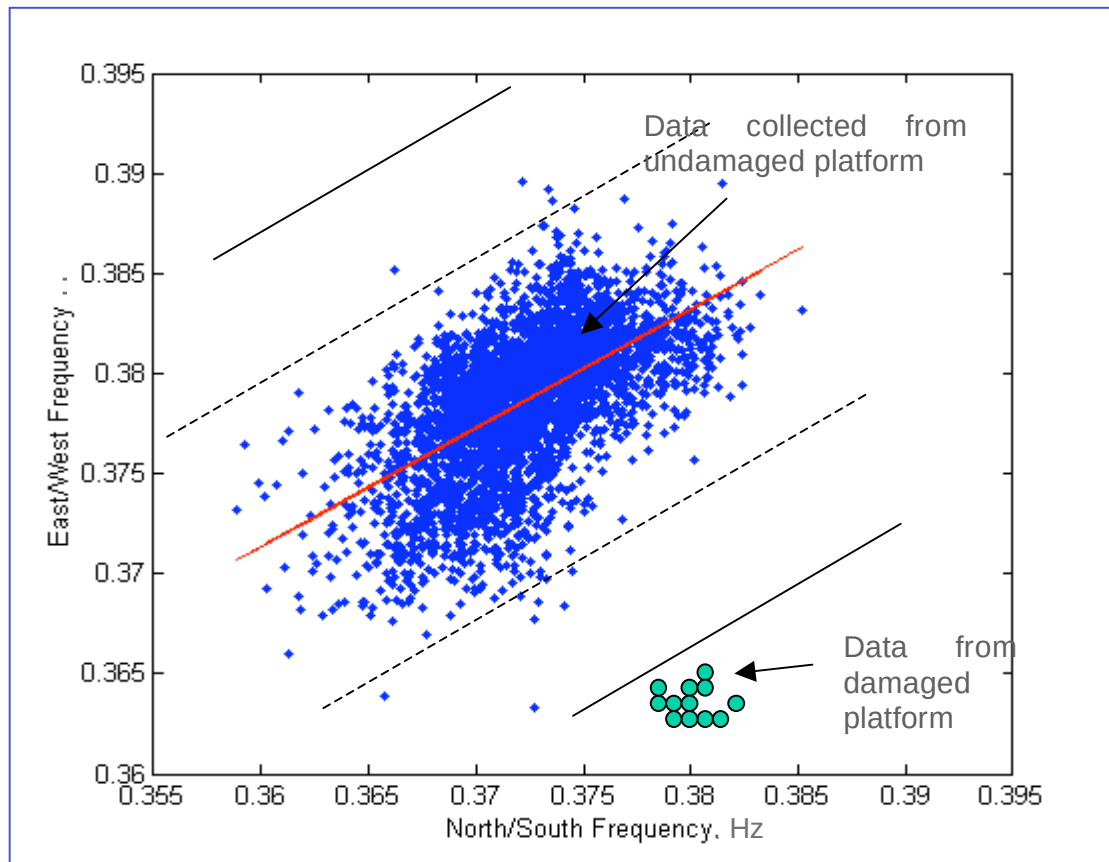
Brief description:

Accelerometers are placed on the topsides of an installation. Subsea accelerometers have also been employed. The response of the jacket to wave loading is continuously monitored and the accelerations are transformed into the frequency domain to identify the natural sway modes of the jackets. Typically, finite element analysis is performed alongside the measurement to assist in identifying which mode shape corresponds to which frequency.

Any major structural damage to the platform is reflected by a change in the sway stiffness in one or more modes. This results in a reduction in the platform's natural sway frequency which is detected and reported by exception.

Changes in soil stiffness are reflected by changes to frequencies in both platform directions. Changes in frequency caused by damage to a member tend to occur in the sway direction to which the member contributes stiffness. In this way, global factors like water depth, marine growth etc can be screened out.

A failure library is created using FEA so that immediately a change in frequency is reported, it is possible to identify which member is the most likely to have failed.



Purpose:

To continuously monitor for the change in platform frequency and then to identify the most likely failed members. NFRM can be used to detect pre- and post-effects of incidents such as an extreme storm, an earthquake, a ship collision or a dropped object. It can also be used to detect changes in foundation stiffness.

Maturity in offshore industry:

Mature technique, which has been in operation since late 1970's on a number of platforms. A system was installed on Ninian South following a member severance. Following repair the platform's frequency was detected as increasing.

Discussions with UK vendors revealed that there are at least twenty platforms with natural frequency monitoring systems installed worldwide.

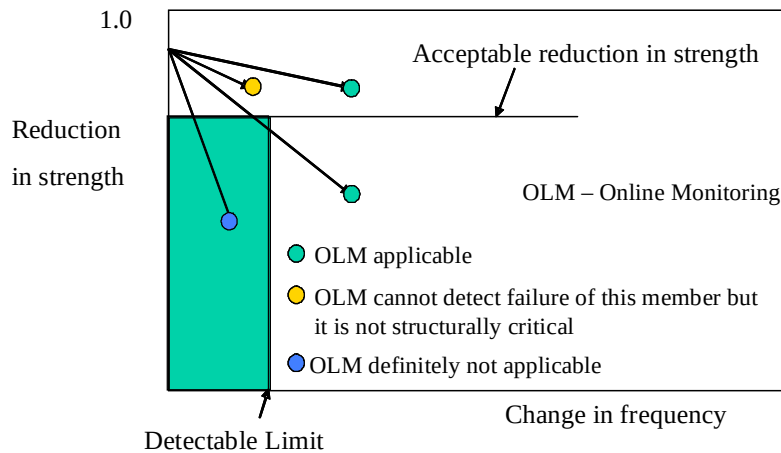
Confidentiality prevents the naming of all of these but on the UKCS there are some 7 systems, 3 in the rest of Europe with the remainder split between Mexico, Canada, Caspian, and West Africa.

It is worth noting that one vendor mentioned a recent upturn in business with eight orders being placed in the last 12 months.

Limitations:

The method is only sensitive enough to detect changes in frequency of approximately 0.5%. This means that the method cannot detect minor damage such as small defects. A Joint Industry Project (JIP) performed in which HSE participated showed that in low redundancy jackets with single diagonal bracing systems an 80% circumferential through-wall defect is detectable using this method.

However, the limit in sensitivity means that the method is less easy to employ for heavier jackets with high redundancy bracing schemes. For jackets with more than 4 legs the detection of damage may become more difficult. It may be possible to incorporate a larger array of accelerometers and to link them together in the time domain to monitor modal shapes as well as frequencies in order to identify damage.



Further, as illustrated above, members which cause small changes in frequency tend not to be structurally significant members. It is usually the members which cause a large reduction in structural strength that also cause a large change in frequency.

Regulatory requirement:

None at present, however the publication of API RP 2SIM [10] is expected in 2008 which includes guidance on the installation of natural frequency monitoring systems

OPERATIONAL REQUIREMENTS

Ease of Installation:

- In the hands of an experienced 3rd party vendor, relatively straightforward.
- Self contained units placed on the topsides - these are already designed to be intrinsically safe.
- Cabled back to PCs in control room or hard-wired through to the beach.

Interrogation Method:

Daily interrogation of the data. Changes reported by exception.

Reliability / Probability of detection:

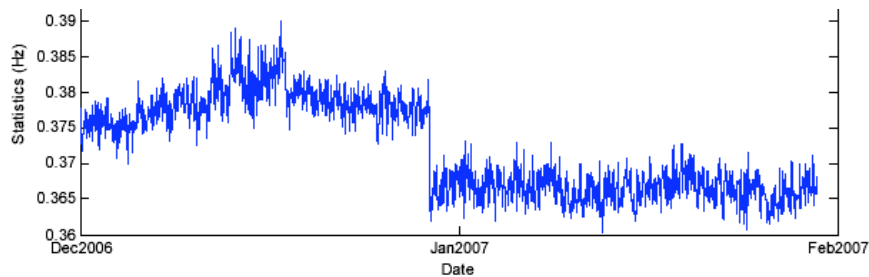
These changes for different platforms and members. Usually NFRM should be accompanied by finite element analysis (FEA) which identifies the expected changes in frequency for severing each member. If the FEA predicts that members have frequency shifts of less than 0.5% then this may be an undetectable failure. Members with changes less than 1% may also require examination of more than one sway mode or a torsional mode.

Accuracy:

False positives have not yet been reported. If there is a shift in frequency then it must be attributable to a change in mass or stiffness. If the change in frequency occurs predominantly in one direction then this accurately tells us that the frequency of a sway frame has been affected which can only be due to damage to that frame. NFRM also has the ability to find 80% through-thickness cracks on a continuous basis in low redundancy structures, thus enabling improved detection and prevention of severance as well as general structural failure resulting from the propagation of through-thickness cracks.

Maintenance:

Minimal.

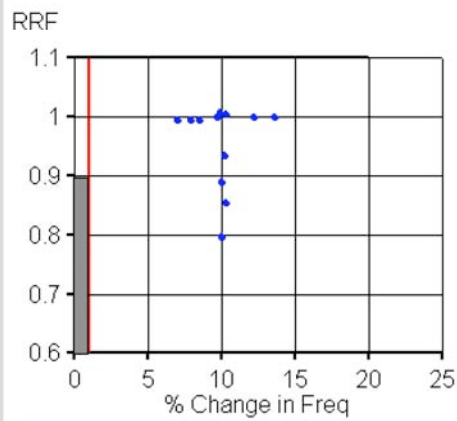
Illustrations

The above shows an actual active detection of a member failure

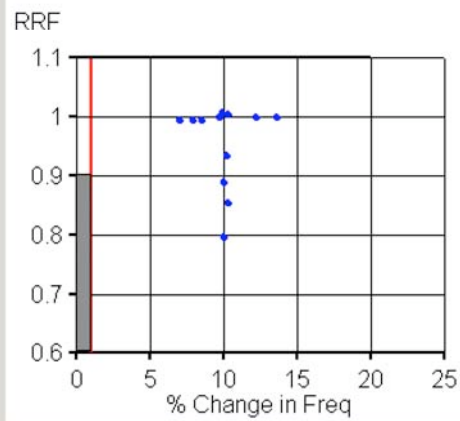
The following graphs were taken from the Online Monitoring Joint Industry Project (OLMJIP) study showing how applicable natural frequency monitoring is for four legged jackets of different bracing configurations. In these cases the green area shows the combined limit of a reduction in strength of no greater than 10% with 1% change in frequency (since a 1% change in frequency can be detected with confidence) .

Please note that six- and eight-legged jackets-the results of which are shown below-did not form any part of the OLM JIP study.

**Plot of Max % Change in 1st 3 modes
Frequency Against RRF**



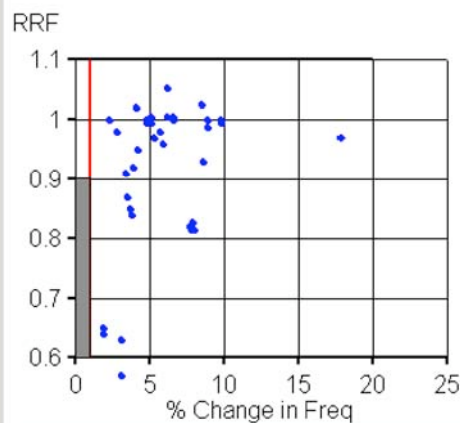
**Plot of Max % Change in 1st 6 modes
Frequency Against RRF**



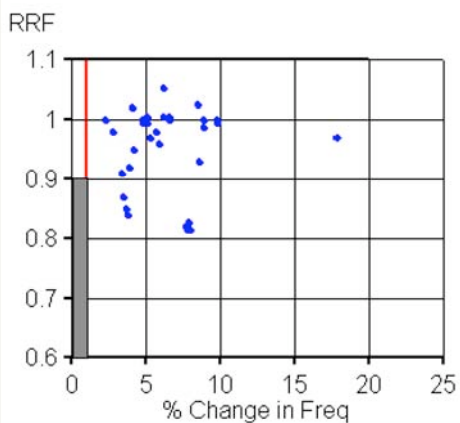
Single Diagonal

RRF- Relaxation
Resonance Frequency

**Plot of Max % Change in 1st 3 modes
Frequency Against RRF**

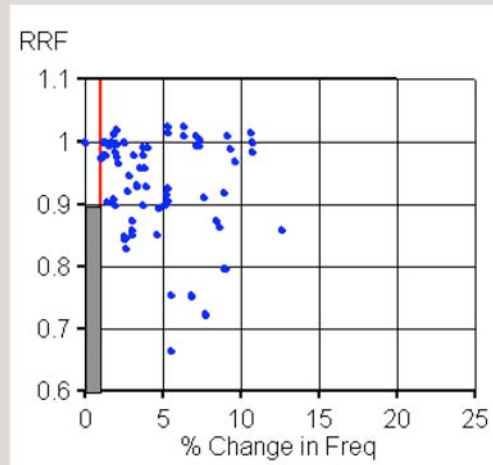


**Plot of Max % Change in 1st 6 modes
Frequency Against RRF**

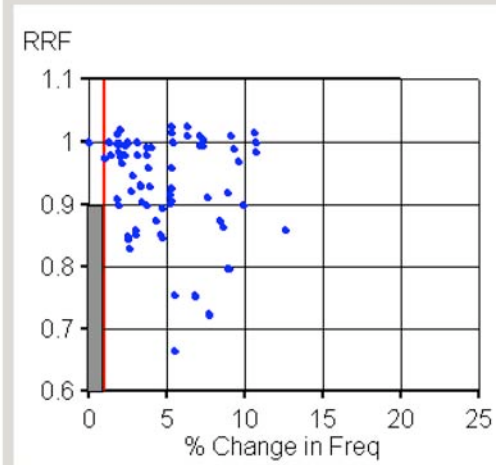


K-bracing

**Plot of Max % Change in 1st 3 modes
Frequency Against RRF**

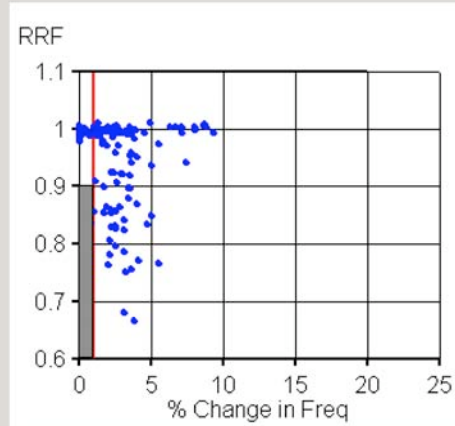


**Plot of Max % Change in 1st 6 modes
Frequency Against RRF**

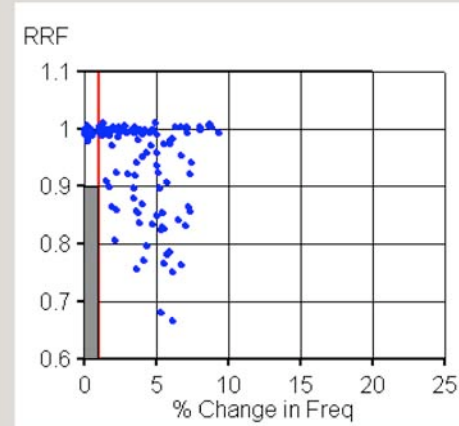


Inverted K-bracing

**Plot of Max % Change in 1st 3 modes
Frequency Against RRF**

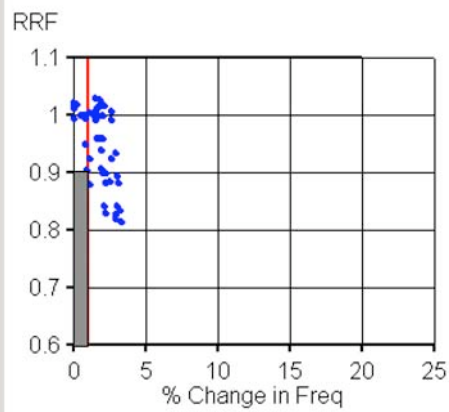


**Plot of Max % Change in 1st 6 modes
Frequency Against RRF**

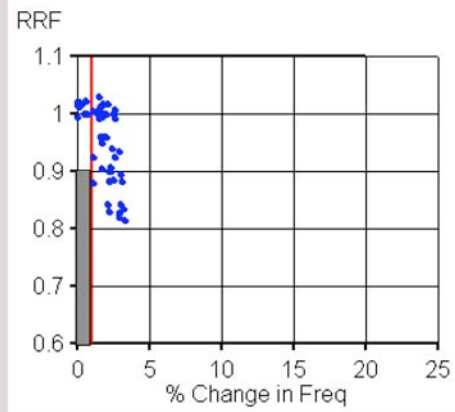


Diamond Bracing

**Plot of Max % Change in 1st 3 modes
Frequency Against RRF**



**Plot of Max % Change in 1st 6 modes
Frequency Against RRF**



These graphs show that almost all member severances which reduce strength by more than 10% are detectable using an online monitoring system. If a 0.5% limit was considered then all of the cases considered could be detectable.

