Integrity Management and Structural Monitoring Technology: Reduce Risk and Improve Efficiency

Mr. Edmund Jenkins - Pulse Structural Monitoring

Dr. Pei An - Pulse Structural Monitoring

ABSTRACT:

The field of Integrity Management in the oil and gas industry is bigger than it's ever been and is of particular consideration when operating in deepwater and otherwise difficult offshore environments. The consequences of undetected structural deterioration can be catastrophic and it is commonly accepted that proactive Integrity Management plays a vital role in improving safety record, reducing risk and improving economic efficiency of assets.

Integrity Management relies on information collected from the structural asset. Periodic inspection, as part of an Inspection, Maintenance and Repair (IMR) schedule can provide data about the rate of wear and tear of structures at the point of inspection; however, this lacks the continual information between inspections about the loading actually experienced by the structures and their dynamic response. Success in the Integrity management of a structural asset will be a balance between IMR and continual structural monitoring.

The cost and reliability of structural monitoring instrumentation for the offshore industry has been improved so much in the past decade that it has become economical to use data from the monitoring to drive IMR schedules preventing unnecessary expenditure. Since the data is

collected directly from the concerned structures continuously, it can also be used for understanding the structural response and drive future designs with a view to improve safety but at the same time improve design efficiency.

The paper first presents the state of the art of subsea structural monitoring technology – sensors, electronics, communication scheme and data processing. A typical riser motion monitoring project is described to demonstrate the interconnections and interaction between technologies and its benefit for the real world application. The paper finally presents an overview of other structural monitoring architectures for various offshore components as part of the continuous integrity management plan. These components include mooring systems, risers, flexible jumpers, flowlines/pipelines, wellheads, flexjoints, hulls and fixed offshore structures.

BACKGROUND:

Integrity Management of Offshore Structures

For well over a decade, the search for oil and gas has taken drilling and production facilities into deeper and deeper waters. 30 years ago, operations in 1,000ft of water were pushing the limits of current technology. 10 years ago operations in 5-7,000ft of water were considered ground breaking, now production is taking place in 8,000ft. Some of the world's deepest include the Espirito Santo FPSO in the Campos Basin, Brazil moored in 5905ft of water, BP's Thunder Horse PDQ in the Gulf of Mexico at 6050ft, Shell's Perdido Spar in the Gulf of Mexico at 8,000ft and drilling has taken place in 10,000ft..

The challenge of designing facilities for safe operation in these depths is significant; Environmental loads are difficult to predict due to availability of data and mechanical loads are significantly increased particularly regarding the mooring and riser systems [6]. Furthermore, continued safe operation of these facilities for the remainder of the field life (typically 20-25 years) requires validation of the long term and extreme event fatigue modelling and on-going observation to warn of potential failure of components.

In deepwater environments, offshore operations are carried out solely from floating platforms of various types. These comprise;

- MODUs - Drillships & Semisubmersibles (Figure 1 top left);

- FPSOs - Spread and turret moored (Figure 1 top right);
- Production platforms - spar, semisubmersible, mindoc, TLP (Figure 1 bottom).

