Proceedings of the ASME 2010 29th International Conference on Ocean, Offshore and Arctic Engineering
OMAE2010
June 6-11, 2010, Shanghai, China

OMAE2010-20870

MID-WATER FLOWLINE INTEGRITY MONITORING STRATEGY

Tze King Lim
2H Offshore Engineering Sdn. Bhd.
Kuala Lumpur, Malaysia

Shreenaath Natarajan
2H Offshore Engineering Sdn. Bhd.
Kuala Lumpur, Malaysia

Pei An
2H Offshore Engineering Ltd.
Woking, Surrey, United Kingdom

ABSTRACT

Mid-water flowlines are a more efficient way of product transfer between floating facilities in deepwater, with flow assurance benefits compared to traditional risers and seabed flowlines. However, the design process for mid-water flowlines is complex as these flowlines are subjected to both environment and vessel loading. During the operational phase, changes in vessel offsets, fluid composition or uncertainties in environmental data and vessel motion characteristics may lead to increased loads and escalated risk of failure.

Various mid-water flowline configurations have been considered and the design issues such as strength and fatigue are discussed for each configuration. This paper also outlines an integrity monitoring strategy for mid-water flowlines to track system performance and manage the risk. A case study of such a monitoring system deployed on a mid-water flowline is also presented.

This paper also discusses the methodology through which certain Key Performance Indicators (KPIs) are obtained to effectively manage the inspection intervals, and enable pre-cognition to trigger repair or remedial measures. The benefits of using a combined approach of monitoring and inspection to ensure integrity, improve operational efficiency, and develop cost-effective inspection regimes for mid-water flowlines are also presented.

INTRODUCTION

Deepwater field developments often encounter challenging reservoir chemistry that includes wax and hydrates which requires the processing of the crude prior to exporting the fluid. The processing equipment imposes severe limitations on the deck space requirement on the host platform. Employing a separate facility for processing, storage and fluid export can offer significant cost benefits. Traditionally the fluid transfer systems are achieved through flexible hoses attached between the production and processing facilities. However in deepwater developments, extrapolating the use of such flexible hose connections may increase the dynamic loading on the flowlines and the at the vessel interfaces. Also, due to the increased length of the transfer lines, the overall cost from the fabrication and installation of flowlines as well as the flow assurance issues are magnified. Therefore, a careful assessment of the structural response, fabrication and installation strategy, and the associated risks during the operational phase for each configuration is required. The mid-water transfer lines considered in this assessment include an all steel, an all flexible, and a hybrid steel and flexible flowline configurations.

The mid-water flowlines are subjected to complex loading due to the combination of vessel motions at either ends, as well as hydrodynamic loads due to wave and current loading. Such mid-water flowlines are custom-designed for specific host vessels and environment loading. Therefore, any changes in the operating conditions such as mooring line failures, changes in production fluid composition during the field life, or inherent uncertainties in the site-specific environmental data can introduce additional risk of unanticipated loading on the mid-water flowline and hence increase the risk of failure.

The key design drivers for mid-water flowlines are related to the structural strength and fatigue limits. The structural strength and fatigue can be monitored using multiple motion sensors, strain gauge-based devices, or a combination of both. For the flexible flowline option, typically the collapse pressure ratings will also define the system limits, and a pressure gauge can be utilized to monitor the flexible pipe collapse limits. Similarly, the temperature gradient through the water depth can cause flow assurance issues, and therefore mid-water flowline depth excursion will need to be monitored as well.

A case study of such a monitoring system deployed on a bundled mid-water flowline is discussed. This system is based on ROV-installable accelerometers and depth sensors. An in-depth understanding of the system response is required to determine the placement of the sensors. A sensor placement strategy is outlined to maximize the data recorded and enable the response away from the discrete monitored locations to be extrapolated is outlined.

Monitoring data can be used to generate Key Performance Indicators (KPIs) that are used to effectively track the performance of the flowlines. The findings from the monitoring program will allow operators to fine-tune inspection intervals and execute pre-emptive repair or remedial measures.