4.9 ACOUSTIC FINGERPRINTING

SI monitoring method:	Acoustic Fingerprinting
OVERVIEW	
Brief description:	
Acoustic fingerprinting involves the transmission of acoustic signals into a jacket structure at locations above the maximum water level. The signal is generally transmitted into one or more legs. Receivers are placed also above the water level and ‘listen’ to the signal that is returned, reporting and interpreting changes to diagnose damage from the change in signal.	
Purpose:	
This technique would enable continuous SI monitoring to be retrofitted onto any platform. It relies on the complex behaviour of acoustic signals through the steel, with reflections and refractions occurring at section changes and nodes. The technique relies upon the fact that if the transmitted signal is self-same, then so will be the received signal. Research has been carried out to diagnose failure by using time of flight computation on the received signals. This work claims that the technique would be able to identify the member or possibly a structural locale in which the damage is located.	
Maturity in offshore industry:	
Untested in major structures. Research work isolated to laboratory scale tests at present.	
Limitations:	
Lab work introduced major damage (i.e. sawing through members). This is considered to be unrepresentative of damage induced by fatigue in which opposite faces of the defect may well remain in contact for most of the time. If the technique were to be proven it is likely that it would be sensitive enough to detect fully-severed members only.	
Regulatory requirement:	
None	
OPERATIONAL REQUIREMENTS	
Ease of Installation:	
In the hands of experts relatively easy to install, requiring no access to restricted areas. Transmitting and receiving equipment generally installed above splash zone. Cabling may be required back to Control Room.	

Interrogation Method:

Algorithms which analyse the received signal in the frequency domain are interrogated for changes brought about by the presence of an exception. The signal may be transmitted as often or as infrequently as desired.

Reliability / Probability of detection:

Unproven.

Accuracy:

Unproven.

Maintenance:

Claimed that the device will be standalone, but in order to meet performance standards it is expected that the equipment will require periodic calibration.

Illustrations

The research work carried out to develop this technique is illustrated by reference to HSE Research Report 325 – Cost Effective Structural Monitoring [11].

<http://www.hse.gov.uk/research/rrhtm/rr325.htm>

4.10 RISER AND ANCHOR CHAIN MONITORING

SI monitoring method:	Riser and Anchor Chain Monitoring
OVERVIEW	
Brief description:	
Riser and anchor chain monitoring systems consist of a sonar array positioned beneath the platform, which emits signals in and around the horizontal plane. The system then detects and analyses reverberating signals from items that are within the monitoring region. This data can then be used to determine the precise location of these items and to continuously monitor their position. If there is a problem with the mooring of a platform, the system will alert the operator to the issue immediately via an audio/visual alarm.	
Purpose:	
The purpose of this technique is to monitor the position of risers and anchor chains and alert the operator to any displacements outside of predefined limits. In addition, failure-analysis can be performed using the resulting computerised data.	
Maturity in offshore industry:	
This technique is widely used in the offshore industry. The number of beams, beam resolution, range, transducer type, etc. can be altered to suit the particular application environment.	
Limitations:	
Beam scatter: The transducer may not always detect a considerable amount of the reflected beam for numerous reasons (e.g. the riser or anchor chain may be at a non-reflecting angle or the transmitter may be located too far away from the riser or anchor chain, leading to reflective sonar wave degradation);	
Feasibility: It may not always be feasible to locate an RACM system in certain offshore environments. Technical constraints may arise from factors such as the presence of other unwanted obstacles within close proximity to the system.	
OPERATIONAL REQUIREMENTS	
Ease of Installation:	
The system is relatively easy to install as there are no mechanically moving parts. Also, long-term deployment is possible.	
Two main deployment techniques:	
1. Deploy the system externally to the pattern of risers or anchor chains and then monitor the returning signals using a pair of transducers; 2. Deploy the system within the centre of the risers and anchor chains and then monitor using a compact 360° conformal sonar transducer array.	

Interrogation Method:

The system includes an audio/visual alarm which indicates a potential movement outside the given parameters. Also, the relative position data is converted from analogue to digital form, and automatically fed into a computer to be analysed.

Reliability / Probability of detection:

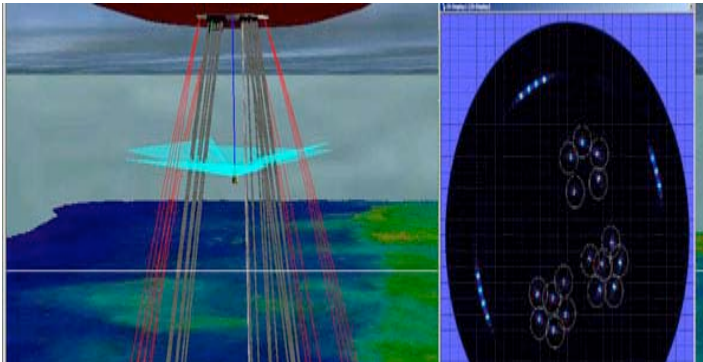
Riser and anchor chain positions can be closely monitored as any potential movement outside the given parameters will immediately generate an alarm.

Accuracy:

The system enables simultaneous monitoring of all riser and anchor chain positions, providing high precision measurements of absolute and relative positions. High resolution sonar rays are used and reflected signals converted to precise digital data forms. A 360° transducer or electronic steering capability will allow the transducer to detect most of the reflected sonar waves.

Maintenance:

1. Requires relatively minimal maintenance as there are no moving/user-serviceable parts;
2. Long-term deployment/immersion is possible.

Illustrations:

Sonar wave transmission

4.11 STRAIN MONITORING

SI monitoring method:	Strain Monitoring
OVERVIEW Brief description: Strain monitoring is carried out to determine the stress or loading regime in part of a structure. There are a number of strain measurement techniques available including conventional strain gauging, fibre optics and stress probes. Typically, gauges are installed away from stress concentrations and in such a way that the global structural loading can be determined (e.g. 4 quadrants around a brace). Purpose: To monitor local stress variations to provide information on the local structural loading and/or stress regime-local hot spot stresses can then be determined from numerical modelling. Strain monitoring in areas of steep stress gradients (e.g. at stress concentrations) is not generally carried out due to the sensitivity of the results to the gauge location. Large strain gauges designed for uniaxial strain measurement may be useful for strain measurement on hull and deck plates. Maturity in offshore industry: Widely applied across many industries including the offshore industry. A large amount of relevant documentation is available, e.g. [12]. Limitations: – Most methods only applicable for measuring stress variations and not absolute stress levels; – Equipment can be sensitive to damage by the environment especially cabling up the legs through the splash zone; – Requires calibration and can be sensitive to drift over time; – Sensitive to positioning of gauge in areas with steep stress gradients.	
OPERATIONAL REQUIREMENTS Ease of Installation: Installation of strain gauges is generally not problematic, but appropriate surface preparation is required. Cabling requirements may complicate installation in remote locations and interactions with the environment should be considered. Interrogation Method: Usually through a computerised system which provides a time-strain history. Reliability / Probability of detection:	

Widely applied and generally reliable.

Accuracy:

Generally high. Can be affected by external causes such as wiring interference, temperature variations, bridge set-up and other factors.

Maintenance:

Requires periodic maintenance to ensure integrity and connection of strain gauges.

4.12 COMPARISON OF CHARACTERISTICS OF SI MONITORING METHODS

A tabulated comparison of the characteristics of the SI monitoring systems discussed in the previous sections is provided in Appendix 2. This section provides a comparison of these characteristics for each monitoring method.

Maturity in offshore industry

A number of monitoring methods have been used for a decade or more in the offshore industry, and can be regarded as mature technologies. These include:

- Acoustic emission monitoring;
- Air gap monitoring;
- GPS monitoring;
- Leak detection;
- Natural frequency response monitoring;
- Strain monitoring; and
- Riser and anchor chain monitoring.

Although some of these methods have been used for some considerable time, their application has generally been on bespoke applications. This is particularly the case for acoustic emissions monitoring and natural frequency response monitoring.

Limitations

Limitations are generally specific to each method and are not compared here.

Ease of installation

The installation requirements of monitoring methods can broadly be arranged into three groups as follows:

Requires installation equipment above splash zone only:

- Acoustic fingerprinting;
- Air gap monitoring;
- Global positioning system monitoring; and
- Natural frequency response monitoring.

Requires installation of equipment on or below the splash zone:

- Acoustic emissions monitoring;
- Riser and anchor chain monitoring;
- Continuous flooded member detection (external);
- Fatigue gauge monitoring;
- Leak detection; and
- Strain monitoring.

New build only:

- Continuous flooded member detection (internal).

Interrogation methods

The type of interrogation of monitoring data and the level of post-processing and interpretation required is a significant in-service consideration when selecting SI monitoring methods. Where post-processing or interpretation of the data is required to form a view on parameters relating to structural integrity, appropriate budgets, personnel and reporting systems should be put in place.

SI monitoring methods which do not require post or interpretation of information include:

- Riser and anchor chain monitoring;
- Continuous flooded member detection (external/internal);
- Global positioning system monitoring; and
- Leak detection.

Other methods require some form of post processing or data interpretation. This varies between applications, but may be considerable.

Reliability, probability of detection and accuracy

Most techniques have been applied successfully offshore with acceptable levels of reliability, probability of detection and accuracy. The following methods have either not been proven in practice, or limited information is available to date:

- Acoustic fingerprinting;
- Continuous flooded member detection (external/internal); and
- Fatigue gauge monitoring.

Maintenance

Maintenance requirements vary considerably between methods, particularly the need for subsea maintenance. This can be arranged broadly into three groups as listed below:

Methods which require sensor maintenance (may be subsea):

- Acoustic emissions monitoring;
- Strain monitoring;
- Fatigue gauge monitoring; and
- Continuous flooded member detection (external).

Methods which require limited or no maintenance:

- Air gap monitoring;
- Riser and anchor chain monitoring;
- Natural frequency response monitoring;
- Global positioning system monitoring; and
- Leak detection.

Methods for which maintenance not possible:

- Continuous flooded member detection (internal).

Conclusion

A number of SI monitoring methods have been well developed and are available for monitoring of integrity related parameters without the requirement for significant further development. These include:

- Acoustic emissions monitoring;
- Air gap monitoring;
- GPS monitoring;
- Leak detection;
- Natural frequency response monitoring;
- Strain monitoring; and
- Riser and anchor chain monitoring.

With the increasing need to demonstrate that structural integrity risks are managed and as low as reasonably practicable, the need to consider structural monitoring as part of the platform safety case is anticipated to increase in the future and these mature technologies would be prime candidates.

Methods which would require further development before they would become practicable as widely applied SI monitoring methods include:

- Acoustic fingerprinting;
- Continuous flooded member detection (external/internal);
- Fatigue gauge monitoring.

5. OVERVIEW OF CURRENT INSPECTION TECHNIQUES AND LIMITATIONS

5.1 INSPECTION TECHNIQUE CAPABILITIES

The annex to Section 23 of ISO 19902 [6] provides some details on the capabilities of several inspection techniques, including deployment capabilities. The limitations are noted in Table 3 as a guide to where SI monitoring techniques might be able to compliment existing methods.

Table 3 Limitation of current inspection techniques (from annex 23 - ISO 19902 [6])

Inspection technique	Defect or damage capability	Limitations noted	Deployment issues
Air gap measurement	Air gap	Need to calibrate and maintain equipment for continuous recoding of wave height	Surface use only
Marine growth recording	Measurement of marine growth (soft and hard)	Measurements are unreliable, particularly for soft growth and for single estimates of large components.	Can operate from ROV
Visual inspection without marine growth cleaning	Gross damage	Only suitable for gross damage (large deformations, severed connections, missing members, debris).	Can operate from ROV
Visual inspection with marine growth cleaning	Corrosion, visible cracks, dents, gouges, abrasion, deformations	Need for cleaning of marine growth.	Can operate from ROV
Dimensional measurements	Marine growth thickness, scour depth, dent size, out-of-straightness, crack length, corrosion pit size	None listed.	Can operate from ROV for gross measurements
Cathodic potential readings	Performance of CP system	Probes require calibration in the field.	Can operate from ROV
Flooded member detection (FMD)	Member flooding as a result of through-thickness cracks or damage	Only able to detect through-thickness cracks or damage, which has led to member flooding. Not able to detect cracks on the leg side of connections where the leg is intentionally flooded or grout filled. Through-thickness cracks opening for a limited period (e.g. storms) may not flood. Finding the cause of cracks requires further investigation, using other	Health and safety aspects of using a radioactive source (for this method)

Inspection technique	Defect or damage capability	Limitations noted	Deployment issues
		inspection methods. Ultrasonic FMD method: relatively diver intensive, accurate placing of probe required for reliability.	
UT (ultrasonic compression wave)	Wall thickness	None listed	Can operate from ROV
UT (ultrasonic) shear wave, creeping wave, TOFD	Cracks and internal volumetric indications. Can size indications found by other techniques	Requires qualified UT inspector if performed remotely (i.e. if probe is manipulated by diver, a qualified UT inspector monitoring the display screen increases reliability).	Not normally by ROV
MPI (magnetic particle inspection)	Surface breaking defects	Surface cleaning or coating removal required. Can only detect surface breaking defects.	Not normally by ROV
ACPD (alternating current potential drop)	Sizing defects found by other techniques	Requires cleaning to bare metal and a trained diver. Multiple measurements along crack length may be required if good resolution required.	Not normally by ROV
ACFM (alternating current field measurement)	Detect and size surface flaws	Training needed to avoid poor reliability. ACFM cannot find indications in certain geometries (edges of gussets due to edge effect)	Not normally by ROV
Eddy current	Detect and size surface flaws	Requires a diver to operate probe underwater and an inspection technician above water to read the screen. Training required.	Not normally by ROV
RT (Radiographic inspection)	Internal defects	Not normally used for underwater inspection due to health and safety considerations.	Not normally by ROV

6. REVIEW OF DAMAGE MECHANISMS FOR WHICH MONITORING CAN COMPLEMENT INSPECTIONS

Tables 1-5 (Appendix 4) list the common current inspection and SI monitoring techniques used to detect defects in the underwater, splash zone and topsides regime of the platform, as well as on moorings and semi-submersible hulls. These tables highlight areas where SI monitoring techniques could complement current inspection techniques, based generally on the following criteria:

- Effectiveness (including sensitivity and the ability to detect damage before it becomes critical);
- Improved health and safety (e.g. minimise diver/RAT involvement); and
- Cost reduction (e.g. minimise diver involvement or frequency of inspection).