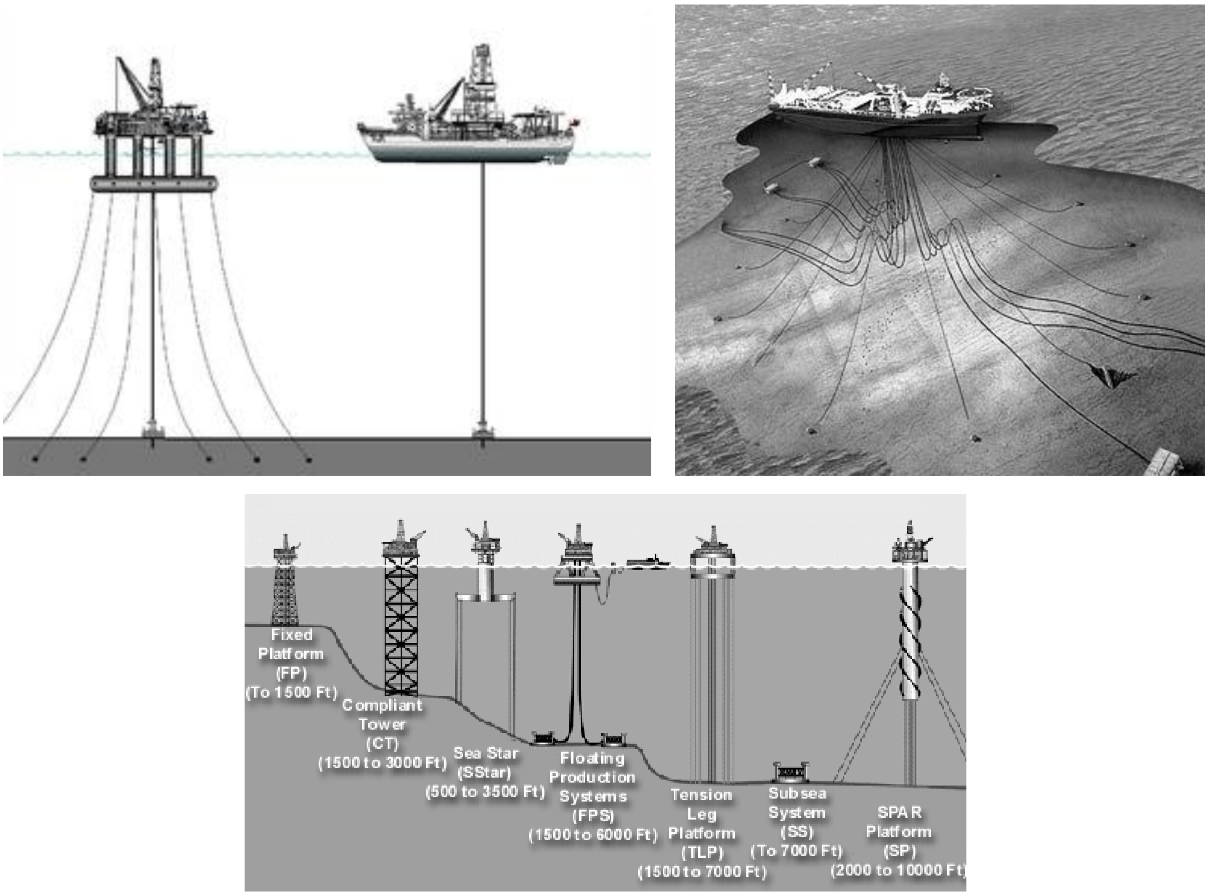

Figure 1 – Types of Deepwater Facility

The critical structural areas for concern that these facilities all have in common are their riser systems and the mooring system, due to the nature of their incredibly dynamic response. It's no wonder that increasing focus has been placed upon the use of integrity management (IM) techniques in the offshore oil & gas industry. And in particular, risk based inspection (RBI) being commonly adopted as an efficient tool for planning inspection & maintenance routines for components and systems. Guidance exists in the form of API-RP-580 [1] which has been in existence for some time, regarding fixed equipment and piping. And DnV-RP-F206 [2] has come about more recently for subsea riser systems. As these documents show, the application of IM techniques are tailored to the wide arena of offshore equipment i.e. fixed units, floating units, risers, subsea flowlines, pipelines, subsea equipment, moorings and so on. Ultimately the use of IM results in definition of a programme of inspection and performance monitoring. A large number of published papers have addressed these areas, in particular with regard to deepwater facilities; the following papers [3], [4] and [5] describe the use of monitoring systems as an integral part of the integrity management plan from the Gulf of Mexico to the South China Sea. The operation of such instrumentation contributes to:

- Verification of in-place performance (including severe events)
- Minimise downtime
- Operation of facilities in a safe, efficient manner
- Maximise capabilities
- Improvements to design of future facilities
- Post-mortem investigations

They also state that such systems need to be in place from the early stages of design, to contribute fully to the process of IM. But this may not always have been considered at such and early stage and there is much interest surrounding retro-fit and non-intrusive types of instruments for these eventualities.

Verification of In-Situ Performance

Oversights in the design, errors in fabrication or installation are all uncertainties which may creep in to the final facility. Full scale field measurements allow validation of original design basis and analysis. These data will allow comparison of the actual and predicted responses, which could be shown to be under or over conservative. Using the example of an FPSO, environmental (wind, wave, current) and vessel response (heave, surge, sway, roll, pitch, yaw) measurements would be all that was required to make an assessment of the global FE model comprising the risers and mooring system. In the case of extreme storm events, the actual field measurements could be used to make an assessment of the extreme metocean data available for the location.

Minimising Downtime

The monitoring of key performance indicators (KPI) can enable timely responses to impending failure situations. KPIs are values which are either directly measured (e.g. production fluid temperature) or calculated from actual measurements (e.g. riser stress joint fatigue damage rate) and subsequently compared with operational and or extreme limits. Should the KPI exceed one or other limit, action is taken in accordance with the pre-ordained integrity management plan (IMP). Typically KPIs are fatigue related and observation of trends over time can yield timely planning for refurbishment or replacement of an ailing component prior to its imminent failure. This in turn avoids being caught off-guard without adequate spares & resources or worse, a catastrophic component failure. Both of which would lead to downtime and potentially lost production. The monitoring system data can also be used to assist with on the spot operational decisions, for example, enabling one to restart operations more quickly after an extreme event or disconnect a drilling riser in the event of high rates of riser fatigue damage.

Maximisation of Capabilities

Through the verification of the original design using real world measurements, areas of over-conservatism could be identified. For example, this could result in the capacity for an FPSO to handle additional topside processing and even extra risers for tying back to new wells. If over conservatism was identified in the fatigue lives of the components, the life of the field could possibly be extended.

Operation of Facilities in a Safe & Efficient Manner

This may be considered the main goal of integrity management. All feedback from the inspection and monitoring systems enables the operations staff to maintain and operate the facility safely and efficiently. The continuous improvement via regular review of the integrity management data will drive frequencies of inspection for critical areas, or physical mitigation. For example where a production riser flexjoint may be experiencing bending moments greater than allowable, this may indicate impending elastomer failure and potential hydrocarbon release. Increased inspection frequency or implementation of video surveillance could be used to provide sufficient warning of failure.