MID-WATER FLOWLINE DESIGN

Design Features

Typical mid-water flowline configurations considered are shown in Figure 1. A simple catenary shape configuration is considered for short distances between production and processing facility, and both steel and flexible flowlines are utilized, [1]. The flexible flowline in simple catenary configuration are limited by the flowline diameters and collapse pressure rating. Larger diameter or lengths impart larger horizontal and vertical loads on to the end terminations due to the increased flowline weights. These may overstress the connections and/or the flowline itself. The vessel interface loading increases when the host vessel offsets away from each other. On the other hand, the maximum sagbend depth increases when the vessel offsets towards each other thus increasing the susceptibility to flow assurance issues and exceeding collapse pressure limits.

In order to overcome these limitations, pliant or lazy-wave configurations, such as [2], are proposed where buoyancy modules are fitted along the middle section of the flowlines. These reduce the weight of the flowlines that need to be supported by the vessels and the sag bends are located in shallower water. However, the added buoyancy modules will see increased hydrodynamic loading from currents. Also, the buoyancy modules results in hogging of the middle section of the flowline, increasing the susceptibility to increased wave loading. In the event where the host vessels offset towards each other or if there is a reduction in internal fluid density, the middle flowline section can reach the surface thus creating a potential hazard for vessels. The stresses along the flowline section adjacent to the buoyancy modules may also exceed the limits during installation of these buoyancy sections.

In another hybrid configuration, multiple steel flowlines are bundled around a central buoyant steel carrier pipe, [3]. The carrier pipe provides structural support and buoyancy to the bundled flowlines. Flexible jumpers are used a conduit between the bundled flowlines and the host vessels. The entire configuration is tied up with the host vessels using tether chains. The vessel motions are partially decoupled from the bundle response due to the presence of flexible jumpers and hence the vessel interface loads are lower than the other configurations. Despite the improved motion characteristics, the large diameter of the carrier pipe and its proximity to the wave and high current region near the surface makes it susceptible to over-stressing during extreme event loading conditions and increased fatigue loading along the entire bundle. The hybrid bundles are also typically fabricated onshore and then towed to site, which is another source of significant fatigue accumulation, [4].

The high current regions tend to be located near the surface in almost all known regions where deepwater developments are carried out. All of the mid-water flowline configurations are susceptible to current loading and the resulting vortex-induced vibrations (VIV). Therefore, the design process for mid-water flowlines often require significant amounts of finite element (FE) and computational fluid dynamics (CFD) analyses to ensure that the fatigue and strength performance of the design is adequate. All of the mid-water flowline configurations are relatively new with little or no track record. Therefore, significant engineering efforts are required in terms of design qualification and testing.

Integrity Challenges

With the increasing number of deepwater developments in un-chartered territories, the environmental data assumed during the design process may contain inherent uncertainties. Also, the design methodologies involve simplification of the hydrodynamics and fluid/structure interactions.

In addition, the mid-water flowline is custom designed for the specific host vessel motion characteristics and environmental loading anticipated. During the service life of the system, however, changes can occur in operational conditions such as mooring line damage during an extreme event increasing the vessel excursion, changes in production fluid composition increasing the susceptibility to internal corrosion, and changes in fatigue characteristics. Such changes may accelerate some of the failure mechanisms.

Additional challenges that all deepwater developments face are material selection, weld qualification, detailed testing and qualification for new products and technology. Another key challenge is the potential for lapses in quality control while executing fast-tracked project developments on tight schedules.