For each damage mechanism listed, the general effectiveness of the different inspection and SI monitoring technique is assessed and graded ‘high’, ‘medium’ or ‘low’. A summary of the adequacy of the inspection technique is provided in the ‘Assessment of Current Inspection Technologies’ column. A number of damage mechanisms were selected as potentials for future development of SI monitoring based on the general adequacy of current inspection methods. These are discussed below for the underwater, splash zone, topsides and semi-submersible hull structures. A brief discussion on moorings is included in Appendix 6.

6.1 UNDERWATER STRUCTURE

Table 4 below is a summary of SI monitoring techniques which can potentially complement current underwater inspections for selected damage mechanisms. Information is taken from Tables 1 and 3 (Appendix 4).

Table 4 Complementary SI Monitoring Techniques – Underwater and Topsides

Damage Mechanism	Assessment of Current Inspection Technologies	Complementary SI Monitoring Technique(s)
Surface breaking cracks (critical to the integrity of the structure)	Diver/RAT involvement required; Local effective inspection only.	Localised AE NFRM (possible for 80% through thickness crack in low redundancy jackets)
Through-thickness cracks	Effective method available using ROV/RAT; Other underwater techniques require diver involvement; Not applicable to braces which are intentionally designed to be flooded (underwater).	Localised AE NFRM (particularly suited to low redundancy platforms, e.g. 4-legged jackets) CFMD

Damage Mechanism	Assessment of Current Inspection Technologies	Complementary SI Monitoring Technique(s)
Far-surface and embedded cracks (critical to the integrity of the structure)	Diver/RAT involvement required.	Localised AE UT using angled longitudinal wave technique (for cracks in ring stiffeners and possibly other internal cracks).
Bolt loosening	No effective method available although GVI by ROV can provide some indication. Can be re-tightened, probably by ROV/RAT.	SM
Severance	Effective method available using ROV/RAT; Other underwater techniques require diver involvement.	CFMD (underwater) Localised AE NFRM (for full member severance)

Surface Breaking Cracks

Underwater inspections such as crack detection NDE can be performed to detect surface breaking defects. Diver deployment will be necessary. This introduces health and safety risks as well as increased costs. Also, practical issues such as bad weather and inaccessibility may compromise scheduled inspections.

Localised AE monitoring can be used to complement inspections, providing a continuous remote monitoring alternative without the need for diver deployment-except for the initial placement of sensors and any maintenance. This method is localised and cannot be used to screen a whole jacket.

Also, use of NFRM is possible to monitor at least 80% through-thickness cracks in low redundancy jackets.

Through-Thickness Crack

Although effective inspection methods using an ROV are available, these methods are not suitable for braces which are intentionally designed to be flooded or flooding may not occur with the through-thickness crack present.

SI monitoring techniques such as localised AE and NFRM may be employed and sensors fitted at selected target locations. These techniques do not depend on brace flooding. NFRM techniques to monitor through-thickness cracks are particularly suited to low redundancy platforms. These methods would also provide real-time detection of any member severance.

Far-Surface and Embedded Cracks

Figure 1 illustrates the inspection of far-surface and embedded cracks as listed in Table 1 in Appendix 4 and Table 4 above.

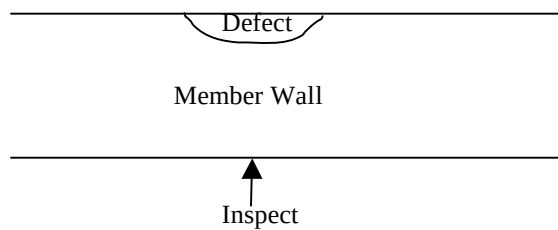


Figure 1 Illustration of the inspection of far-surface cracks

Localised UT inspection techniques may be used to inspect far-surface cracks. Phased Array UT, Conventional Pulse Echo UT and TOFD inspections may involve divers and the associated risks need to be considered.

Localised AE monitoring can be used to complement or replace inspections, thus providing a continuous remote monitoring alternative, without the need for diver deployment (except for initial placement of sensors and any maintenance). Typically, the identification of a growing defect would be followed up by a targeted inspection.

UT using an angled longitudinal wave monitoring technique can be used to monitor cracks in ring stiffeners and other internal cracks.

Bolt Loosening

There is no effective inspection method available. In practice, bolts can be re-tightened by ROV or divers. In cases where loss of pre-tension is critical, strain monitoring (or similar methods) could be used to continuously monitor the bolts, by careful placing of gauges.

Severance

NFRM can be used to detect/monitor for full member severance. Once an underwater member has severed, CFMD can be used to monitor member flooding. Localised AE may be used to monitor through-thickness cracks which may lead to severance.

6.2 SPLASH ZONE

The splash zone is particularly difficult to inspect and members in this area are subject to accelerated degradation. RATs will not routinely go down to the splash zone area for health and safety reasons. Possible inspection techniques include GVI using binoculars and CVI using either RATs or specialised equipment such as guided cameras. NFRM can also be used to detect/monitor for the severance of members in the splash zone.

If damage is found through GVI or CVI then it is possible to undertake detailed inspection following removal of the coating. This would not normally be part of an ongoing inspection.

6.3 TOPSIDES

Table 4 is a summary of SI monitoring techniques which can potentially complement current topsides inspections. The main driver for requiring monitoring is to replace the RAT requirement, which has an associated health and safety risk. It is also difficult to inspect effectively by rope access. It is not common to put in place a monitoring system on the topside structure as in general this can be inspected by conventional methods.

Corrosion

Corrosion is a significant problem for topside steelwork due to the exposure to marine environment. Corrosion under PFP/protective coating could be difficult to detect without coating removal.

Methods such as Long Range UT could be used to detect such corrosion, although the technique is still only at the development stage for many applications.

Severe local and general corrosion can be inspected effectively and at relatively low cost using methods such as Ultrasonic Wall Thickness techniques and CVI, without the need for SI monitoring (refer to Table 3 in Appendix 4).

6.4 SEMI-SUBMERSIBLE HULL STRUCTURE

This includes the inspection or monitoring of the subsea structure of a semi-submersible. It is important to note that defects in the structure leading to local breach of watertight integrity can be significant. Breach of watertight integrity may not lead to structural failure but may lead to loss of stability.

Table 4 (Appendix 4) which assesses the inspection and monitoring techniques for the underwater jacket structure shows that almost all the techniques are also relevant to semi-submersibles. However due to the different configurations, a number of the inspection/monitoring techniques are not relevant, and these are:

- Flooded member detection;
- Continuous flooded member detection;
- Natural frequency response monitoring; and
- Acoustic fingerprinting.

Leak Detection

LD is a particularly important technique for semi submersibles due to the need to detect any loss of watertight integrity at the early stages. There is also a requirement for LD in ageing semi-submersibles in Norway [12]. There are leak detection techniques already in use as discussed in Section 4.2.

Crack Monitoring

AE techniques are already in use to monitor crack growth internal to semi submersible structures and this is discussed in Section 4.1. Particularly for monitoring cracks in the hull structure, where through thickness cracking would lead to a breach of water tight integrity, AE has particular benefits as it can detect cracks before they extend through the thickness.

7. OPPORTUNITIES FOR DEVELOPMENT OF SI MONITORING TECHNOLOGIES FOR LIFE EXTENSION

An increasing number of North Sea installations are reaching or have exceeded their original design lives and are either already into or are being considered for a life extension stage. This is because of the increased need to continue producing oil or gas or to act as a hub or host to nearby subsea completions.

Consideration of life extension requires knowledge of the relevant ageing mechanisms such as corrosion and fatigue, as well as having and maintaining a good understanding of the current state of the structure. This requires inspection and maintenance, for which SI monitoring technologies can play an important part.

One of the difficulties in obtaining knowledge of the current level of structural integrity is the lack of information on parts of the installation which are difficult to inspect by normal methods. These include welded pile sections, ring-stiffened joints and parts of the splash zone. This limit on knowledge of the structural integrity required for the life extension stage is significant and opportunities for application of SI monitoring technologies to these difficult to inspect items are important. Typical examples are described below:

1. **Welded pile sections:** these play an important part in maintaining the integrity of the foundation. The welded circumferential welds are difficult to inspect once installed. An additional problem is that some part of the welded connection's original fatigue life will have been used up to an unknown extent during pile driving. Corrosion of steel is also a possibility in sections below ground where the CP system may be less effective.
2. **Grouted connections:** These are formed at the installation stage and therefore difficult to inspect at that stage and also in subsequent operational inspections.
3. **Shear plates for pile-sleeve connectors:** these form the main load path from the piles to the structure and are also difficult to inspect.
4. **Ring-stiffened joints:** Many platforms contain a number of ring stiffened joints. The stiffeners provide additional strength to resist static loading and can also assist in increasing fatigue life. The stiffeners are welded to the joint and can also contain welds within their own structure. Fatigue testing of such joints has shown that stiffeners do fail and this is not visible from the outside until major damage has occurred internally, significantly reducing the effectiveness of the joint. Cracks at the ring inner edge have been seen in fatigue tests; propagating to reduce the stiffness of the ring and the joint. This type of damage is also not visible externally in its initial stages.
5. **Widespread fatigue damage:** This type of damage has occurred in airframes and is a recognised problem for life extension of aircraft. Widespread fatigue damage (WFD) is defined as the simultaneous presence of cracks at multiple structural details that are of sufficient size and frequency such that the structure will no longer meet its damage tolerance requirement. There are two types of WFD:
 1. Multiple site damage is characterised by the presence of multiple cracks in the same structural element, leading to a loss of the required residual strength.
 2. Multiple element damage occurs where cracks occur in similar adjacent structural elements, again leading to a potential loss of residual strength.

The development of cracks at multiple locations could result in significant interactions and transfer of stress that could affect fatigue growth and subsequent fracture, and predictions for local cracking may no longer apply.

WFD is a potential failure mechanism for ageing offshore structures, particularly where Flooded Member Detection (FMD) is the only inspection tool being used. Cracking is not found until it is through-thickness at which stage many other cracks could be developing locally but not yet detected because they are not at the through-thickness stage.

It is important to note however, that NFRM may be used to monitor for WFD, as it will identify a single severance immediately and allow the operator to act thereupon. Should another severance occur the system would pick this up thus highlighting possible global structural integrity problems.

6. **Accumulated damage:** damage resulting from accidental events over a period of time such as ship collision or dropped objects can accumulate to cause loss of member or joint strength. Individual damage can often be found immediately after the event and repaired but studies have shown that ~20% of such damage is only found during subsequent periodic inspections and by this stage is often covered by marine growth, making it difficult to locate. NFRM is probably the best existing technique to detect/monitor for gross damage immediately following an incident. NFRM cannot however monitor for indentation or partial loss of strength.
7. **Members in the splash zone:** This zone is very difficult to inspect using normal tools and close visual inspection is the accepted method (using for example binoculars), which limits the level of detail which can be found. In addition the CP system is ineffective in this zone and mitigating the effects of corrosion is done by using coatings and adding a corrosion allowance at the design stage. This allowance is usually only intended for the design life of the structure. While existing NFRM techniques are effective in monitoring for full member severance of even the inaccessible items in the splash zone, other damage mechanisms like cracks may be difficult to monitor.
8. **Structural parts in water depths >150m:** Diver inspection is not usually accepted in water depths > 150m, and inspection is limited to techniques which can be operated from an ROV.

Table 5 lists a number of SI monitoring techniques, which can be potentially used to provide information on structural items which are difficult to inspect using normal methods.

Table 5 Potential SI Monitoring Techniques for Items which are Difficult to Inspect

Difficult to inspect item	Deterioration mechanisms	Potential Monitoring or Inspection Technique
Welded pile sections	Fatigue at circumferential welds, corrosion near or below seabed	Long range UT, NFRM
Grouted connections	Corrosion, loss of bonding of grout	
Shear plates for pile-sleeve connectors	Fatigue, corrosion	Diver inspection, NFRM

Difficult to inspect item	Deterioration mechanisms	Potential Monitoring or Inspection Technique
Ring-stiffened joints	Fatigue cracking at welds attaching the stiffeners to the inside of the chord tubular, fatigue cracking in the ring stiffeners themselves - starting at the inner edge and propagating radially outwards.	UT using angled longitudinal wave technique [12].
Widespread fatigue damage	Multiple fatigue cracking	Natural frequency response monitoring
Accumulated damage	Dents and bows from accidental damage	Long Range UT
Splash zone	Corrosion, fatigue at welds	Thickness measurement by UT (remote operating tool)
Deep water components	Corrosion, fatigue	ROV inspection technology

From Table 5, three techniques are identified as having the potential to provide structural information. These are reviewed below:

1. **Long Range UT** has been identified for inspection of fatigue cracking in welded piles, beyond 25 year life. This technology can be used to detect internal and external metal loss using long range wave energy in difficult to access locations without the need to remove insulation or coatings. The technology works on cylindrical geometries (e.g. circumferential welds). The technology can detect cracks and general metal loss greater than 5% of the cross-sectional area and can inspect about 50metres of pipe (25metres in each direction). Use of Long Range UT can be adapted to enable continuous monitoring of defects such as fatigue cracks, corrosion and coating removal.
2. **Natural Frequency Response Monitoring** can be used monitor for severance and potential primary member failure (refer to Section 4.8).
3. **Angled UT** can be used to monitor defects such as severance, through-thickness cracks and far-surface cracks. Refer to [12].

Table 5 shows that there is no current SIM or inspection technique available for monitoring the state of grouted connections.

8. REQUIREMENTS FOR DEVELOPMENT OF SI MONITORING TECHNIQUES

This review has shown that existing SI monitoring techniques have several limitations in respect of the need for offshore deployment and other factors. These are described in Section 4. Some development work is already underway with the equipment suppliers. However it is felt useful to list potential developments which could improve the capability of SI monitoring methods to complement existing inspection techniques. These are:

- ROV deployment: Section 4.1 describes the need for diver deployment as a significant limitation (for AE monitoring) recognising the costs of operating a diving support vessel and the health and safety hazards which may arise from having divers in the water. A particular need is to be able to attach sensors or gauges and associated equipment underwater using a ROV.
- Replacement of RAT requirement: rope access is a recognised method of access to the splash zone and parts of the topside structure to use inspection techniques, such as UT for thickness monitoring. There is a health and safety risk associated with this method. It may also be difficult to inspect effectively by rope access. Alternative methods which do not require rope access would be beneficial.
- Cabling through the water and splash zone: the transmission of signals from underwater sensors to the topside is a requirement in many cases. Cabling is vulnerable to damage caused by wave action or dropped objects. Some progress has been made with through-water telemetry or transmission of signals through the structure but further work would be beneficial.
- Need for experienced and qualified operating personnel: some SI monitoring techniques require interpretation of the output by qualified and experienced operators. A particular example is acoustic emissions monitoring where it is known that data can be difficult to interpret and the raw data needs to be processed by specialist software which is usually owned by the supplier of the system. External accreditation of these methods would be useful and lead to more confidence in the results.
- Extended battery life: one of the listed limitations of external CFMD is the limited life of current battery systems (i.e. 10 years maximum). Battery replacement by ROV or longer life batteries would enable this technique to have wider applicability.
- Reduction of background noise: background noise from wave action or from equipment on the installation limits the sensitivity of some SI monitoring methods. For example the ability of NFRM to detect smaller defects is limited by background noise. Improved methods of filtering or noise cancellation could lead to higher sensitivities. An acoustic emissions system can be prone to background noise which can affect its accuracy and reduce the probability of detection.
- Robust sensors: deployment of sensors underwater can lead to damage from wave action or other mechanisms. Replacement of sensors can be difficult and costly. The development of more robust sensors and attachments would be beneficial for these applications.
- Development of existing methods: Section 4 shows some limitations of existing SI monitoring methods. Improvement of the methods to overcome these limitations would be beneficial. An example is leak detection which is a

particularly important technique because of the need to maintain watertight integrity in semi-submersibles.