Improvement to Design of Future Facilities

The global system response in addition to the various component level responses can all be used to feed back into future design bases and methodologies. It can help validate design tools and refine safety factors by demonstrating the robustness of the original design. Environmental data, if gathered, can add to the metocean statistics for the region of installation, providing more accurate design data. In addition, this full scale performance data

Post-Mortem Investigation

In the event of structural failure, routinely recorded measurements can greatly enhance investigation of when a failure occurred and what events led to the fact. For example, unusually high fatigue damage could be calculated for a failed top-tensioned riser due to otherwise undetected vortex induced vibrations (VIV). This could indicate compromise of the VIV suppression strakes due to excessive marine growth in combination with the presence of a loop current.

MONITORING SYSTEM SENSORS:

The sensors typically used for capturing structural responses fall into the following broad categories;

1. Motion
2. Load (mainly measured as strain)
3. 2D/3D Position
4. Environmental

Environmental is also listed since its considered key to the evaluation of structural performance. The following tables illustrate examples of situations where given sensors from each category may be used.

Example of Motion Sensor Use	Accelerometers	Angular rate (gyro)	Inclinometer	Draw wire	Acoustic position
Measurement of riser motion response due to vortex induced vibration, vessel motion, drag loading.	●	●			
Measurement of vessel motion due to wind, wave, current, mooring/DP system oscillation.	●	●			●
Tensioner system/riser stroke.				●	
Flexjoint rotation.	●	●	●		
Subsea equipment motion and displacement, e.g. conductor and BOP.	●	●	●		

Subsea buoyancy tank response due to current loading, vessel motion, ballasting.	●	●	●		●
Mooring line tensions, positions, integrity.	●	●	●		●

Table 1 – Motion Sensor Examples

Example of Load Sensor Use	Strain	Load Cell	Ultrasonic
Measurement of riser stress response due to vortex induced vibration, vessel motion, drag loading.	●		
Conductor, BOP, LMRP, riser lower stress joint bending & tension, fatigue.	●		
Riser upper stress joint, pup joint bending & tension, fatigue.	●		
Buoyancy tank upthrust.	●	●	●
Pipelay vessel stinger tension, compression, bending.	●		
Mooring line tensions, integrity.	●	●	
Riser fatigue ‘hot spots’ e.g. SCR touchdown zone.	●		

Table 2 – Load Sensor Examples

Example of Environmental Sensor Use	Wind Velocity	Wave Height	Current Velocity	Hydrostatic Pressure	Draft
Correlation of specific structural responses to environmental data (e.g. occurrence of riser VIV due to a particular current velocity profile).	●	●	●	●	●
Comparison of original met ocean design criteria to actual field measurements (i.e. verification of in-place	●	●	●	●	●

performance).					
Design limits exceedence e.g. extreme vessel motions overstressing riser system.	●	●	●	●	●

Table 3 – Environmental Sensor Examples

Example of Position Sensor Use	Acoustic Xponder	DGPS	Sonar
Vessel offset	●	●	
Mooring line position, integrity	●	●	●
Buoyancy tank position	●		●

Table 4 – Positioning Sensor Examples

MONITORING SYSTEM ARCHITECTURE:

The architecture is nominally based upon how the monitoring systems elements are interconnected (if at all) and if they are interconnected, how communication is achieved. All of the previously mentioned sensors can be integrated into any of the system architectures. There are 4 main categories of system architecture, each trading the ease of access to measurement data against cost (Figure 5);

1. Hardwired;
2. Stand alone;
3. Acoustic;
4. ROV stab.

Hardwired

A hardwired system is most convenient in terms of its real-time data delivery and low maintenance. It is usually permanently installed and uses interconnecting cable to carry power and data to and from the sensor units back to the main topside control unit. Copper and fibre can be used for data and typically RS485 is used for long distance serial data, and in recent years, Ethernet is becoming increasingly common. Subsea cabling is armour braided stock with integrally moulded metal shell subsea connectors or ROV stab connectors depending upon the system Pressure balanced oil filled (PBOF) hoses can also be used for ease of field maintenance and reliability. Sensor modules can be built for retrieval by ROV from suitably designed docking mounts. The main benefit of such a system is the continuous acquisition of data to topside where it may be stored, processed and interpreted as it arrives. This allows real-time decisions to be made. The main inconvenience is the difficulty of installing such a system. Routing hundreds or even thousands of metres of cabling is a disadvantage not only in terms of the task itself, but also the cost of the labour and materials. Figure 2 shows at right an overview of a hardwired riser monitoring system for a production SCR suspended from a spar production platform. This shows the areas of instrumentation employed on the SCR. Some 15 measurement stations are used. 2 subsea measurement units are shown on the left, one in service at the TDZ. Shown at the top in the middle is a curvature sensor which is connected to the measurement station to detect bending, and below that is a typical topside interface unit and display.