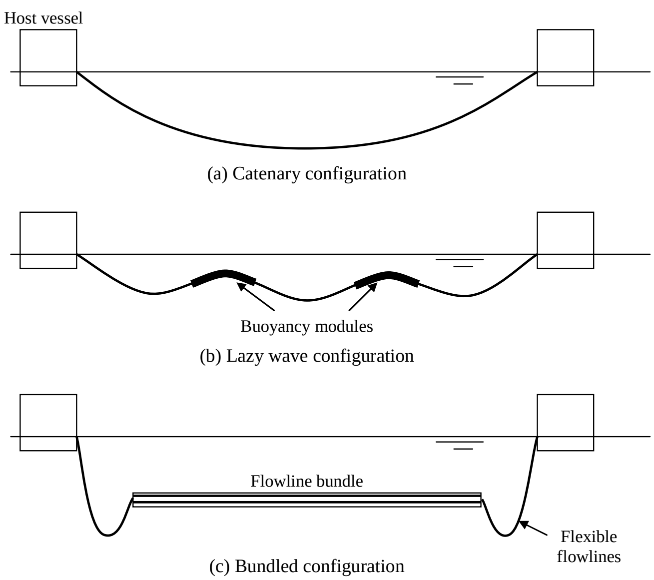

Figure 1 – Mid-Water Flowline Configurations

INTEGRITY MONITORING STRATEGY

An integrity monitoring strategy for mid-water flowlines is proposed to address the design and integrity challenges discussed above, and manage the risks. The strategy is effectively based on a combination of monitoring and inspection methods similar to that utilized for other subsea assets, [5]. Monitoring data can assist in tracking the performance throughout the service life compared to snapshots in time captured by inspection. Also, the monitoring data can assist in interpretation of component performance that may be difficult to inspect. On the other hand, the system will need to be inspected at regular intervals depending on the component design and associated risks. The inspections can capture visually any obvious deviations from the design, such as external anode degradation, excessive marine growth, impact damages, and external coating degradation.

The dynamic mid-water flowlines are affected by vessel motion, environment loading conditions, and internal fluid composition. In order to capture the system response, the monitoring system is categorized in to two: condition monitoring and structural monitoring, [6]. The condition monitoring captures the essential parameters that drive the system global response while the specific component response is addressed through structural response monitoring devices. The condition monitoring is achieved through wave radars, Acoustic Doppler Current Profilers (ADCPs), pressure and temperature sensors, and vessel offset monitoring devices, while structural monitoring is achieved through the usage of motion and/or strain monitoring devices.

The monitoring data should be collected in sufficient resolution such that the extreme storm events and regular seastates causing structural fatigue are captured. The data can be collected on a real-time basis through hardwired monitoring equipments or using stand-alone equipments collecting the data in multiple campaigns throughout the service life. Typically, a combination of both hardwired and standalone equipments are used to provide a cost-effective monitoring solution. The on-board equipment for environment and vessel motion monitoring can be hardwired, while subsea equipment providing structural response can be programmed to record intermittently with durations suitable to capture the extreme event peaks and long-term fatigue loading.

An additional benefit of performance monitoring is that the monitoring data collected can be used for benchmarking finite element (FE) analysis predictions. Such calibration exercises can help fine tune the FE model predictions, [7], and enable forecasting the remainder life of the system.

Condition Monitoring

Environmental loading

Environmental loading have a direct effect on the mid-water flowline response and also an indirect effect through the associated vessel motions. The wave, through-depth current, and wind loading should be monitored. Both surface and through-depth current loads can be monitored using ADCPs. The mid-water flowlines with longer spans may require forward looking ADCPs to capture variations in the current loading along the length of the flowlines. Wave heights can be monitored using wave radars mounted on a host vessel which measure the distance between the instrument location and the top of the wave surface. Subsequent processing of this air gap data can yield the wave height and period. The wave height measurements should be corrected to account for vessel motions.

The wind loading on the vessel superstructure results in the slow drift motion effects. Wind speed and direction can be measured using mechanical propeller type anemometers positioned at a location on the facility topsides away from any appurtenances that can shield or magnify the wind speeds.

Vessel motion

Both the static vessel offsets and dynamic wave induced vessel motions are relevant to mid-water flowline response. The static vessel offsets are captured using Differential Global Positioning System (DGPS). The dynamic vessel motions can be monitored using a package of accelerometers, gyroscopes and inclinometers located on the host vessels.