- Wider applicability of current SI monitoring methods: an example is long range UT which has been demonstrated for inspection for corrosion on pipework over long distances. It is seen as a potential method for inspecting welded piles which are difficult to inspect using existing methods; however, long range UT would need to be demonstrated for this particular application through a test programme.
- Development of new methods: the report notes that no existing SI monitoring or inspection method is available for detection of damage in grouted connections or in shear plates for pile-sleeve connectors (both relevant to life extension). There is an opportunity for new techniques to be developed.

9. CONCLUSIONS

On the basis of the review presented in this report, the following conclusions have been made:

1. A review of relevant codes and standards has been carried out. While there are a number of codes and standards which make reference to SI monitoring, no standard on its application in the offshore industry exists.
2. A significant number of SI monitoring techniques exist and these have been reviewed. A number of SI monitoring methods have been well developed and are available for monitoring of integrity related parameters without the requirement for significant further development. These include:
 - Acoustic emissions monitoring;
 - Air gap monitoring;
 - GPS monitoring;
 - Leak detection;
 - Natural frequency response monitoring;
 - Strain monitoring; and
 - Riser and anchor chain monitoring.
3. With the increasing need to demonstrate that structural integrity risks are managed and as low as reasonably practicable, the need to consider structural monitoring as part of the platform safety case is anticipated to increase in the future and these mature technologies would be prime candidates.
4. Methods which would require further development before they would become practicable as widely applied SI monitoring methods include:
 - Acoustic fingerprinting
 - Continuous flooded member detection (external/internal)
 - Fatigue gauge monitoring
5. A qualitative assessment has been carried out to identify where SI monitoring can complement periodic inspection methods. Damage mechanisms for which SI monitoring techniques can complement inspection methods include:
 - Surface-breaking cracks – localised acoustic emissions monitoring, natural frequency response monitoring (80% through-thickness cracks);
 - Through-thickness cracks – localised acoustic emissions monitoring, natural frequency response monitoring, leak detection;
 - Far-surface and embedded cracks – localised acoustic emissions;
 - Full-member severance – natural frequency response monitoring;
 - Loss of mooring line tension – anchor chain monitoring: suitable for long term deployment; sonar rays continuously scan the global mooring arrangement monitoring mooring presence and positioning.
6. The special inspection requirements for demonstrating life extension in ageing installations have been addressed. SI monitoring techniques can be used to detect damage mechanisms on difficult to inspect items. These include:
 - Welded pile sections;

- Ring-stiffened joints and items in the splash zone; and
- Deep water components.

Potential SI monitoring techniques for these items include long range UT, UT using angled probes, NFRM and thickness measurement using UT with a remote probe.

7. Further development of existing SI monitoring techniques is required to meet offshore requirements and some examples are given of potentially useful developments.

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APPENDIX 1

Review of SI Monitoring published reports and documents

	Report title	Author	Date	Report number	Publisher
TO 97	Review of structural monitoring	Fugro	1997		HSE
	This HSE published report reviewed the monitoring of the response characteristics of fixed steel jacket structures with a view to comparing the measured characteristics with a previously measured baseline. The technique is based on the principle that the natural frequencies (and mode shapes) of a jacket structure will change as a result of a reduction in the stiffness of the jacket, resulting from damage. The report reviewed the principles of monitoring, identifying the mode shapes for the first three natural frequencies of a jacket. These natural frequencies are measured using sensitive accelerometers, mounted on the structure and can detect sway movements of the platform due to wave loading. By measuring movements at different locations in the structure sway and torsional natural frequencies can be distinguished. Measuring movements at different elevations on the jacket structure makes it possible to distinguish between the first sway natural frequency and higher order sway natural frequencies. The natural frequency and mode shape are controlled by the distribution of mass and stiffness of the system. Assuming that the foundation stiffness and the system mass can be assumed to be constant then the natural frequency will vary only with changes in the platform stiffness. Mode shapes also provide a useful measure of performance, as the ratio of movement of one face of the structure to that on another face should be constant. However damage to one face will result in relative movement which can be measured. Relative movements of different platform elevations can also indicate changes of stiffness between elevations and hence a possible indication of damage. The report then reviewed three OSO commissioned studies to evaluate the potential of structural monitoring. The platforms involved included Forties A, Heather and Piper Alpha. The studies used accelerometers both subsea and at deck level. Results from these and some other related studies led to some significant conclusions: – Stability of natural frequencies: measurements taken over one year showed that the variability for a typical 4 leg platform could be up to 1-2%. Indications of change outside this variability could be considered significant. – Sensitivity of natural frequencies to damage: severance of a single member would affect the overall natural frequency to an extent dependent on the level of member redundancy of the jacket and also on the contribution that that member makes to the dynamic stiffness of the platform at that particular frequency. Models were developed in several of the studies and the report reviewed the findings. In some cases member severance resulted in changes to sway or torsion frequency by as little as 1-2% and hence was masked by the variability in the natural frequency. In other cases member severance resulted in changes of up to 10% and hence measurable as significant. The change was very dependant on the type of platform. Severance of individual members on the 8 leg Ninian northern platform resulted in frequency changes no more than 1.8% and hence not measurable compared to the background variability. Changes due to member severance for the 4 leg Ninian southern platform were larger, up to 11.5% for severance of a main diagonal and hence measurable compared to the background. It was				

	concluded that severance of a single member could be detected on platforms with low-redundant member configurations, whereas for a higher level of redundancy several severances would be required to produce a significant change which could be detected. Active monitoring of a 4 leg platform with low-redundancy bracing was able to demonstrate the changes due to severance of a horizontal member and its subsequent repair. The measured changes (in the range of 2.5-4.5%) compared well with finite element predictions. A subsequent test with a severance of a diagonal member resulted in a measured change of 10.3% compared with a predicted value of 10.7%; showing close agreement. In general the studies undertaken at that time were considered disappointing in their ability to detect sufficient damage to make the techniques worth developing further. The report also reviewed current technology and costs, based on 1997 values. Changes in the operating environment were also reviewed, including the effects of CRINE, extension of platform life etc. Overall the report concluded that natural frequency monitoring is a cheap and reliable method of detecting changes in platform response which equate to changes in stiffness of ~3%. This level of change in stiffness is sufficient to detect severance of individual main members on some configurations of jacket type structures. However for more highly redundant types of structures the detectable level of change in stiffness would equate to severance of several members. The report postulated that the level of stiffness change that could be detected would be less than that before the residual strength became critical, although this was not demonstrated.
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2	Progress in structural monitoring	Matsu	1998	OTO 98 046	HSE
	This report was prepared as a technical support task on behalf of the HSE, to examine progress and the future of structural monitoring. Literature on structural monitoring was reviewed and following discussions with some relevant people a number of conclusions were drawn, which were as follows. Structural monitoring using several sets of accelerometers positioned above the water line is sensitive enough to detect 1-2% reductions in fundamental natural frequencies and which face of the structure is affected. Assessment of damage to individual specific members is not possible using a global monitoring system, with sensors above the water-line. Monitoring for damaged members would require a network of transducers, possibly one on each member. It is recommended that the effects of different levels of damage to each generic type of structure needs to be assessed so that the sensitivity of a suitable structural monitoring system can be determined. Methods for calculating safe and unsafe structures need clarification. Improvements to the modelling of complex structures using finite element analysis can be made if access to real data is available to allow model updating. It was also suggested that structural monitoring could be part of the design process to aid optimisation of structural design with respect to future monitoring. Recommendations for future work were made in the report. These were associated with improving finite element push-over analyses to determine relevant critical levels of damage and investigating the practicalities of using Lamb waves for monitoring individual members, with an ROV being used for mobile local monitoring of individual members.				

3	Structural Integrity Monitoring for the offshore Industry	Marine Technology Directorate	1993	Marine Research Review 1	Marine Technology Directorate, London
	This review includes seven projects that developed potential products for offshore inspection from a programme supported by the Science Research Council, entitled “Structural Integrity Monitoring”. The techniques included; – Eddy current instrument for offshore application; – Integrated eddy-current/ probe system for detection and sizing of cracks; – 3D imaging of underwater structural sections with marine growth; – Hall effect probes for crack detection and monitoring in steel structures; – Low cost acoustic imaging; – NDT hydrogen sensor; – Plate, leaky Rayleigh and creeping wave NDT for offshore structures. In the context of this current study none of the techniques were intended for permanent deployment, but to be operated from an ROV or by a diver.				
4	Structural monitoring – its development and promotion by a dedicated web site (Simonet)	J.V.Sharp, M.J.Locke, W.D.Dover	2001	Paper for BINDT conference	
	This paper for the 2001 BINDT conference reviewed the history and basis of SI monitoring and relevant applications in a number of industry sectors. Specific applications included a concrete cable stay bridge across the Dee, the Channel Tunnel and monitoring of deep-water risers. New developments in SI monitoring were also reviewed, including optical fibre methods and monitoring changes in magnetic permeability. The paper also outlined the background and status of the SIMoNet web site, which had been set up to facilitate communication between those involved in SI monitoring.				

5	Cost effective structural monitoring	Mecon Ltd	2001	OTO 2000 092	HSE
	This report described the results of a test programme, using a new method for detecting damage in jacket structures. The method is aimed at detecting and locating significant changes in the structural properties of a jacket type structure e.g. a crack at a joint), via the changes they would cause in elastic wave propagation through the structure. Demonstration work was carried out in air on a small scale 2D cross braced frame made from a well damped material. The frame had two main legs with three cross members and was instrumented at each node. One end of one of the cross members was progressively cut to simulate a crack. The response at every node to excitation at one extreme of the frame was analysed, together with its impact on the identification of cracks in a larger structure. The results obtained showed some evidence that increasing damage (in the shape of progressive cutting) could be seen at the relevant locations. It was concluded that for a full scale rig it might be possible to use roughly one sensor per ten members with excitation at the top of each vertical leg. However although the results showed some promise the model was very simple and the application of the technique to a real steel structure required significant further work (see later reports).				

6	Cost effective structural monitoring – an acoustic method, Phase II	Mecon Ltd	2005	Research Report 325	HSE
	This report describes the results from the second phase of the HSE funded study and includes details of the numerical simulations and of physical experiments on the scale model. The plastic model involved was a 1/100 scale of the Claymore platform. The report claims that the numerical simulations were sound in principle. In the experiments a set of acoustic sources were placed at the top of the structure to transmit signals to a set of receivers at the bottom. However it was recognised that it would be better to have both transmitters and receivers at the top of the structure for practical reasons. It is also claimed that numerical simulations of this arrangement provided better results than the previous arrangement. Further work was planned to test this arrangement in practice.				

7.	Cost Effective structural monitoring – an acoustic method, phase IIb	Mecon Ltd	2005	Research Report 326	HSE
This report describes results from tests where the transmitters and receivers were both placed at the top, to simulate the arrangement when all transducers were placed above the water-line. Results obtained show that this arrangement can locate structural damage more accurately than the earlier geometry (described in the previous report). However it was also found that the results were more dependent on changes in temperature in the plastic rig, creep in the glue used to join the model and some problems with the recording equipment. It was recognised that the next critical stage was to test a metal structure immersed in water at larger scale.					

8	Acoustic monitoring of the hulls of floating production storage and offloading facilities (FPSOs) for corrosion and damage	Mecon Ltd	2005	Research Report 328	HSE
This report describes the results of a series of interviews with personnel involved in the design, build and operation of FPSOs, together with a detailed review of the literature on acoustic methods of structural monitoring. Available methods were examined for their suitability for monitoring FPSOs on the general design in use on the UKCS. Three methods were identified as possibly being feasible. These included monitoring the frequencies of localised structural modes, acoustic emissions and sparse array monitoring using Lamb wave excitation. However further evaluation showed that the first method would be too insensitive to be useful. Acoustic emissions would be suitable for crack monitoring in the outer hull, although large numbers of transducers would be required. Although monitoring of corrosion in onshore tanks using this method is an established technique it was concluded that it would be much more difficult to apply on an FPSO because the emission levels are very low and could be masked by other noise on the installation. Sparse array Lamb array monitoring for location of cracks or patches of corrosion would be based on injecting travelling ultrasonic waves into tank wall plates and detecting reflections from sites some distance away. Progressive damage would be recognised by an increase in the signal reflection strength over time. However it was noted that this technique is still at the development stage and would be unlikely to be available commercially for several years. The report recommended carrying out trials of acoustic emissions and of sparse array Lamb wave monitoring (when available). Trials of the former should be applied to crack detection in the splash zone of the outer hull, whilst the latter would be more appropriate for detection of corrosion (e.g. in the slop tanks).					

9	Underwater inspection of steel offshore installations: implementation of a new approach	Marine Technology Directorate	1989	MTD publication 89/104	Marine Technology Directorate
This wide ranging review included a section on monitoring, both structural vibration and acoustic emissions methods. The report addressed acquisition of data from different types of sensor as well as transmission of the data, either via cabling, through water transmission or using taut-wire transmission. It was noted that both cables and taut wire transmission are vulnerable to damage, as had been found in practice. Vibration monitoring using ambient excitation was reviewed, based on natural frequencies being excited by wave motion. Monitoring of a structure could be carried out by obtaining vibration frequency spectra above or below the water-line. It was noted that frequencies can be obtained to accuracies to ~1% and deformed shapes to about 10%. It was noted that trials had been carried out on several North Sea platforms. Forced excitation methods were also reviewed. One technique using impulse excitation from a small impactor had been used offshore. The advantages and disadvantages of this method are reviewed. It is noted that it should be possible to use a small “portable” vibrator to induce vibrations over a range of frequencies in a specified structural area of interest and hence produce information relevant to the monitoring of mode changes as a result of damage. However monitoring the whole structure would require a very large vibrator capable of applying vibrations at several locations simultaneously, with responses detected by accelerometers at various points on the structure. Another problem with forced excitation is that vibrations from environmental forcing may mask responses from the former. The report also reviews acoustic emissions methods, noting that commercially available systems have been used offshore. A system targeted to one localised part of a structure is more effective than global monitoring. It points out that acoustic emission methods should not be considered for crack detection since they are unsuitable to locate unknown, non-propagating cracks. The report assesses the emission characteristics of steels used offshore, noting that emission from steels under cyclic loading is much greater than under steady loading and depends mainly on the fracture toughness of the steel rather than its strength. It is also pointed out that the signals from structural cracking need to be separated from extraneous noises. The report indicates that recent advances in instrumentation and analysis methods have provided effective methods of achieving this separation. Two type of filtering are described, spatial filtering, based on the time of arrival of the AE signal, and parametric filtering, which links the AE signal to the tension portion of the loading cycled. The latter is less successful in the field. Distribution analysis based on displaying the distribution of received signals has also been used. The report also considers the large problem of data handling, given the vast amount of data generated by the technique.					