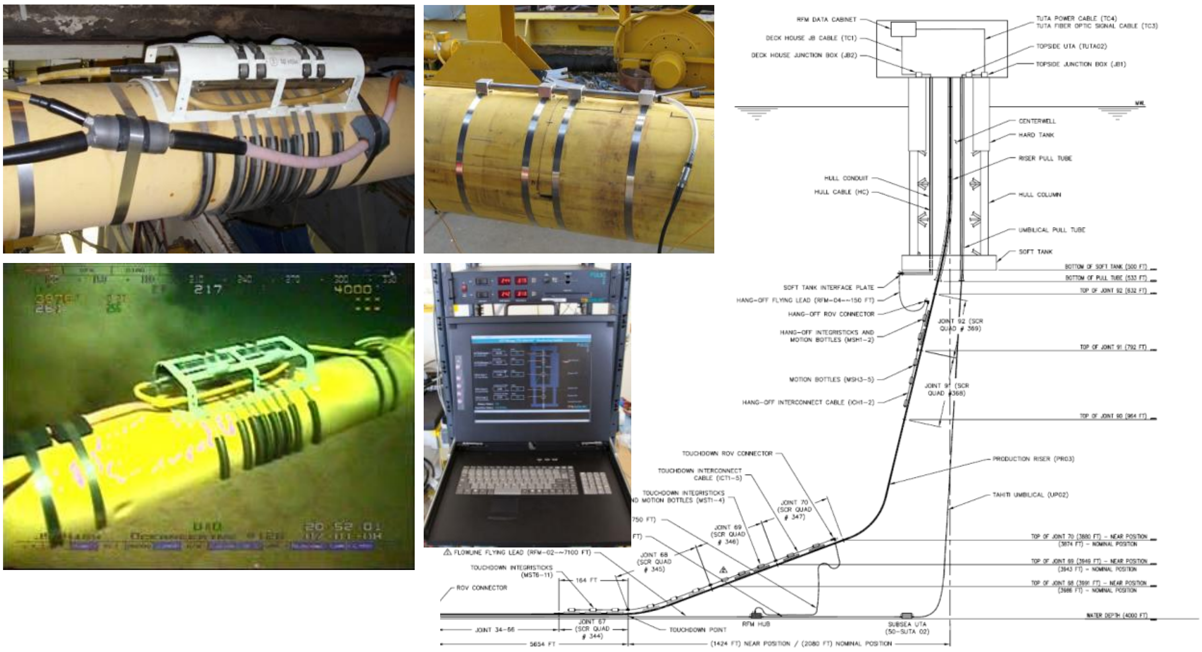

Figure 2 – Hardwired Architecture

Standalone

Standalone systems are extremely convenient in terms of installation and price. However functionality over a hardwired system is restricted. These devices are typically self-contained battery powered data loggers with on-board data storage. A logging schedule is programmed before deployment and set to run either continuously or intermittently to extend memory and battery life. Once deployed subsea, the device cannot be reprogrammed and data cannot be downloaded unless the unit is retrieved. Periodic retrieval is therefore a necessity, since either the battery or the memory will expire before too long. However, there are no cables, interconnections or expensive connectors and the topside equipment comprises a piece of interface software which can be used for programming and downloading the device. The logger can be deployed and retrieved by ROV if required and brought back to the surface for downloading and refurbishment. The data from such a system is not available instantaneously as with the hardwired system, but the convenience and price make it an easy retrofittable system in situations where real-time feedback is not required. Figure 3 shows at left a logger installed on a drilling riser by hand, in the centre an ROV retrievable logger on a drilling riser; at top right a magnetically clamped logger on an LMRP and at bottom right an ROV retrievable logger on a top tensioned riser.

Figure 3 – Standalone Architecture

Acoustic

Monitoring systems using an acoustic communication system represent a halfway-house between fully hardwired and fully standalone. Functionally speaking the acoustic data logger is reasonably similar to a standalone data logger, with the addition of an acoustic modem and transducer for communication through the water column to the surface. The devices are battery powered and contain on-board data storage. But they are capable of being reprogrammed and downloaded without retrieval to the surface. A temporary dunking acoustic modem can be lowered into the water from a support vessel or platform to communicate with several subsea data loggers. Pseudo real-time modes of operation are also possible where the device periodically responds to a permanent surface positioned acoustic modem. They can be ROV retrieved for battery replacement and refurbishment, intervals for which would depend upon the rates of communication used during normal operation. The transmission and reception of the acoustic signal is a power hungry activity and if communication is short and infrequent, the battery life can be greatly extended. The downside is that acoustic communications are interfered with by a few factors, the most crucial being the operation of DP thrusters. The thruster noise interferes with the modem signal often rendering transmission impossible. Figure 4 shows at top left an acoustic receiving modem, at bottom left a close-up of an acoustic mooring line data logger and on the right shows a wider view comprising 3 off mooring line data loggers in-situ beneath a turret moored FPSO.