Internal Fluids

The internal fluid pressure, temperature and flow rates should be monitored at both the vessel ends. Elastomer materials such as any bend stiffeners or flexjoints in the mid-water flowlines are sensitive to internal fluid temperature and pressure. Similarly, the flow rates can be used to identify fluid blockage effects. In the event that chemical injection is required for wax or hydrate inhibition, inhibitor injection rates should be monitored. Depending on the product characteristics, regular fluid sampling may be required to monitor corrosivity in the produced fluids. The sand erosion probes and corrosion coupons may also be implemented.

Structural Response Monitoring

Flowline response

The flowline structural response is captured using motion, strain or curvature focussed along the fatigue critical locations, [8]. Such instrumentation can be either mounted to the flowlines prior to installation or retrofitted using divers or ROVs once installed. Multiple motion, inclination and strain monitoring devices can be distributed at discrete locations of the flowline. The placement of such instruments depends on the data interpretation scheme. The motion/strain sensor placement methodology for global response interpretation is discussed in detail in [9]. Additionally, pressure gauges can be used to track the vertical excursions of the sag bends.

Such instrumentation can be hard-wired with the data and power for the instruments relayed through a dedicated umbilical attached to the flowline. Alternatively an ROV installable off-line monitoring solution can also be adopted for data transmission, and these systems can often provide significant cost benefits. Both monitoring systems can provide operators crucial information on the system response to extreme events such as storms beyond the design operating envelope and confirm the likelihood of any damage.

Inspection Requirements

Corrosion

Mid water flowlines are at risk of both external and internal corrosion. External corrosion is monitored through visual surveys to ensure that adequate cathodic protection is provided by sacrificial anodes.

Material degradation

General visual inspection may be required to identify any damage to the external coating for both steel and flexible mid-water flowlines.

Performance Tracking

The monitoring data collected is compiled into Key Performance Indicators (KPIs). The KPIs are developed to provide a quantitative measure of the health of the system. The inspection requirements and intervals are determined based on findings from the monitoring data. Regular appraisals of the risks associated with the system are conducted to optimize the inspection and maintenance intervals in addition to ensuring the integrity of the system, [10].

MONITORING DATA PROCESSING

The KPIs are compared against threshold values determined from the design stage. In the event of KPIs exceeding design limits, alerts will be raised. Depending on the alert level, appropriate actions will be taken to perform any inspection or repair measures. The alert levels will determine whether immediate action is required before commencing normal operations. Typical KPIs based on monitoring data are discussed below:

Condition Monitoring

Environmental loading

KPIs for environmental loading include wave heights, wind speeds and current speeds. The KPI threshold limits are derived based on the design limits. For example, 67% of allowable stresses can be defined as a limit for normal operations while 100% of allowable stresses or unusually large storms where extreme responses have been observed can be defined as the ultimate limit, [11]. In the event of KPIs exceeding the threshold limits, alarms will be set to trigger an early inspection focused on a particular system threat. When the ultimate limits are exceeded, visual inspection will be required globally prior to commencing the normal operations. An example of KPI tracking for wave heights is shown in Figure 2.

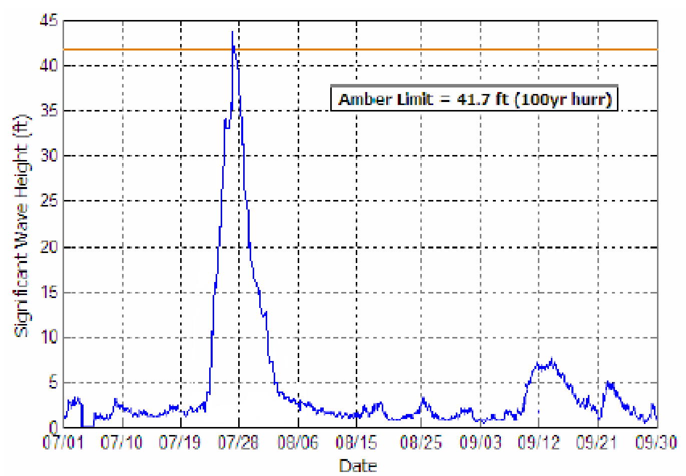

Figure 2 – Example KPI Tracking for Wave Heights

Vessel motion

The relative distance between the host vessels is used as a KPI and will be determined based on vessel offsets. Shortest distance between the host vessels that results in maximum allowable sag bend depth will be set as one KPI threshold value. Similarly, the maximum vessel offset that results in maximum allowable flowline end termination loads will be set as another KPI threshold value.