10	Crack detection by acoustic emissions	L.M.Rogers, Lloyds Register Marine Division	1998	Journal of Offshore Technology	
This paper describes the acoustic emissions technique, the source of the emissions and the likely propagation distance in steel structures. The report also describes the use of acoustic emissions techniques as a supplementary method for monitoring fatigue cracks in large welded tubular joints as part of the UK Offshore Steels Research Programme undertaken in the 1970-80's. This work showed that the acoustic emissions behaviour changed with the crack growth rate, enabling an estimate to be made of the crack depth from the character of the acoustic emissions signal. The report also highlighted a case study which involved monitoring crack growth on a nodal joint below water. A general visual survey had shown that a horizontal brace at an elevation of -43m was severed. Failure had occurred at one end of an access window in the brace, due to a root weld defect. Detailed inspection of other access windows indicated a large number of similar defects, of which ten were repaired using saturation diving. Fracture mechanics analysis methods showed that the remaining windows had adequate fatigue life. A later analysis predicted fatigue lives as short as five years for one particular access window. To avoid an expensive repair acoustic emissions transducers were attached around the window to monitor the crack growth. The sensors were installed by divers using the taut wire method to relay signals back to the surface. Monitoring of the crack was undertaken over two winters, with claimed accurate location of the defects present. The length and approximate depth of each indication was found to agree with available NDT data. More significantly there was no evidence of significant crack growth which would require repair. The paper notes that applications of acoustic emissions monitoring on offshore installations has been limited to known cracked nodes and other similar areas at that time.					
11	Progress in acoustic emission monitoring of offshore installations	L.M.Rogers, Subsea Offshore Ltd	1994	6 th European conference on Non-destructive testing	
This paper reviews the application of acoustic emission monitoring to fatigue crack detection in offshore steel jacket structures. It provides results from monitoring a known crack in a nodal joint below water during the winter of 1993/94. An array of sensors was used with a spacing of up to 2m. This enabled the surface length of the active crack front to be defined with an accuracy of between 20-40mm. A brace to chord joint was detected as acoustically active using 3 sensors of a larger array used to monitor this node. The paper describes the results from one year's monitoring to illustrate the reliability of the crack location and sizing capability. As a result of the monitoring it was concluded that the defect did not pose an immediate threat to the integrity of the joint. Decisions to delay repairing the defect resulted in significant reduced maintenance costs.					

12	Monitoring structural integrity of North Sea production platforms by acoustic emission	J.S.Mitchell (Chevron (UK) Ltd)& L.M.Rogers (Subsea Offshore Ltd)	1992	OTC Conference, Houston 1992	OTC Conference proceedings, Paper OTC 6957
This paper describes the background to the use of acoustic emission (AE) monitoring of North Sea platforms and the application of the method to the monitoring of subsea welds in the Ninian South platform. This monitoring was fully automated and initially used a taut-wire system to relay signals to the platform and to a modem for data transfer to shore. The decision to use AE monitoring was taken following the severance of a horizontal brace as a result of a fatigue crack growing at one end of an access window. Detailed NDE inspection of other access windows had shown a large number of similar defects of various sizes. Several were repaired using saturation diving. It was decided to monitor some of the remaining ones by using conventional NDE methods, such as ultrasonics. One particular remaining defect had a predicted remaining life of only 5 years and it was decided to monitor this using AE methods. It was found that measured defect sizes from the AE results were in good agreement with previous data from other NDE methods. Over the three year monitoring period defect growth was found to be minimal and it was concluded that a repair was not necessary at that stage. The paper also describes the development of a miniaturised AE sensor capable of remote operation, which was trialled on the Ninian platform with some limited success. It was intended to operate the sensor without any wires to the surface, using subsea data storage, but at the stage of preparing the paper this development had not been completed.					

13	Structural and Engineering monitoring by acoustic emission – fundamentals and applications	L.M.Rogers (Lloyds Register)	2001	Lloyds report	
This detailed report outlines the fundamentals of the acoustic emission effect, associated with degradation mechanisms such as fatigue and stress corrosion in both steels and aluminium alloys. The microstructure of fatigue cracks and the different magnitude AE event associated with different stages of the crack growth are reviewed. Expressions are given for the critical plastic zone sizes and the wave displacement amplitudes produced by a sub-surface micro-crack, together with details of how stress waves propagate through the structure. A methodology is described for correcting the measured signal amplitude for attenuation in the structure. Case studies are also presented to demonstrate the application of this technique to several different types of structure, including nodal joints in offshore structures, testing of an aircraft wing panel, stress corrosion cracking of a steel pressure vessel, re-qualification of high pressure gas cylinders and condition monitoring of heavily loaded bearings.					
14	Network for structural monitoring	J.V.Sharp and W.D.Dover	2003	Materials World	Vol. 11, No.6, P.34 June 2003
This paper describes the background to the setting up of the SIMoNet SI monitoring network and web site. Background is provided on the importance of structural integrity and costs of maintenance. Life extension is an upcoming issue in which SI monitoring plays an important part. The network aims to bring together those involved in SI monitoring across a wide range of disciplines and applications. Workshops are held regularly with particular themes. The network also provides information on new and developing techniques for SI monitoring. The cross-industry nature of the network has advantages in enabling members to see where new technologies are being applied and whether these might be relevant to their own field.					

15	Non-destructive evaluation of wire ropes – utilising acoustic emission techniques	G.R.Drummond, J.F.Taylor, R.M.Taylor, Robert Gordon University			
This paper describes laboratory test on five wire ropes with induced flaws of known severity and monitored for acoustic emission. It was found possible to monitor the condition of the wire rope and diagnose the severity of the damage that had been induced. It was shown that there was a reasonably linear relationship between the sum of the acoustic energy emitted during the application of a proof load to the reduction in cross-sectional area due to the induced defect. However application of a “safe working load (SWL)” did not provide this level of demonstration, because the SWL is a smaller fraction of the load required to break an unflawed rope. It was claimed that it could be feasible for this method to provide a method on monitoring wire ropes non-destructively in situ, although there was a considerable amount of further work required to demonstrate this.					

16	Condition monitoring techniques for fibre mooring ropes	G.Rebel, C.R.Chaplin, C. Groives- Kirkby, I.M.L.Ridge (Reading University)			
The long-term integrity of polyester fibre mooring lines, being used to moor floating oil production platforms in deep-water is an increasing problem, as none of the NDE methods developed for steel wire mooring ropes are relevant. The paper describes the possible approaches which have been considered elsewhere for the condition monitoring of fibre ropes. It was decided that the most promising technique is the use of distributed fibre optic sensors, particularly those using multiple Bragg reflection gratings. One of the main problems is the difference in failure strains between the fibres and the mooring lines (1% c.f. 10-15%). The paper also points out other concerns such as the required resolution for the system, the need for ruggedness of the optical fibre within the fibre rope and the failure behaviour of the combined optical/polyester rope.					

17	Report title	Author	Date	Report number	Publisher
	Application of structural integrity monitoring to life extension of ageing offshore installations	A.Stacey (Offshore Safety Division, HSE) J.V.Sharp (Cranfield University)	Dec. 2004	Conference report, published by ERA Technology, Leatherhead	ERA Conference, London. "Major Hazards Offshore & Onshore 2004"
	This conference paper identified the reasons for life extension and the information required for reassessment to support a case for life extension. The assessment process was based on the steps listed in ISO 19902, which include condition assessment. The inspection programmes required for this step were reviewed and limitations identified. SI monitoring techniques were reviewed and the potential for these to complement existing inspection methods assessed. Acoustic emission and vibration monitoring methods were seen as the most promising methods for use in life extension assessment.				

APPENDIX 2

Comparison of Characteristics of Structural Monitoring Methods

Inspection Method	Maturity in offshore industry	Limitations	Ease of installation	Interrogation method	Reliability / Probability of detection	Accuracy	Maintenance
Acoustic emission Monitoring	Generally regarded as suitable for monitoring of safety critical members. Has been used for over a decade. & only for specific high criticality applications, not as a general monitoring technique due to intensive interrogation and high associated costs.	Data can be difficult to interpret and needs to be analysed by an engineer. System can be prone to background noise.	Requires specialist installation - can be expensive. All sensors must be hardwired back to a central control unit which may be some distance away.	Raw data needs to be processed by specialist software. Data is presented to the client in a user-friendly format.	Generally reliable with a high probability of detection.	Modern AE systems are very accurate and can detect crack initiation, propagation.	Requires periodic specialist maintenance and recalibration.
Acoustic Fingerprinting	Untested in major structures. Research work isolated to laboratory scale tests at present.	Only tested on severed members. Not thought to be sensitive enough to detect anything other than fully-severed members.	Relatively easy to install, requiring no access to restricted areas. Transmitting and receiving equipment generally installed above splash zone. Cabling may be required back to control room.	Algorithms which analyse the received signal in the frequency domain are interrogated for changes which are reported by exception. The signal may be transmitted as often or infrequently as desired.	Unproven.	Unproven.	Claimed to be standalone but would need routine calibration to in order to meet any claimed performance standards.
Air Gap Monitoring	Carried out for over a decade but the methods used have changed significantly over time. Now a standard monitoring procedure and is widely used in the offshore industry.	Requires specialist contractor to carry out measurements.	Periodic monitoring methods do not require installation of hardware.	The contractor should provide the survey results in a post processed format and minimal interpretation should be required.	Standard equipment is used for the survey and reliability is not considered problematic.	An accuracy of up to 50mm can be achieved	Any maintenance required would be carried out by the specialist contractor.
Riser and anchor chain Monitoring	Widely used	Beam scatter - the transducer may not always detect a considerable amount of the reflected beam	Relatively easy to install as there are no mechanically moving parts. Also, long-term deployment is possible.	Any potential movement outside the given parameters is detected by an audio / visual alarm. The relative position data are converted from analogue to digital form, and analysed by computer.	High - any movement outside the specified parameters will immediately generate an alarm.	Simultaneous monitoring of all riser and anchor chain positions possible, providing high precision measurements of absolute and relative positions.	Long-term deployment / immersion possible. Requires relatively minimal maintenance as there are no moving parts.

Inspection Method	Maturity in offshore industry	Limitations	Ease of installation	Interrogation method	Reliability / Probability of detection	Accuracy	Maintenance
Continuous Flooded Member Detection (External)	None. Untried. Untested	Battery life - possible to reduce power requirements using periodic signals. However, limit of ten years on battery reliability requiring battery replacement by diver or ROV. Splash zone difficult to monitor.	Requires designing and installing a clamp for the transducer. Problems due to high cost and large wave loads. into the jacket structure.	Periodic checks for changes to the reflected signal. Any change results in the transmission of an alarm signal to the control room.	Unproven	Accuracy potentially as high as for FMD (approx. 90%). Susceptible to signal drift, loss of clamp robustness, interpretation errors.	Requires ROV and diver intervention
Continuous Flooded Member Detection (Internal)	None. Untried. Untested at full scale	Only suitable for new builds. Limitations on signal attenuation (due to losses into the water) can be avoided by using lower frequencies. More power required to generate lower frequencies. Splash zone members difficult to monitor.	Can only be installed during the construction phase. Devices placed inside tubular members and need to remain in position to guarantee good acoustic contact during load-out and installation (incl. piling).	Continuous monitoring. Received signal raises alarm	Unknown	Potential for high accuracy	Not possible after installation: inaccessible – located within members
Fatigue Gauge	Limited development in the offshore industry	Attachment to the structure and sufficiently close to the weld toe for it to respond to damage may be difficult, particularly underwater; may be vulnerable to offshore environmental conditions; and cannot be replaced when damaged.	Attached by either threaded studs or by adhesive bonding. A sealed enclosure is fitted over the whole unit to protect against mechanical damage and corrosion.	On-board electronics unit records data in a memory which can be downloaded to a laptop PC via a wireless link or to a data logger	Limited information to date	Claims to bound a class F detail. However, the significant inherent scatter in the fatigue data needs to be considered.	Limited information available for offshore applications
Global Positioning System Monitoring	GPS is widely used in the offshore industry and is generally a mature technology	Costs can increase significantly; Ongoing subscription may be required (to supplier for processing service)	No installation of permanent equipment required	Monitors position and log data, using enhanced GPS services. System will also raise alarms based on user-defined parameters. Correction data delivered to receiver via communication satellites.	Mature technology with no known problems with reliability	Basic packages offer accuracies in the order of 1m. This is improved to approximately 10cm horizontally from premium services.	Maintenance requirements for GPS systems are generally minimal
Leak Detection	Simple alarm systems have been used for decades to warn of high bilge water in ship hulls. Semi-submersible offshore platforms have also employed leak detectors, which are often fairly dated.	Some systems rely on a clean environment; May be affected by condensation or humidity; Extensive cabling may be required - wireless systems not well suited to typical semi-sub environments.	System requires installation by an electrician	Typical system would raise an alarm when water is detected and will indicate in which zone this occurs	The technology appears to be relatively mature and no reliability issues have been reported with latest systems.	There are a number of different sensor options, some of which can detect water levels of 3mm (measured from the floor level)	Modern water sensors have no moving parts and so require little or no maintenance.

Inspection Method	Maturity in offshore industry	Limitations	Ease of installation	Interrogation method	Reliability / Probability of detection	Accuracy	Maintenance
Natural Frequency Response Monitoring	Very mature technique – used since 1970s on UKCS	The method is only sensitive enough to detect changes in frequency of approximately 0.5%. Cannot detect small defects – JIP data suggest detectable defect is 80% circumferential through-wall defect	Relatively straightforward. Self contained units placed on the topsides. Cabled back to PCs in control room or hard-wired through to onshore location.	Daily interrogation of the data. Changes reported by exception.	Dependent on platform configuration FEA should be used to predict expected frequency changes due to member severance. Predictions of frequency shifts <0.5% may imply undetectable failure. Members with changes less than 1% may also require examination of more than one sway mode or a torsional mode.	False positives have not yet been reported. Any frequency changes are attributable to a change in mass or stiffness. If frequency change occurs predominantly in one direction, this is an accurate indication that this is caused by damage in that frame.	Minimal
Strain Monitoring	Widely used	Only measures stress changes, not absolute stress levels; Equipment can be sensitive to damage by the environment; Requires calibration and can be sensitive to drift over time. Sensitive to positioning of gauge in areas with steep stress gradients.	Strain gauge installation generally -surface preparation required. Cabling requirements may complicate installation in remote locations. Environmental interactions should be considered.	Via a computerised system which provides a time-strain history.	High reliability	Generally high. Can be affected by external causes such as wiring interference, temperature variations, bridge set-up and other factors.	Requires periodic maintenance to ensure integrity and connection of strain gauges

APPENDIX 3

SIMoNet abstracts

Life Extension of Pressure Vessels and Pipelines in Corrosive Service through continuous corrosion monitoring (John Lilley, AEA Technology), 2001

John Lilley described the monitoring method using UT thickness measuring transducers, which can be interrogated remotely. In general pressure vessels and pipelines are retired when the minimum allowable thickness (MAT) is reached; the MAT is normally derived from codes and tends to be conservative.

The overall process involved identifying the presence of corrosion, investigating all potential causes of failure from corrosion, performing corrosion maps, and then permanently attaching corrosion probes at the identified locations to monitor corrosion rates. Fitness for service assessments would then be undertaken, based on the observed corrosion rates, and compared with the specified minimum criteria.

The probes can work up to 150°C continuously. Cable runs can be difficult but radio communication of data is now being investigated. Data is usually recorded on a weekly basis, by connecting a laptop and downloading data. On the basis of the data recorded it has been found possible to defer major inspection programmes, with a considerable benefit in costs.

The technique can also be used on buried pipelines. The remaining life assessment is usually initially based on codes, followed by fracture mechanics assessments using known defect data. Use of local wall thickness data has allowed a considerable extension in life with some pipelines.

Recent developments in the use of on-line structural monitoring for the assurance of the integrity of fixed offshore installations. (Dave Sanderson, ABS Consulting & Alan Dougan, Fugro Structural Monitoring Ltd), 2001

Dave Sanderson said that the idea for the joint industry project had come from the first SIMoNET seminar. It now had six sponsors (5 oil companies and HSE). He outlined the background to current inspection offshore, based on flooded member detection (FMD) + GVI/CVI every 2-3 years. This was low cost and with low risk to divers, but based on the premise that some level of damage is acceptable. This approach fitted with using on-line monitoring (OLM) as a tool. In this respect FMD and OLM are complementary techniques. OLM is based on measuring changes to the stiffness matrix, and correlating these with member failure. Accelerometers are placed on each corner of the topside structure, and wave loading on the structure provides the driving force. Mass variations on the topside can be removed by comparing east/west variations with north/south changes in frequency. OLM requires a degree of structural robustness, which can be determined for each platform. In the study the changes in frequency have been correlated with robustness. This showed the need to improve on the measurement of frequency change compared to background and work by Fugro using several different transformation methods has enabled the sensitivity of the measured frequency change to be improved significantly (by a factor of between 2 and 3).