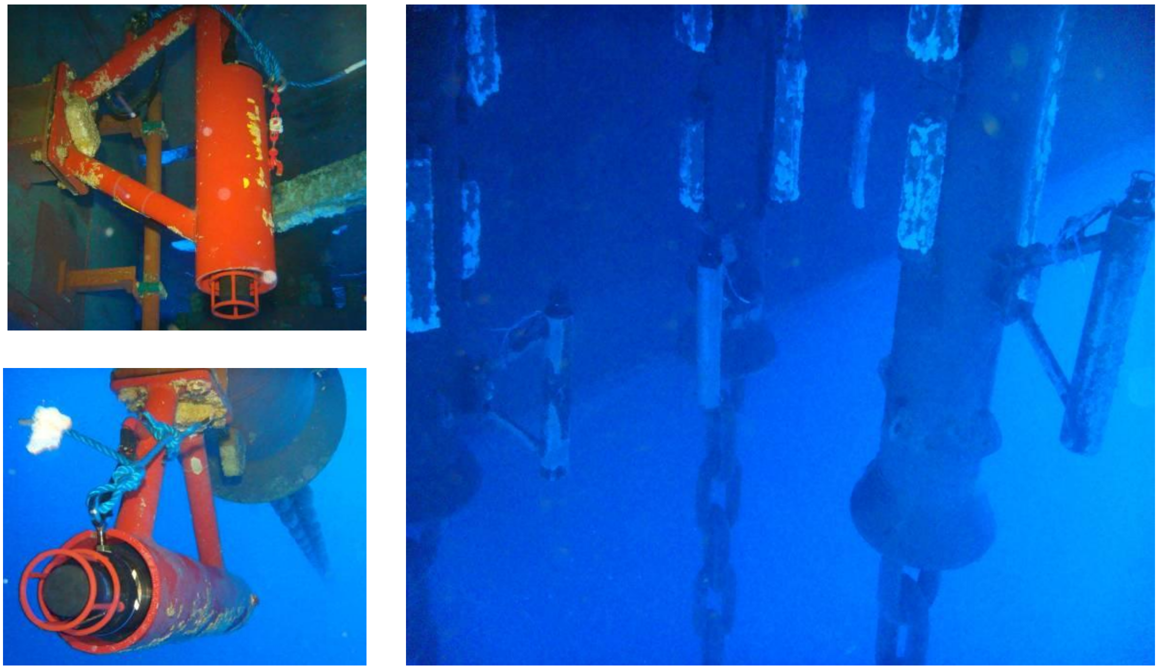

Figure 4 – Acoustic Architecture

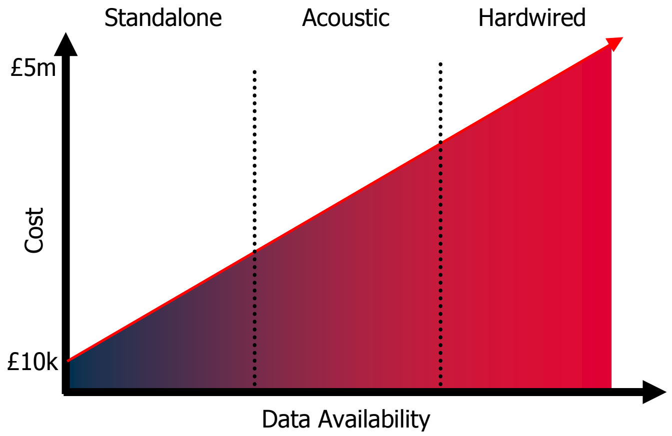

Figure 5 –Comparison of Monitoring System Architectures: Cost vs. Data Availability

ROV Stab

With the advent of affordable and more readily available inspection class ROVs, programming, downloading and even recharging the loggers is possible via the ROV umbilical. The logger unit is equipped with and ROV stab receptacle which provides power and data connections. The ROV is fitted with an ROV stab plug which is linked via the ROVs own umbilical to a topside interface unit and computer. Once the stab connection is made, the logger can be downloaded and reprogrammed as if it were a normal standalone logger on-deck. In addition, the use of rechargeable batteries may allow the ROV to recharge the logger whilst it performs a surveillance duty. It may be possible for such logger hardware to remain in-situ indefinitely with regular visits from a passing ROV. It should be noted that this system requires an ROV as an integral part of its operation. Therefore it can only be considered a complete system by costing in such a facility. This makes it a special case in terms of Figure 5 above, and so it is not shown.

Example of Monitoring System Use	Hardwired	Standalone	Acoustic	ROV Stab
Real time monitoring of KPIs for newly installed production platform and steel catenary production/export risers e.g.: UFJ bending and tension, TDZ bending, riser accelerations.	●			

Real time monitoring of top tensioned riser response for newly installed development platform to determine effectiveness of VIV suppression system over field life e.g. riser accelerations and angular rates, bending at critical locations.	●			
Monitoring of VIV and platform induced motion at BOP to determine potential conductor problems, e.g. riser accelerations, angular rates & inclinations.		●		
Pseudo real-time monitoring of mooring system tension & integrity in turret moored FPSO, e.g. individual mooring line accelerations & inclinations.			●	
Pseudo real-time monitoring of drilling riser stress joint inclination in 6000ft water depth.			●	
Pipeline free span VIV, e.g. pipeline accelerations and angular rates.		●		●
High frequency vibrations in pipeline valve equipment due to slugging, valves opening/closing. E.g. component accelerations.				●