Structural Response Monitoring

Flowline Response

Based on the flowline motion/strain response, the wave and vessel motion induced response can be characterized in two levels:

1. Preliminary evaluation of the measured data in terms of standard deviations of motions and/or strains;
2. Detailed data processing estimating stresses and fatigue damage accumulations.

The stress and fatigue damage can be calculated using the following methodology:

1. Conduct spectral analysis for the data collected at each motion sensor location;
2. Dynamic acceleration spectra is double integrated in frequency domain to obtain displacement spectra;
3. Group adjacent motion sensors for stress calculations;
4. Difference between adjacent motion spectra can provide the slope, and repeating the same procedure provides flowline curvature;
5. Riser curvature spectra is directly proportional to stresses;
6. Stress histograms obtained is used to calculate fatigue damage with the appropriate weld fatigue curves;
7. Strain and curvature measurements can be used to directly monitor component over-stressing, as well as compute fatigue damage accumulated.

The pressure sensors located mid-span can be used to obtain direct measurements of sagbend depths. Similarly, hang-off angle measurement based on inclinometers for catenary shape mid-water flowlines can be used to monitor the configuration and resulting hang-off loads.

BENEFITS

The proposed mid-water flowline integrity monitoring approach leads to reduced risk, increased uptime and enables prediction of the remaining fatigue life. The performance tracking through KPIs based on the monitoring data can be used to define the inspection program and optimize inspection, maintenance and repair intervals.

Early identification of anomalies based on inspection and monitoring are used to trigger pre-emptive repair and mitigation measures. Data from the monitoring system also assist in making better operational decisions, e.g. production shut-down for repairs. Monitoring data also assures system performance during extreme events and enable the calibration of analytical models to improve future designs.

CASE STUDY

A case study of a monitoring system supplied by 2H Offshore for a bundled mid-water flowline installed offshore Malaysia is presented. The bundle design with multiple peripheral lines is used to convey the production fluid from a dry tree facility to an FPSO for processing and water in the reverse direction for injection in to the wells. The entire bundle is fabrication on-shore and towed to the site. The mid-water flowline design analysis indicated that the carrier pipe is a fatigue critical component, especially during tow-out to the field, [4]. The objective of this monitoring system is to track the actual fatigue performance of the flowline carrier pipe both during towing and during in-service operations. In order to be cost effective, a stand-alone battery powered motion monitoring system is deployed along the length of the carrier pipe onshore prior to towing the bundle. The motion monitoring package included 3-D accelerometers, and 2-D angle rate sensors. Similarly, pressure gauges are also deployed at the middle of the flowline to monitor the sag/hog conditions.

The monitoring system, shown in Figure 3, consists of an array of 18 integrated accelerometers and angular rate sensors to measure the flowline motions and 1 pressure sensor to measure the hydrostatic pressure at the mid-point. These sensors are packaged into standalone loggers which have their own batteries for power supply and memory for data recording. The loggers are designed to be ROV-installable. This enables them to be periodically retrieved to download the recorded data and then re-installed on to the flowline carrier pipe after servicing to enable further monitoring.

The loggers with accelerometers/angular rate sensors are grouped into 3 clusters – at both ends of the flowline carrier pipe and at its mid-point. In each cluster, the accelerometers are placed at intervals equal-distance apart along the carrier pipe. This placement corresponds to the fatigue damage hotspots predicted during design and the intervals are selected to enable the different motion responses responsible for fatigue to be identified, as described in [9].