In the study 13 different platform types are being investigated, and the change expected for member loss compared with measurable stiffness changes, with account taken of robustness and platform geometry. It would appear that for many 4 legged platforms OLM is a viable technique, with most member failures detectable. For these FMD is often considered as a marginal technique because of limited redundancy.

Classification Society Perspective on Structural Integrity Monitoring. (David Davenport Jones American Bureau of Shipping), 2001

David Davenport Jones introduced this topic as 'part of the regime that maintains ships' integrity'. It is necessary to understand the strengths and weakness of design using advanced methods, e.g.

- analysis of static and dynamic loads and the resistance to failure modes;
- monitor construction especially critical areas, ie NDT and survey;
- monitor condition and capability of the vessel and the role of coatings;
- link the previous three phases by information management (IT).

He highlighted the necessity for an excess of capability over demand and the fact that Classification Societies have prescriptive rules to define requirements.

Three main phases were described.

1. Design phase with a safe hull regime to define loads, understand failure modes, set criteria for lifetime safety and, after identification of critical areas for robustness and steel weight distribution, to supply a graphical display of acceptable thickness.
2. Construction phase where the safe hull concept identifies critical areas, requires a monitoring plan from the shipyard and ensures rigorous implementation of this during construction.
3. Operational phase where periodic survey is a guide by analysis of service experience using accumulated information from many sources.

Inherent in this is a need for robustness and here Mr Jones introduced the concept of residual resistance factor and showed how this interacted with OLM and changes in the structural vibrational frequencies. Several frequency transforms were tried and the simple Fourier was found to be most suitable.

A Better Way to Monitor Hull Structures. (John Waite, The Salvage Association), 2001

The Salvage Association (a trading style of BMT Salvage Ltd) specialises in damage surveillance for insurance purposes. Many excellent slides from a wide variety of sources were a feature of this presentation which included:

- Cracking in the cross bar supports of the St Yreboelt bridge sections;
- The difficulty of photographing grooving in inaccessible places even though it was readily visible to the eye;
- Small cracks in fruit juice containment vessels which, being on a chilled ship were perhaps not so significant and were on a neutral axis so not as subject to bend loads;
- Bow fatigue where a large chunk was missing; the problem being that selective gauging was not at relevant places;
- A centreline girder crack where fracture through the depth of the web and over 70% wastage precluded load bearing;
- Use of ABS, Safenet and Timeline graphic representations were described.

The importance of monitoring coatings in maintaining structural integrity, especially where pitting was a problem. Increasing use of IT was called for to 'put the information where it's needed'. This must include vessel drawings, maintenance modules, current structural condition and most importantly, where the monitors are.

The author's conclusion were:

- Whereas classification originally assessed risk, a risk-based approach can now assess and limit it;
- SI monitoring was the sole responsibility of the Classifier and not the owners;
- IT should give everyone the information they need.

FOINAVON Umbilical Monitoring System, SI monitoring -VIV Considerations, (Geoff Lyons, Mechanical Engineering Dept. UCL in collaboration with MIT Norwegian Inst of S&T and BP), 2001

Vortex-induced vibrations (VIV) occur on the Foinavon flexible risers at up to 600m off the Shetlands. The problem was to measure the bending and tensile stress at the vessel in respect of the following topics:

- did the expectations match the realities;
- measurements of responses to mooring/wave/VIV frequencies were expected to be minutes/4-20 secs/ up to 10 Hz;
- measurement of accumulated damage was required;
- by implication one would expect similarities with the risers themselves;
- examine VIV and establish feedback for future design;
- measure asset integrity.

A multi-cored curve sensor was incorporated with the riser which passed through a bend constrictor in the hull bottom. The curvature was sensed throughout the riser and tensions and curves associated with heave, roll and pitch were determined.

Planar plots were made and the curvature converted to displacements by FE analysis.

VIV measurements were made for varying currents at known depths.

The conclusion was that VIV can be reasonably modelled - both current and vessel motions reduce VIV. A fibre optic approach was suggested for the future.

Continuous Structural Integrity Monitoring of Offshore Structural Nodes, John O'Brien, Physical Acoustics Ltd, 2002

An overview of Acoustic emission (AE) in providing continuous monitoring of fatigue damage in structural members (e.g. offshore welded nodes) was provided. Types of equipment, software and remote interfaces for accurate monitoring, discrimination of events and swift data processing were presented, based on work at Cardiff University. This is achieved through detecting and locating active emissions and discrimination is feasible to discard emissions due to crack rubbing. A particular application for offshore structures and nodes as an aid to ensuring structural integrity is proving effective enabling a focus on critical areas and nodes. Some trials had been undertaken on a box girder bridge over the M6 motorway and on an offshore floating installation. Cost effective reporting had been achieved via a secure automated web site.

Cost Effective Structural Monitoring: an Acoustic Method, Mark Harper, Mecon Ltd, 2002

This presentation outlined the development of a practical use of AE in continuous monitoring of multiply connected structures, such as North Sea offshore installations. It was based on data generated on a plastic wire frame model at a scale of 1:100, simulating a jacket structure by fixing transmitters and receivers to monitor acoustic functions to detect and locate changes in acoustic response. The conclusions were that AE is applicable to such complex structures. This is achieved through a modified time step method to model and characterise transmissions, hence allowing damage location to be achieved. Locating the transmitters above water line was considered key in obtaining cost effective and realistic data. Further work was planned both using the technique on the existing model and also on a steel structure.

Monitoring with ACFM - Martin Lugg, TSC Ltd, 2002

Martin Lugg outlined how ACFM had originally developed to replace ACPD for underwater crack sizing, and then listed the advantages the technique had for inspection. ACFM is now able to provide many benefits in crack growth monitoring, the main preserve of ACPD. Martin listed the advantages and disadvantages of ACFM and ACPD for monitoring and gave examples of results obtained for both techniques. Finally, two potential future applications for ACFM monitoring were described - monitoring existing cracks underwater during the winter, and remote monitoring of unmanned installations.

Condition Assessment of Ageing Pipelines', Malcolm Wayman , Advanced Engineering Solutions Ltd., 2002

Malcolm outlined the work undertaken by his company, on condition management of ageing pipelines ranging in diameter from 3" to 72". Assessment of the smaller iron pipes involved the checking of critical sections, using external inspection. Samples were often cut out, shot blasted and inspected for defects. Pipeline coatings could be a problem, particularly for the older lines. Corrosion modelling was used to predict life.

For the larger diameter pipelines inspection was for both internal and external corrosion. Stress analysis using FE methods was used to assess critical sections, factors of safety and remaining life. A critical parameter was the remaining wall thickness. The company used a 'bath tub' curve approach, working in the design zone and attempting to predict the end of life section of the curve.

Acoustic emission monitoring of Advanced Composites, Chris Rowland, Pancom, 2003

Chris Rowland described acoustic emission testing and its principles, mainly used for GRP tanks and vessels and more recently CFRP type structures. Examples of testing of aero-engine parts, satellite structures, F1 racing cars and hip joints were shown. Glue line unzipping was a recognised problem and examples of this were also shown.. F1 car components were proof tested for each race. The basis of the 'felicity ratio' (FR) was described; results less than unity indicating permanent damage. Sites of failure and damage were shown linked to values of the FR. Difficulties with composite structures using AE were high attenuation, a noisy material and the need for a history to determine levels of significant damage. Overall AE was a proven technique, which was now being transferred to CFRP type structures with some success.

SI Monitoring in a Marine Environment, David Sanderson, MMI Engineering

David Sanderson outlined the background to flooded member detection and integrity assessment of jacket type structures using this technique. He then described the development of an on-line device for detection of flooded members, in a project about to start with funding from NESTA, HSE and BP. The device consists of a passive detection unit that is inside tubular members of jackets. When it is activated by becoming wet a signal is emitted which can be detected externally. A preliminary feasibility study has shown that signals can be transmitted acoustically to a receiver. Small scale trials have been undertaken on a model of the Thistle jacket which demonstrated that acoustic transmission was feasible. MMI will be providing the technical guidance with UMIST developing the laboratory model and prototypes. In due course field testing of the device would be undertaken and a suitable site still had to be located. One of the objectives of the programme was to select the optimum modes and frequency for effective transmission through the structure, recognising that losses do occur at nodes. The power requirements also have to be established, together with a suitable power source to provide long term energy. In discussion it was noted that the device is primarily for fitting to new structures, and individual devices would need to be coded in some way so that their position could be identified if a signal was received.

Structural monitoring of wave and tidal energy devices – Prof. J.V.Sharp (Cranfield University) 2003

Prof. Sharp outlined the background to the growth of renewable energy in the UK, with a government target of 10% contribution by 2010. Offshore wind was an area of very fast growth whereas wave and tidal were still at the research and demonstration stage, but would be expected to contribute to the UK supply by 2020. Several wave and tidal devices were now at large or close to full scale and he explained the application of sensing systems in these. These included Limpet (Wavegen) , which is an oscillating water column device, based on Islay, already producing power to the local grid. In this case wave pressure was being measured at the front of the collector and up to 4 bars had been recorded from wave slam. The Pelamis wave energy unit, being developed by Ocean Power Delivery Ltd has been tested at several different scales, and was now being developed at full scale for testing at the Orkney test site, early in 2004. This included extensive structural monitoring, with 16 strain gauges at each joint. Data would also be collected from the mooring system. In future machines a fatigue logging system was planned, based on strain gauges at each joint. Two UK tidal stream devices were currently being tested at close to full scale. These included Stingray (Engineering Business Ltd). This was a hydroplane device, with an advanced control system to optimise the power developed on each stroke. It had been deployed in Yell Sound (Shetlands) in September 2002 and generated power. Further testing was underway in 2003. Sensors were being used to measure loads between the hydroplane and the main arm, as well bending loads in the hydroplane structural tubes.

The second large scale tidal stream device is Seaflow (Marine Current Turbines Ltd) which is a 300kW unit installed in the sea , off Lynmouth, in the summer of 1993. It is an underwater turbine installed on a 2m diameter pile. Strain gauges are located in the pile base, on the rotor blades and accelerometers are positioned at the top of the pile and in a rotor tip blade. Dynamic and static loads are being monitored on the pile. Lift and drag forces are being monitored on the rotor blades, as inputs to the assessment of fatigue and the onset of significant cavitation. Data collection is continuing now the turbine is installed. There are plans to develop a larger 1 MW unit, with two turbines on a single pile. Overall structural monitoring is playing a key part in the development of wave and tidal systems.

Structural Instrumentation for the Renewable Energy industry – lessons from offshore oil and gas, A.Dougan, Fugro Structural Monitoring, 2003

Alan Dougan explained how on-line instrumentation had been used to benefit the development of offshore oil and gas structures. Projects such as Shell's Tern and BP's Magnus had provided a much better understanding of the loading on these platforms, enabling more efficient designs to be developed for future structures. Monitoring of damage on offshore structures, such as that on the Ninian Southern platform, gave confidence that operations could continue whilst repairs were being planned and undertaken. He also outlined the background to an ongoing research project relevant to wind farms, which was the development of suction piles. These were an alternative to piled foundations, with significant potential costs savings per foundation. . Fugro was one of the companies involved in the project.

He outlined the large planned growth of the offshore wind industry, in similar offshore environments and proposed that on-line monitoring could also be very beneficial in this industry as well and hopefully the developers would take the opportunity at an early stage. Key issues with offshore wind towers are their dynamic response and strength, whilst for piled foundations their stiffness and possible scour were important factors. The addition of simple structural instrumentation to enable their response to be measured would provide confidence and valuable feedback to enable future structures to be optimized, with potential costs savings.

Wave Dragon, Duncan Dunc, Babcocks, 2003

Duncan Dunc explained the background to the wave dragon wave energy device. It is an 'overtopping' type unit, fitted with a low head turbine, slack moored, with 2 deflector arms. The device originated in the 1980's and with funding becoming available in the 1990's has been tested at model scale. A large scale prototype has been built in Denmark (57m between the arms) which was launched in March 2003. There are a number of project partners, including Aalborg University and Babcocks. It is being tested at a Danish site, which has less extreme conditions than the unit has been designed for. A second site has also been selected for testing with more demanding environmental conditions. In May 2003 the unit was operating and supplied electricity to the Danish grid for a short time. Improvements have since been made to the device. Monitoring systems have been built into the device, both for condition and structural monitoring. A webcam is also available to monitor performance. For structural monitoring strain gauges and accelerometers are being used; an area of particular interest is the joint between the arm and the main body. Work has already started on a larger scale device, aimed at producing power in the MW range.

Permanent Structural Monitoring using Guided Waves for oil Industry structures, Dr.P.Fromme, Dept. of Mechanical Engineering, UCL, 2003

Technical machinery and systems are subject to varying or cyclic service loads and environmental influences, like adverse weather conditions. Such operation conditions can lead to the development of faults during the lifecycle of the structure, e.g., fatigue cracks and severe corrosion damage in offshore oil platforms and oil storage tanks. This damage can lead to the malfunction and ultimately failure of such structures, endangering lives and the environment.

Fast inspection of large areas of plate-like structures can be achieved employing guided ultrasonic waves. Guided ultrasonic wave testing utilizes a lower frequency region than standard ultrasonic testing (UT), usually in the order of several hundred kHz. The excited wave has a mode shape through the thickness of the structure and can propagate over large distances along the structure. Such measurements have been successfully performed on pipelines, where

propagation distances of up to hundreds of meters were realized. This allows the fast and cost-efficient monitoring of difficult-to-access structures from a single sensor location.

For the practical long-term monitoring of structural integrity, a permanently attached guided ultrasonic wave array prototype is being designed and built. The prototype is developed as a remote sensor that runs autonomously, i.e., independent of external energy supply, and transmits data about the condition of the structure wirelessly using a Bluetooth connection. The array consists of a ring of piezoelectric transducer elements for excitation and reception of the guided wave. The properties and coupling of the transducers has been studied and optimized to achieve a sufficient excitation amplitude and good measurement sensitivity. The development of the compact array device for the inspection of large areas with minimum power consumption, necessary for long term operation independent of external power sources, is described. The array operation and data processing schemes are shown and first laboratory measurement results presented.

The sensitivity of the measurement method to typical structural defects is studied experimentally and theoretically. The reflection and mode conversion of the employed guided ultrasonic wave at model defects and structural features is calculated numerically employing a three-dimensional finite element code and verified in laboratory experiments. Corrosion damage often results in large area thickness reduction and is modelled as a circular part-through hole. The scattering and mode conversion of the first antisymmetric Lamb wave mode A_0 at such defects is studied. Good agreement with measurement results in the laboratory is found and the sensitivity of the guided wave measurement to such a kind of defect can be predicted.

Monitoring Using the Stress Probe, Nicholas Stone. TSC Inspection Systems, 2004

TSC Inspection Systems has developed the Stress Probe system for measuring stresses in a number of components including threads, welded components and forgings. In order to measure stress in these components the system takes advantage of magnetic property changes in the material, due to the application of mechanical stress. The system can detect the change in magnetic properties, or more specifically permeability, by the use of multiple induced fields and sensor coils encased in a non-contacting probe. The sign of the change in permeability depends on the relative directions of the stress & applied magnetic field, and on whether the stress is tensile or compressive.

Until recently the use of Stress Probe was limited to those applications where the material was of ferromagnetic type and so therefore, obviously, metallic. With new research it has been possible to develop a sensor patch system whereby a suitable material can be inserted into or on the surface of non-metallic structures. This patch can then convey the representative stress from the component to the StressProbe device in the conventional manner. During tests on the new composite riser technology, being developed by a number of oil and gas companies, this new patch sensor system performed exceptionally well. The implications of the success of this approach means that the StressProbe system is no longer limited to ferromagnetic applications and can be employed on a much larger selection of components in service.