Table 5 –System Architecture Examples

DATA PROCESSING AND DATA MANAGEMENT

Before the measurement data can be evaluated some pre-processing normally takes place. The raw data is converted to engineering units which in turn can be distilled into relevant statistics including extreme values, frequency spectra and fatigue histograms. The algorithms for processing can equally be applied to real-time data from hardwired devices or downloaded data from standalone devices. The final format of the data is dictated by the Integrity Management Plan and the key performance indicators which are to be measured. In fact, the underlying monitoring system should be deemed secondary only to the delivery and presentation of this data. The format must be delivered in a comprehensible and timely manner to the relevant personnel, again as described by the IM plan (Figure 6 below).

The management of the data is therefore also important to consider as this affects it’s accessibility by relevant parties. With ship-to-shore satellite communications and readily available Ethernet based networking on offshore facilities, it is possible to heavily integrate hardwired and acoustic systems via these networks to permit rapid access to the data. OPC, Modbus and various other industry standard interfaces can be utilised for transfer of information to relevant systems. It also permits on-site and shore based backup of the data to nominated servers. Exceedence of pre-programmed thresholds can be used to automatically notify personnel or trigger alarms independently or as part of an integrated vessel-wide notification system.

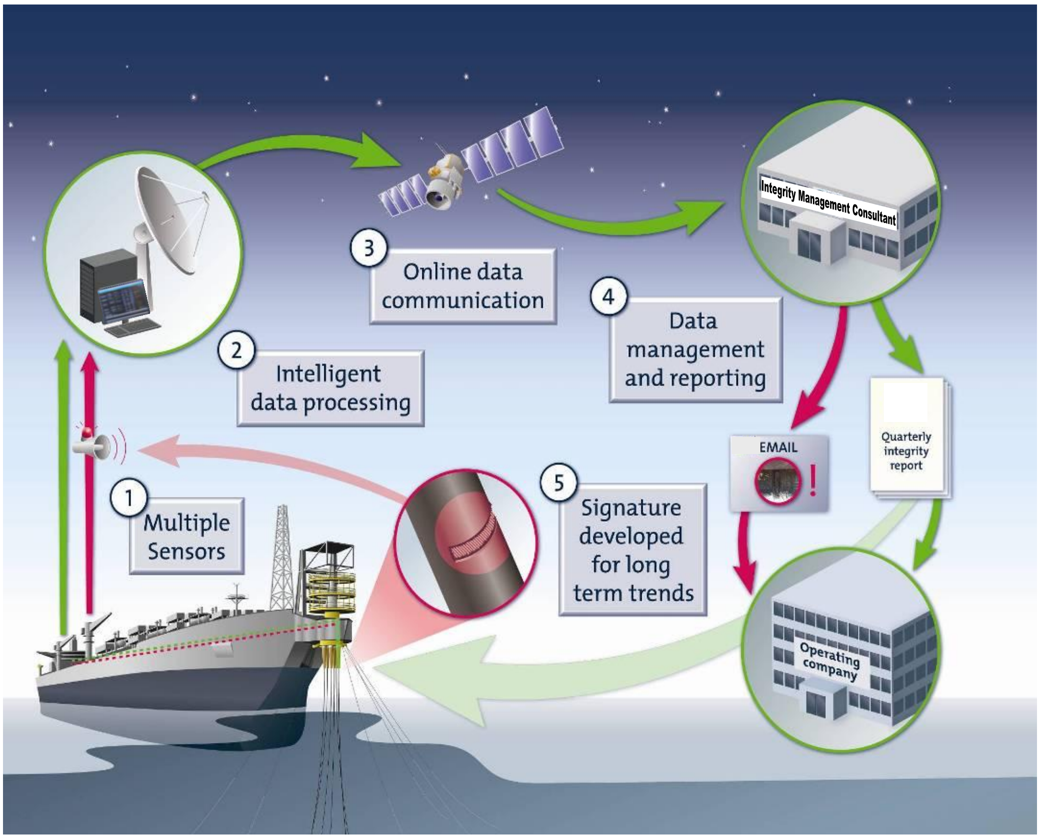

Figure 6 – Monitoring System Data Flow

CASE STUDY: TOP TENSIONED RISER MOTION MONITORING SYSTEM:

An online motion monitoring system is described. The objective of the system is to measure fatigue damage accumulation in the upper section of a top tensioned production riser connected to a spar production platform. VIV in this region is expected to be significant.

Sensors

3 sets of acceleration and angular rate sensors are chosen to monitor riser motion and a pair of curvature sensors are chosen to detect bending at the pull tube location. All measurements can be fed into a global fatigue model allowing calculation of fatigue damage rate.