The story of Buchan Alpha, David Linkens, Atkins, 2005

This talk gave an overview of the Buchan Alpha production platform, and the structural issues which have been dealt with, to enable it to operate successfully and safely for the last 25 years.

Originally constructed as a drilling rig, Drillmaster, it was converted by BP to a production platform from 1978-1981. It is now under the ownership of Talisman Energy. During the conversion work, in 1980, the worst offshore disaster of the decade occurred. The Alexander Kielland, a sister platform, broke up in a storm, and overturned within 30 minutes, with the loss of 123 lives.

An urgent and thorough review was carried out by BP, and independently by Sir High Ford. A number of necessary improvements were made, to ensure structural safety. The floating pentagon design of the 1970's has a lack of redundancy in the tubular bracework which connects the five pontoons. To operate safely it is necessary to apply a stringent ongoing inspection regime, to detect any fatigue cracking well before it becomes critical.

Several photographs of the original construction, and transport of various node sub-assemblies, and assembly afloat at Normandy were shown. The range of inspection approaches which are used to manage the integrity were described, including installation of an acoustic monitoring system in recent years.

In this talk it was shown how vigilance and ongoing attention have enabled a critical structure to operate safely, and to continue to do so.

Ageing Offshore Structures, Dr.John Sharp (Cranfield University) and Dr.Alex Stacey (HSE), 2005

Dr.Sharp said that many offshore structures were now beyond their original design lives and that life extension was now being demonstrated. There were a number of hazards to ageing structures which included fatigue, extreme weather, subsidence and accidental damage. He also showed the 'bath tub' curve, with three phases (early life failures, constant failure rate and the wear out phase) and indicated that although an increase in failures would be expected in the wear-out phase due to ageing it was not clear on what timescale this would occur. Life extension was addressed in a number of codes and standards and in particular the draft ISO 19902 standard on fixed steel structures [6] had a new section on assessment of existing structures. Reassessment included condition monitoring, and this was an area where structural monitoring could play a significant part. Structural vibration monitoring and acoustic emission had been used in the past to monitor defects and there was a new development of fatigue sensors which could be useful in life extension assessment. It was concluded that SI monitoring techniques were improving and new developments in vibration monitoring were indicating significant promise. However it was felt that the offshore industry did not yet fully appreciate the benefits of SI monitoring and that SIMoNET could play an important part in publicising these techniques.

Measurement of Marine Fouling, Dr. Martin Lugg, TSC Inspection Systems, 2005

Dr. Lugg explained that TSC Inspection Systems are best known for the ACFM technique for crack detection and sizing. However, the company has also developed a couple of spin-off applications using the same electromagnetic technology. One is the measurement of stress in steel, the other is the measurement of lift-off (the distance between a probe and a metal surface).

ACFM probes are normally designed to minimise the effect of lift-off, but for spin-off applications, probes are instead designed to maximise the effect. This is done by using a field direction perpendicular to the metal surface and using balanced differentially-wound sensor coils.

TSC have produced probes suitable for a variety of applications from pipe ovality measurement, where sub-millimetre accuracy is required up to marine fouling thickness measurement where separation from the metal surface can be up to 300mm.

Marine growth is a problem for offshore structures, especially in warm waters, because of the increased loading on the structure caused by increased drag. Conventional methods of measuring marine growth thickness (encircling tape measure by diver or calipers by ROV) only provide an average thickness. However, marine growth is usually unevenly distributed and local thickness variations influence both the loading and the procedure for removal.

The probe developed by TSC, deployable by diver or ROV, provides spot measurements of marine fouling thickness to an accuracy of about $\pm 10\%$ on any tubular steel member. The system has been used in waters off Australia and Thailand and is expected to be used in similar waters more widely in the future.

Fatigue Damage sensor for welded structures, Peter Tubby, , 2005

Peter Tubby described CrackFirst™ [12] which is a new fatigue damage sensor system specifically designed for welded steel structures. It was developed within a DTI funded collaborative project managed by TWI, involving Caterpillar Peterlee, Micro Circuit Engineering Ltd, Fatigue Monitoring Bureau and UMIST. The CrackFirst™ sensor itself consists of a thin metallic coupon containing a central fatigue crack, which is attached to the structure adjacent to a critical welded joint. Stress cycles in the structure cause extension of the fatigue crack, the magnitude of which is proportional to the cumulative fatigue damage in the target joint. Sensor readings therefore provide an estimate of the rate at which the structure's design life is being consumed, allowing the remaining safe life to be estimated and service inspection intervals to be defined on the basis of usage.

A combination of capacitor discharge welded studs and adhesive bonding is used to attach the sensor to the structure. A tensile pre-stress induced in the coupon during attachment ensures that it responds to both tensile and compressive applied load cycles, in the same way as a welded joint containing tensile residual stress. Sensor electronics with an expected battery life of ten years are used to interrogate the sensor and store results, which can be downloaded to a PC for further analysis. Twelve sequential step changes in the electrical output occur during the life of the sensor.

Fatigue tests on fillet welded plate specimens under constant amplitude loading were conducted to check sensor performance. In all cases the sensors failed before the test joints, the sensor giving a characteristic fatigue endurance similar to the 'Class F' design curve in the UK fatigue design rules for welded steel structures. The sensor therefore matches the design fatigue strength of typical fillet welded details such as stiffeners or other welded attachments commonly used in plate structures.

Variable amplitude loading measured by Caterpillar on an articulated truck undergoing endurance trials in a quarry was also used in the validation. For the particular sequence investigated, test lives of the welded joints were significantly greater than predicted by Miner's rule, due to stress cycle interactions resulting in crack growth retardation. A similar effect was observed in the sensors, although in all cases they still failed conservatively, i.e. before the test welds. These results suggest that the CrackFirst™ sensor will provide a more accurate assessment of damage accumulation than conventional methods based on strain cycle counting and Miner's rule. Further tests under different loading sequences are planned to explore this.

Field trials on earth moving equipment, ships and offshore structures are planned. TWI is in the final stages of development and in bringing the system to market. Companies interested in using the system are invited to contact the author.

Acoustic emission monitoring and its application on structures, Jon Watson, Physical Acoustics, 2005

Jon Watson gave a presentation on the use of Acoustic emission (AE) monitoring on civil and offshore structures. He gave a brief summary on the wide variety of steel structures that Physical Acoustics have worked on which included (amongst other things) steel box girders, welded I beams, orthotropic bridge decks, various bridge bearings and shear studs.

Differences in AE monitoring strategy and use were defined.

Global monitoring – used to identify damage hotspots and also strategically to screen large numbers or large areas of structures for active defects

Semi Global monitoring – used for detailed investigations of structures, commonly those that have already been identified as having potential problems.

Local monitoring – highly accurate active source location used on structural details and areas of concern, commonly applied on welds and bearing.

Tying in with the days earlier presentation by Atkins, Jon summarised Physical Acoustics long term continuous AE monitoring project on the Buchan Alpha platform, shown pictures of the installation and data from the commissioning. The AE system on Buchan Alpha automatically updates a secure website accessible to authorized persons on and offshore with the latest monitoring information. The system has now been running continuously for almost 4 years.

In the final slides of the presentation another example of long term monitoring on Thelwall Viaducts roller bearings was shown. This system monitored the cracking occurring within the rollers and utilised “feature data extraction” which enabled differentiation between noise from bearing movement and that from fracture. Transient signal feature extraction is essential for monitoring on bridge structures and is available on all Physical Acoustics AE systems.

The presentation was concluded with reference to the Highways Agency's Advice note BA 79 “Management of Substandard Structures” saying that AE monitoring met the requirements for monitoring and that the technical application of AE on civil structures would be specifically covered within an extension to the current Highways Agency Advice Note BA 86/04 on Non Destructive Testing, which is expected to be published in 2006.

IRIS-RMS Riser Monitoring System, Donogh Lang, Alan Dougan, MCS/Fugro, 2006

The talk described the IRIS RMS (Riser Monitoring System) which is an advisory system for deepwater drilling risers. It combines measurements of deepwater riser response parameters with a state-of-the-art finite element model to accurately determine the 3D riser response to a wide range of loading scenarios, including transient events, such as vessel drift-off. This is achieved by the incorporation of MCS' industry-leading riser analysis software Flexcom and Freecom in the RMS analysis engine.

A key advantage of the RMS is its ability to improve operational safety. The IRIS RMS achieves this by providing both an accurate record of riser joint usage (including fatigue damage) on a joint-by-joint basis, and a predictive riser response capability. This allows management of the riser components in such a way so as to maximise riser integrity, and has the further advantage of reducing unnecessary drilling down-time.

APPENDIX 4

Review of relevant SI Monitoring Techniques in other Industries

Shipping

Structural monitoring in the form of strain monitoring has been applied in the shipping industry for a number of years now. It has been made primarily for monitoring in-service cracks but can be installed before launch. It is often used in regions of structural problem afterwards, to help diagnose and predict future defects, after remedial works. Larger monitoring systems have been used on oil tankers and bulk carriers, but these are not suitable for smaller vessels where space can be at a premium. This has led to the development of smaller systems in recent years. Accurate measurements of both peak and cyclic strains are required for reliable fatigue and ultimate strength predictions.

Aerospace

Comparative Vacuum Monitoring (CVMTM) is a technique that has been developed for use in the aerospace industry. The technique has been independently tested and is being used by several major aerospace manufacturers and military organisations. The system monitors crack initiation and crack growth and works by positioning a sensor directly in an area that is of concern. The sensor is directly in contact with the material and contains many small cavities, some of which are connected to atmospheric pressure and some to a low vacuum source. The sensors are simply adhered to a prepared surface. If a through-wall crack initiates and passes through an atmospheric cavity into a vacuum cavity, fluid begins to flow which is subsequently measured. The monitoring of the measured flow rate serves as the basis for the system.

No electrical hard wiring is required, however if the system is to be monitored from a centralised location, small pneumatic piping is required. The technique is capable of detecting cracks as small as 1mm but this is strongly dependent on the local geometry. Advantages of this system are that it is small, has a high probability of detection and can be installed in places with relatively poor accessibility. The system is also low-maintenance and requires calibration every 12 months. Disadvantages are that the technique does not cover a large area and is only really relevant to locations known to be at a high risk of fatigue cracking. Additionally, the system needs to be managed by a suitably qualified and experienced person.

Process

Acoustic emission is used increasingly commonly during pressure testing of vessels, both static and railroad transportable (there is an ASME code case 1968-1 which permits this formally).

It is used during the pressure test to highlight areas that need closer inspection by NDT, such as MPI or ultrasonic techniques. These techniques complement each other.

Similar AE technology has been deployed by Transneft, Gazprom, Lukoil, SIBUR, Caprolactam and many other process and Oil and Gas companies, often operating in harsh environments.

Power Generation

Leak before break is an important integrity argument in safety cases for high pressure steam pipework and vessels. Steam leakage is detected by different means (including moisture detection in the building and acoustic detection).

Marine renewables

Wave and tidal are still at the research and demonstration stage, but would be expected to contribute to the UK supply by 2020. Several wave and tidal devices are now tested at large or close-to-full scale. The application of sensing systems to these tests is described below. The Pelamis wave energy unit, being developed by Ocean Power Delivery Ltd has been tested at several different scales. This included extensive structural monitoring, with 16 strain gauges at each joint. Data would also be collected from the mooring system. In future machines a fatigue logging system is planned based on strain gauges at each joint. Two UK tidal stream devices have been tested at close to full scale. These included Stingray (Engineering Business Ltd). This had been deployed in Yell Sound (Shetlands) in September 2002. Further testing was undertaken in 2003. Sensors were being used to measure loads between the hydroplane and the main arm, as well bending loads in the hydroplane structural tubes.

The second large scale tidal stream device is Seaflow (Marine Current Turbines Ltd) which is a 300kW unit installed in the sea, off Lynmouth, in the summer of 1993. It is an underwater turbine installed on a 2m diameter pile. Strain gauges are located in the pile base and on the rotor blades. Accelerometers are positioned at the top of the pile and in a rotor blade tip. Dynamic and static loads are monitored on the pile. Lift and drag forces are also monitored on the rotor blades, and the result used to assess fatigue and the extent of cavitation. Overall structural monitoring is playing a key part in the development of wave and tidal systems.

SimoNet

SIMoNet (structural integrity monitoring network) is a joint venture between industry and government organisations, managed by University College London to facilitate communication between workers, researchers and all those interested in the field of SI monitoring and Non-destructive Testing. It organises regular and well attended seminars together with an active website (www.simonet.org.uk). Over the course of the programme, a number of presentations specifically relevant to the offshore industry have been given. Abstracts of these are provided in Appendix B.

APPENDIX 5

Qualitative Review of Inspection and SI Monitoring Techniques

Table 1. Underwater

Damage Mechanism	Current Inspection Technologies										Assessment of Current Inspection Technologies	Complementary SI Monitoring							Summary of Complementary SI Monitoring Technique	Comments
	Detailed Inspection						Screening Inspection					Inspection / Monitoring Methods for Detecting Related Information								
	Flooded Member Detection "L"	Ultrasonic Wall Thickness (0 degrees) "L"	Conventional NDE-Crack detection "LD" (angled) "LD"	Pulse Echo UT "LD"	Time of Flight Diffraction "LD"	Phased Array UT "LD"	Digital Radiography "LD"	General Visual Inspection	Close Visual Inspection	Leak Range UT		Localised Acoustic Emissions "L,R"	Continuous Flooded Member Detection "R"	Natural Frequency Response Monitoring	Acoustic Fingerprinting	Cathodic Protection	Strain Monitoring "L"	Fatigue Gauge "LR"		
Surface breaking cracks (critical to the integrity of the structure)	-	-	-	-	-	-	-	-	-	-	Over involvement required; Local effective inspection only.	-	-	-	-	-	-	Current method requires sensors fitting of sensors to target locations.		
Through thickness cracks	-	-	-	-	-	-	-	-	-	-	Effective method available using RCV (i.e. FMDCVI); Other techniques require diver involvement; Not applicable to boxes which are automatically depressed to be flooded.	-	-	-	-	-	-	Current method requires sensors fitting of sensors to target locations.		
Severance	-	-	-	-	-	-	-	-	-	-	Effective method available using RCV (i.e. FMDCVI); Other techniques require diver involvement.	-	-	-	-	-	-	Current method requires sensors fitting of sensors to target locations.		
Surface breaking cracks at multiple locations on the jacket (not localised)	-	-	-	-	-	-	-	-	-	-	FMD effective at through thickness stage only.	-	-	-	-	-	-	One potential technique available to detect multiple cracks which are not localised; requires specialist equipment.		
Flaw surface and embedded cracks (critical to the integrity of the structure)	-	-	-	-	-	-	-	-	-	-	Other methods require diver involvement.	-	-	-	-	-	-	Current method requires sensors fitting of sensors to target locations.		
Severe general external corrosion	-	-	-	-	-	-	-	-	-	-	Over involvement required.	-	-	-	-	-	-	Current method requires sensors fitting of sensors to target locations.		
Severe local corrosion	-	-	-	-	-	-	-	-	-	-	Effective method available using RCV (i.e. CVI).	-	-	-	-	-	-	No directly relevant monitoring technique available.		
Severe denting	-	-	-	-	-	-	-	-	-	-	Effective method available using RCV (i.e. CVI).	-	-	-	-	-	-	No directly relevant monitoring technique available.		
Severe bowing	-	-	-	-	-	-	-	-	-	-	Covered by RCV/CVI.	-	-	-	-	-	-	No effective method available.		
Damage to supporting structure e.g. conductor guide frame	-	-	-	-	-	-	-	-	-	-	Effective method available using RCV (i.e. CVI) and remote detection. Can be negative in some RCV.	-	-	-	-	-	-	Specialised method available.		
Ball loss/drop	-	-	-	-	-	-	-	-	-	-	Effective method available using RCV (i.e. GVI/CVI).	-	-	-	-	-	-			
Scour	-	-	-	-	-	-	-	-	-	-	Effective method available using RCV (i.e. GVI/CVI).	-	-	-	-	-	-			
Debris	-	-	-	-	-	-	-	-	-	-	Effective method available using RCV (i.e. GVI/CVI).	-	-	-	-	-	-			
Marine growth	-	-	-	-	-	-	-	-	-	-	Effective method available using RCV (i.e. GVI/CVI).	-	-	-	-	-	-	Cannot screen a whole jacket structure.		

Sensitivity/Effectiveness

highly effective
high effectiveness
medium effectiveness
low effectiveness

Limitations

"L"
Retrospective
Over required
NOTE: Limitations referred to are MRI, ECD, DP and ACFM

Table 2 Splash Zone

Damage Mechanism	Current Inspection Technologies				Assessment of Current Inspection Technologies	Complementary SI Monitoring		Summary of Complementary SI Monitoring Technique		
	Screening Inspection					Natural Frequency Response Monitoring	Acoustic Fingerprinting			
	General Visual Inspection (using binoculars, probably from the cellar deck)	Close Visual Inspection (possibly RAT access) *D	Camera Deployment Frame *L							
Surface breaking cracks (critical to the integrity of the structure)	-	-	low	Only screening techniques available; Cracks may show up in zoomed camera image; Available screening techniques not very effective as small cracks may not be easily visible.				No effective method available.		
	-	low	low	Only screening techniques available; Cracks may show up in zoomed camera image or CVI; Available screening techniques not very effective as small cracks may not be easily visible.				No effective method available.		
Through-thickness cracks	medium	high	high	Effective method available using binoculars (CVI) and/or camera deployment.				medium	medium	Available techniques may detect member severance.
Severance	-	low	low	Only screening techniques available; Cracks may show up in zoomed camera image or CVI; Available screening techniques not very effective as small cracks may not be easily visible.				-	-	No effective method available.
Cracks at multiple locations on the jacket (not localised)	-	-	-	No effective method available.				-	-	No effective method available.
Far-surface and embedded cracks (critical to the integrity of the structure)	-	-	-	Effective technique available using binoculars (CVI) and/or camera deployment.				-	-	No effective method available.
Severe general external corrosion	medium	high	high	Effective technique available using binoculars (CVI) and/or camera deployment.				-	-	No effective method available.
Severe local corrosion	low	high	high	Effective technique available using binoculars (CVI) and/or camera deployment.				-	-	No effective method available.
Severe denting	medium	high	high	Effective technique available using binoculars (CVI) and/or camera deployment.				-	-	No effective method available.
Severe bowing	medium	-	-	Binocular/naked eye GVI method available; This method will not be very effective if obstructions are in the way for example.				-	-	No effective method available.
Damage to supporting steelwork e.g. conductor guide frame	low	medium	-	Effective method available using binoculars (CVI) and/or camera deployment. May require RAT deployment.				-	-	No effective method available.
Bolt loosening	-	medium	-	Binocular/naked eye GVI method available; This technique will not be very effective if obstructions are in the way for example.				-	-	No effective method available.
Debris	medium	high	high	Effective technique available using binoculars (CVI) and/or camera deployment.				-	-	No effective method available.
Marine growth	medium	high	high	Effective technique available using binoculars (CVI) and/or camera deployment.				-	-	No effective method available.

Sensitivity/Effectiveness

highly effective
high
medium effectiveness
low effectiveness

Limitations

*L Localised installation of sensors necessary
Retrospective
*R RAT may be required
*D NDE techniques referred to are MPI, ECD, DP and ACFM
**

Table 3 Topsides

Damage Mechanism	Current Inspection Technologies											Assessment of Current Inspection Technologies	Complementary SI Monitoring				Summary of Complementary SI Monitoring Technique	
	Detailed Inspection					Screening Inspection							Localised Acoustic Emissions - LR	Neural Response Monitoring	Acoustic Fingerprinting	Inspection / Monitoring Methods for Detecting Related Information		
	Ultrasonic Wall Thickness (0 degrees) °L	Conventional NDE** crack detection °L	Pulse Echo UT (angleθ) °L	Time of Flight Diffraction°L	Phased Array UT °L	Digital Radiography °L	General Visual Inspection	Close Visual Inspection	Long Range UT	SLOPEC™	Pulsed Eddy Current Inspection					Strain Monitoring °L		Fatigue Gauge °LR
Surface breaking cracks (critical to the integrity of the structural)	-											Effective technique available; RAT involvement may be required.		-	-			Current method requires fitting of sensors to target locations.
Through-thickness cracks	-											Effective technique available; RAT involvement may be required.		-				Current method requires fitting of sensors to target locations.
Severance	-											Effective technique available; RAT involvement may be required.						Current method requires fitting of sensors to target locations.
Fin surface and embedded cracks (critical to the integrity of the structural)	-											Effective technique available; RAT involvement may be required.		-				Current method requires fitting of sensors to target locations.
Severe general / external corrosion			high									Effective technique available; RAT involvement may be required.		-	-			No directly relevant monitoring technique available.
Severe local corrosion			-	-	-							Effective technique available; RAT involvement may be required.		-	-			No directly relevant monitoring technique available.
Severe denting	-		-	-	-							Effective technique available; RAT involvement may be required.		-	-			No directly relevant monitoring technique available.
Boat loading	-		-	-	-							Effective technique available; RAT involvement may be required.		-				Specialised method available.
Coating breakdown	-		-	-	-							Effective technique available; RAT involvement may be required.		-	-			No effective method available.
Corrosion under PWP	-		-	-	-							RAT involvement may be required; SLOPEC and SLOPEC are relatively new technologies, currently used in some applications.		-	-			No effective method available.

Sensitivity/Effectiveness

high
medium
medium effectiveness
low effectiveness

Limitations

Localised installation of sensors necessary
RAT may be required
°L
°R
**
NDE techniques referred to are MPI, ECD, DP and ACFM

Table 4 Semi-Submersible Hull Structure

Damage Mechanism	Current Inspection Technologies										Assessment of Current Inspection Technologies	Complementary SI Monitoring				Summary of Complementary SI Monitoring Technique
	Detailed Inspection						Screening Inspection					Leak detection	Localised Acoustic Emissions *LR	Inspection / Monitoring Methods for Detecting Related Information		
	Ultrasonic Wall Thickness (0 degrees) *L	Conventional NDE** crack detection *L	Pulse Echo UT (angled) *L	Time of Flight Diffraction *L	Phased Array UT *L	Digital Radiography *L	General Visual Inspection	Close Visual Inspection	Long Range UT	Cathodic Protection				Strain Monitoring *L	Fatigue Gauge *LR	
Surface breaking cracks (critical to the integrity of the structure)	-	high	-	-	-	medium	-	-	low	Internal hull inspection to be performed; Local effective inspection only.	-	high	-	Relevant	Relevant	Current method requires fitting of sensors to target locations.
Through-thickness cracks	-	high	high	high	high	high	-	low	high	Internal hull inspection to be performed; Not applicable to braces which are intentionally designed to be flooded.	high	high	-	Relevant	Relevant	Current method requires fitting of sensors to target locations.
Cracks at multiple locations on the structure (not localised)	-	high	-	-	-	medium	-	-	low	Internal hull inspection to be performed; Local effective inspection only.	-	high	-	Relevant	Relevant	One potential technique available to detect multiple cracks which are not necessarily through-thickness.
Far-surface and embedded cracks (critical to the integrity of the structure)	-	high	high	high	high	medium	medium	medium	high	Internal hull inspection to be performed; ROV involvement possibly required.	-	-	-	Relevant	-	No directly relevant monitoring technique available.
Severe general external corrosion	high	-	-	-	-	high	medium	medium	high	Internal hull inspection to be performed.	-	-	-	Relevant	-	No directly relevant monitoring technique available.
Severe local corrosion	high	-	-	-	-	high	medium	medium	high	Internal hull inspection to be performed; ROV involvement possibly required; Structural surface/components may require cleaning.	-	-	-	-	-	No directly relevant monitoring technique available.
Severe denting	-	-	-	-	-	-	medium	medium	high	Internal hull inspection to be performed; ROV involvement possibly required.	-	-	-	-	-	No effective method available.
Severe bowing	-	-	-	-	-	-	medium	medium	-	Internal hull inspection to be performed; ROV involvement possibly required.	-	-	-	-	-	No effective method available.
Damage to supporting steelwork	-	-	-	-	-	-	medium	medium	high	Internal hull inspection to be performed - may require cleaning.	-	-	-	-	-	No effective method available.
Bolt loosening	-	-	-	-	-	-	-	medium	medium	No effective method available. Can re-tighten, possibly by ROV.	-	-	-	Relevant	-	Specialised method available.
Scour	-	-	-	-	-	-	high	high	high	Internal hull inspection to be performed; ROV involvement possibly required.	-	-	-	-	-	No effective method available.
Debris	-	-	-	-	-	-	high	high	high	Internal hull inspection to be performed; ROV involvement possibly required.	-	-	-	-	-	No effective method available.
Marine growth	-	-	-	-	-	-	high	high	high	Internal hull inspection to be performed; ROV involvement possibly required.	-	-	-	-	-	No effective method available.

Sensitivity/Effectiveness
high
medium
low

Limitations
*L Localised installation of sensors necessary
*R Retrospective
** NDE techniques referred to are MPI, ECD, DP and ACFM

Table 5 Moorings

Damage Mechanism	Current Inspection Technologies			Assessment of Current Inspection Technologies	Complementary SI Monitoring				Summary of Complementary SI Monitoring Technique
	Detailed Inspection	Screening Inspection			Riser and Anchor Chain Monitoring System	Inspection/Monitoring Methods for Detecting Related Information			
		Conventional NDE** crack detection *LD	General Visual Inspection			Close Visual Inspection	Strain Monitoring *L	Fatigue Gauge *LR	
Surface breaking cracks (critical to the integrity of the structure)	high	-	-	Will have to raise anchor chain onto deck to perform CVI or detailed conventional crack detection NDE; May possibly need to take anchor chain on-shore to perform more sensitive NDE.	-	Relevant	Relevant	-	No effective method available.
Through-thickness cracks	high	-	low	Will have to raise anchor chain onto deck to perform CVI or detailed conventional crack detection NDE; May possibly need to take anchor chain on-shore to perform more sensitive NDE.	-	Relevant	Relevant	-	No effective method available.
Cracks at multiple locations on the anchor chains (not localised)	high	medium	high	Effective method available using ROV (i.e. CVI); Will have to raise anchor chain onto deck to perform CVI or detailed conventional crack detection NDE; May possibly need to take anchor chain on-shore to perform more sensitive NDE.	-	-	-	-	No effective method available.
Abrasion	-	low	high	Effective method available using ROV (i.e. CVI).	-	-	-	-	No effective method available.
Severe general external corrosion	-	medium	medium	Effective method available using ROV (i.e. GV/ICV); Will have to raise anchor chain onto deck to perform detailed CVI.	-	-	-	-	No effective method available.
Severe local corrosion	-	medium	high	Effective method available using ROV (i.e. CVI).	-	-	-	-	No effective method available.
Bent chains	-	high	high	Effective method available using ROV (i.e. GV/ICV).	-	-	-	-	No effective method available.
Elongated chains - loss of mooring line tension	-	-	low	Refer to Strain Monitoring and Tension Monitoring columns. Effective method available using load sensors. Can be complemented by relevant SI Monitoring technique.	high	medium	-	medium	Specialised SI Monitoring technique available; Method requires subsea fitting of sensors to target locations.
Bolt loosening	-	-	medium	No effective method available. Can re-tighten, possibly by ROV.	medium	medium	-	-	Specialised method available.
Scour	-	high	high	Effective method available using ROV (i.e. GV/ICV).	-	-	-	-	No effective method available.
Debris	-	high	high	Effective method available using ROV (i.e. GV/ICV).	-	-	-	-	No effective method available.
Marine growth	-	high	high	Effective method available using ROV (i.e. GV/ICV).	-	-	-	-	No effective method available.

Sensitivity/Effectiveness

high
medium
low

highly effective
medium effectiveness
low effectiveness

Limitations

*L Localised installation of sensors necessary
*R Retrospective
*D Will need to bring anchor chain out of water
** NDE techniques referred to are MPI, ECD, DP and ACFM

Appendix 6

Structural Integrity Monitoring of Moorings

Moorings Inspections

Inspection of wire ropes and anchor chains is a specialised area and it is not intended to cover all aspects of mooring inspection and monitoring here. Typically, for in-service monitoring, load sensors are used as tension monitoring systems on risers and anchor chains. Anchor chains may be brought out of the water for visual inspections. For more detailed investigation, i.e. NDE, the anchor chain may need to be taken on-shore. ROV inspections can also be carried out on the anchor chains in-situ. This is inherently error-prone and unreliable particularly if long lengths of anchor chain are to be inspected.

In order to improve quality of in-situ mooring chain inspection, TWI are currently developing and testing an automated vehicle which will be able to detect fatigue cracks, corrosion, bent chains and abrasion. Reference [14] indicates that the vehicle will have an onboard cleaning kit which would be able to clear away marine growth and corrosion scale, to allow NDT to be carried out. This technology is still in the development and testing phase.

SI Monitoring of Moorings

The Riser and Anchor Chain Monitoring System has been developed to provide continuous monitoring of the presence, position and tension of moorings in-situ. Refer to Section 4.10 for overview of technique.

The table below is a summary of SI monitoring techniques which can potentially complement current mooring chain inspections for selected damage mechanisms. Information is taken from Table 5 in Appendix 4.

Complementary SI Monitoring Techniques – Moorings

Damage Mechanism	Assessment of Current Inspection Technologies	Complementary SI Monitoring Technique(s)
Breakage	Effective method available using ROV (i.e. GVI/CVI). May need to raise anchor chain onto deck to perform CVI or detailed conventional crack detection NDE.	RACM
Loss of mooring line tension	Effective method available using load sensors. Can be complemented by relevant SI monitoring technique.	RACM
Bolt loosening	No effective method available. Can re-tighten, possibly by ROV.	RACM

Mooring Line Breakage

ROV inspections for a mooring line breakage would be to locate the breakage point. Inspections may not identify a severed line if the ROV is not targeted at the right place. This method can therefore be unreliable. Additional costs and health and safety risks will have to be considered when bringing the anchor chain onto deck for more detailed CVI.

SI monitoring methods such as RACM may be used to continuously monitor the global position and tension of anchor chains/mooring lines so that severance can be detected as soon as it occurs without the need to raise the anchor chain onto the deck for every scheduled inspection.

Loss of Mooring Line Tension

Strain monitoring and load sensors may be used to provide relevant information on the tension of the mooring lines, and can be useful tools for the inspection of mooring lines.

In addition, SI monitoring techniques such as RACM may be used to continuously monitor mooring line tension. Sensors attached to the mooring lines feed-back positional and tensile loading information.

Structural integrity monitoring

Review and appraisal of current technologies for offshore applications

With the ageing of the North Sea fleet of platforms and semi-submersibles, the importance of maintaining structural integrity offshore is increasingly recognised and structural inspection plays a significant role in demonstrating ongoing integrity and the potential for life extension. Structural integrity (SI) monitoring can complement existing inspection techniques to provide greater confidence in structural integrity or to reduce inspection cost. It has been found that offshore experience of SI monitoring is limited to date and that current systems are for bespoke applications. This report focuses on fixed steel structures, topsides and semi-submersible hulls.

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