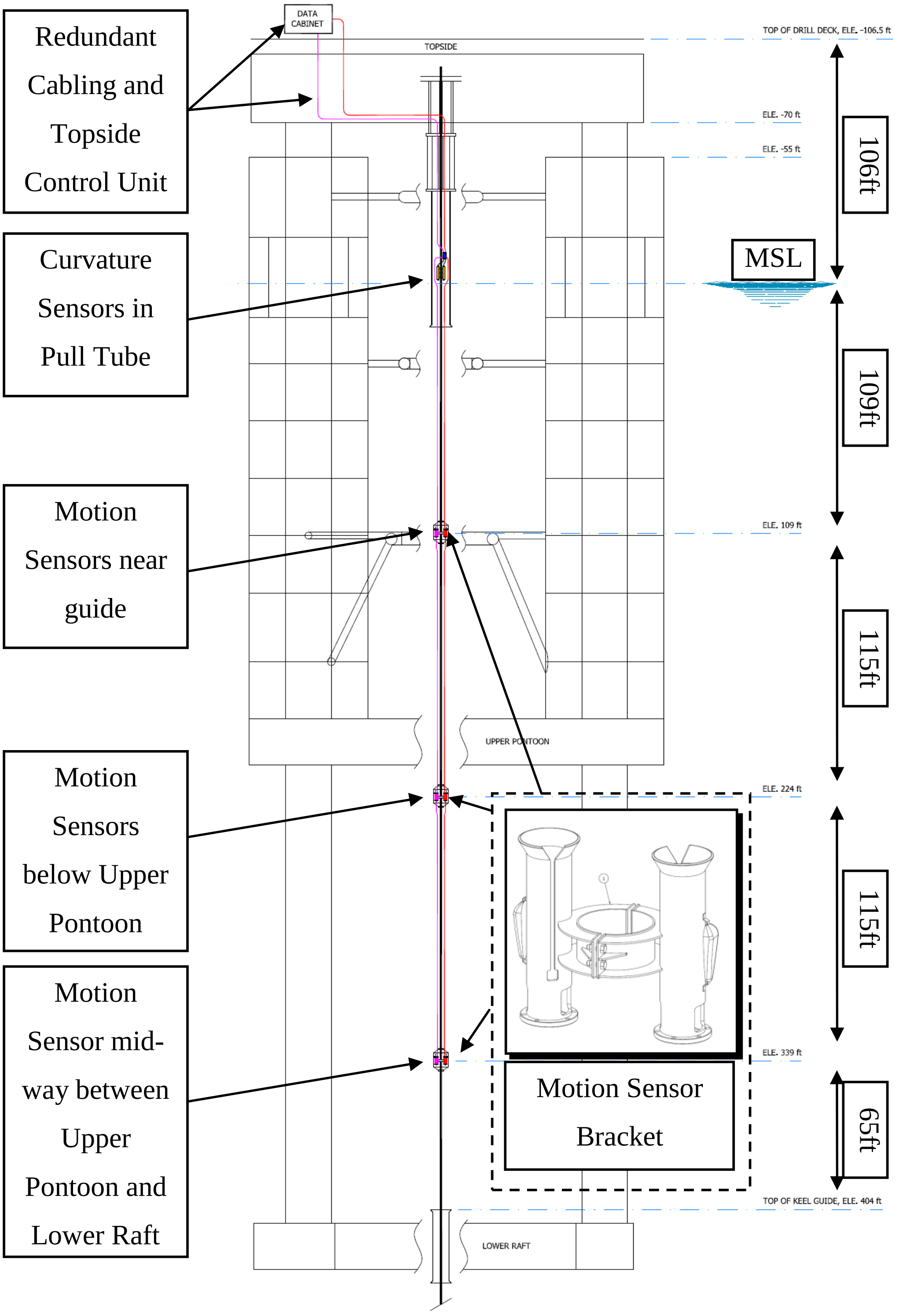

Figure 7 – Instrumented Upper Section of Top Tensioned Riser within Spar Super Structure. Dual Motion Sensor Bracket shown inset.

Architecture

The system is hardwired and uses a pair of identical cables for redundant operation should damage to one cable occur. The subsea sensor units are positioned at 4 locations along the upper section of the riser as shown in Figure 7 below. At each of these locations one of the 3 off motion sensor modules is located in a bracket shown inset in Figure 7. The bracket allows the redundant cable to have a redundant sensor receptacle, should the primary receptacle and or cable become inoperable. In this eventuality, the sensor module can be removed by ROV and replaced in the adjacent receptacle. The pair of curvature sensors are redundant because of their location, once installed they will not be accessible. The system also comprises a battery back-up system to ensure that during hurricane events, the data can continue to be recorded locally for up to 8 days. This ensures capture of critical structural response events.

Data Processing and Data Management

The topside controller manages the operation of the subsea measurement units and acquired time stamped readings from all measurement channels at 10Hz. The raw data is stored on redundant hard disks and the unit is also connected to Ethernet on-board the vessel which accommodates data back up and access to the equipment from on-shore. In this system, data is not processed on board, but instead sent back on-shore for final post processing and analysis. The continuous stream of data is fed back to experts and analysts who will interpret the data and make decisions according to the integrity management plan, based on the accumulated fatigue damage and damage accumulation rate.

OTHER MONITORING SCENARIOS:

Some other areas of deepwater facility monitoring have already been alluded to in the previous sections. Common areas of monitoring for integrity are listed below;

Mooring System

Attention to mooring system integrity has become the focus of attention of the marine engineering community in the last few years. One particular driver for this change is the recent discovery of mooring lines which have been lost without any indication. Usual mooring survey intervals are months or even years apart and so the condition may exist for some time before detection. As a result, Norwegian vessels are now required to be built with mooring monitoring systems. Such systems may measure tension directly, but there is a danger that even in a broken line, large tensions can still be registered at the chain-stoppers.

Inclination of the line itself can be used alone or in combination with tension to provide indication of integrity and line tension. Sophisticated analysis and computation is necessary for inclination alone, but this has been achieved. A typical system can be battery powered with acoustic communication which greatly simplifies installation and improves reliability.

Risers – SCR, TTR, Drilling

Riser fatigue damage accumulation is topmost in the list of KPIs for most types of riser. Fatigue can be introduced by Vessel induced motion and VIV due to subsurface currents. Global fatigue measurement can be achieved via standalone equipment, as this is most convenient to install and remove, in combination with sophisticated post-processing. In some cases hot spots are identified such as TCZ and Upper flex or stress joints in SCRs. In these cases or where continuous data are critical an online system may be more appropriate. In either case, accelerometers and angular rate sensors can be used for measurement of riser mode shapes as part of the fatigue post-processing. And curvature or strain sensors can be used in the critical locations for actual bending stresses.

Flexible Jumpers

Tension, strain, motion and acoustic noise are used to assess flexible jumper fatigue. Data is accumulated over time to provide damage, totalled from an initial baseline. These four parameters are measured by strain/displacement sensors either clamped on the jumper exterior or in the case of fibre optic strain measurement sensors, woven into the structure of the jumper. Motion is given by angular rate sensors and acoustic noise measured by microphone both of which give indications of internal wire fatigue.

Flowlines & Pipelines

A wide variety of parameters can be assessed for example;

- Internal fluid temperature and pressure, corrosion
- Bending and axial loads due to expansion and contraction
- VIV of pipeline free spans

Locally installed sensor equipment can be interfaced to topside systems via existing subsea equipment control umbilicals or via through depth acoustic transmission via dedicated modems or by ‘piggy backing’ data via existing positioning network transponders. Temperature and pressure can be monitored intrusively using flange mounted instruments or non-intrusively using strain based methods. Also a variety of corrosion monitoring equipment exists (e.g. iCorr FSM spool) which can be hardwired or uses a local ROV retrievable logger & battery pod.

Wellheads

Typically displacement and vibrations are of interest and so inclinometers and accelerometers can be employed to capture this information. Standalone loggers can be quickly deployed to test viability of speculations. Permanent systems are rarely required.

Flexjoints

Bending and rotation of the flexjoint extension can be monitored using strain based methods and inclinometers mounted above and below the joints centre of rotation. This type of system commonly feeds back in real time to displays on board the vessel and data is recorded for later assessment.

Hulls

Monitoring of FPSO and tanker hulls can provide information about fatigue and global structural response to heavy seas. Typically measurements will be recorded and displayed in real-time. Strain and displacement sensors adequately positioned are suitable for this task.

CONCLUSIONS:

Deepwater structural monitoring systems are becoming cheaper, more robust and more reliable. The cost of employing such systems when compared with the cost of potential down-time makes them a relatively inexpensive option to safeguard operations and improve future design methodology.

The benefits can be summarised as follows;

- Full-scale field response data allows assessment of conservatism in the design and decisions can be made about the efficient future operation of the asset. This feeds back into future design work improving efficiency of new designs.

- The monitoring data is a vital input into the risk based inspection process of asset integrity management. This drives efficient and timely inspection and maintenance schedules safeguarding livelihood and environment and ultimately saving money.
- Should failures occur, data shall be available to track cause and effect, aiding post-mortem investigation and leading more quickly to the root cause.

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ABBREVIATIONS:

API	American Petroleum Institute
BOP	Blowout Preventer
DNV	Det Norske Veritas – Norwegian Standards Institute
DP	Dynamic Positioning
FE	Finite Element
FPSO	Floating Production, Storage and Offloading vessel
GoM	Gulf of Mexico
IM	Integrity Management
IMP	Integrity Management Plan
IMR	Inspection, Maintenance and Repair
KPI	Key Performance Indicator
LMRP	Lower Marine Riser Package
MODBUS	Standard protocol for industrial data transmission and control.

MODU	Mobile Offshore Drilling Unit
MSL	Mean Sea Level
OPC	Open Process Control – Software architecture for interfacing with process plant and instrumentation
PBOF	Pressure Balanced Oil Filled
PDQ	Production, Drilling and Quarters platform
RBI	Risk Based Inspection
ROV	Remotely Operated Vehicle
RS485	Interface standard for digital serial data transmission
SCR	Steel Catenary Riser
TDZ	Touchdown Zone
TLP	Tension Leg Platform
TTR	Top Tensioned Riser
VIV	Vortex Induced Vibration