The entire flowline response due to wave and current loading can be captured by processing the recorded motion measurements both in time domain and frequency domain, as discussed in the data processing section above. The motion response spectra is used to identify the source of loading, such as a broad-banded frequency response indicating wave-induced motion, and a narrow-banded response indicating current induced VIV. To assess VIV fatigue, the measured acceleration amplitudes are matched against the predicted mode shapes to determine the VIV response amplitudes and the fatigue damage incurred along the entire flowline, [12,13]. Apart from the response correlation, the adjacent motion sensors are also processed together to obtain the stress response at discrete locations along the flowline, which are converted to fatigue loading.

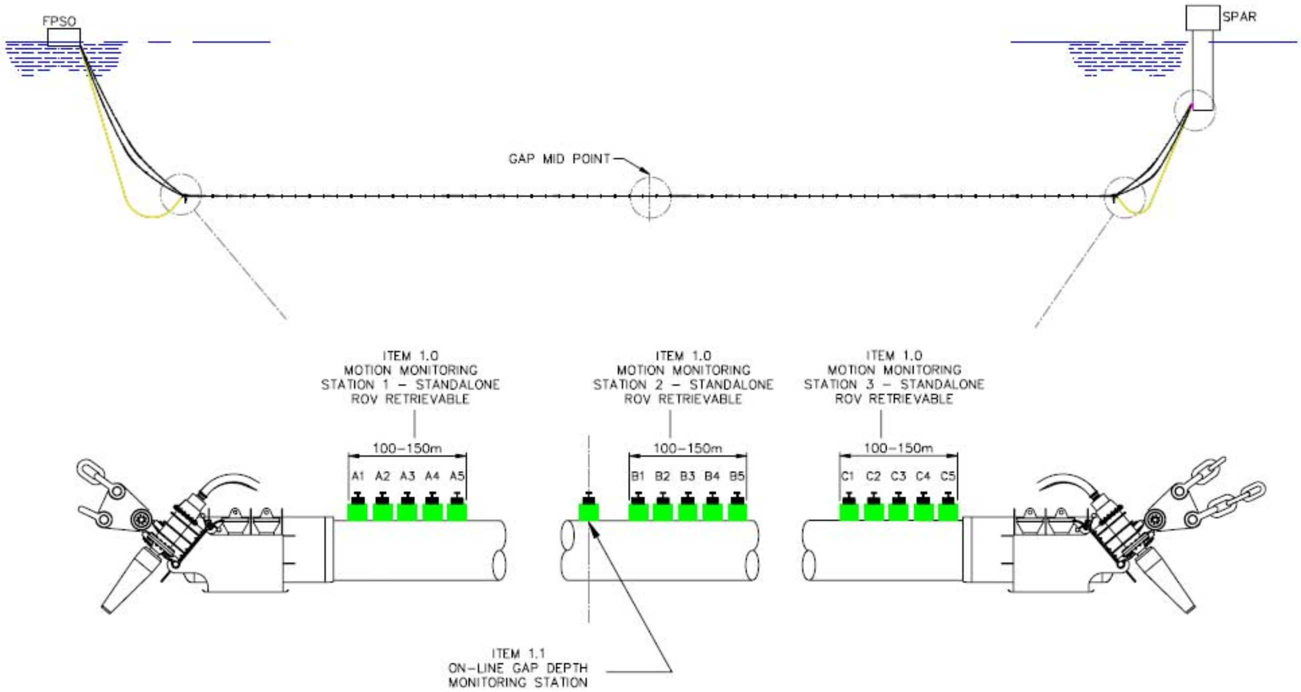

Figure 3 – Bundled Mid-Water Flowline Monitoring System

The pressure sensor, on the other hand, allows for the sagbend depth at the middle and one end of the carrier pipe to be monitored during the in-service operation. Any changes in the internal fluid density of the produced fluid causing any change in the flowline configuration can affect the overall response. The flowline sagging can increase the loading on the tether connections between the flowline and the host vessels. Conversely, hogging conditions result in increased wave loading on the flowline. Therefore, the depth measurements from the pressure sensors are used to determine the flowline configuration prior to response interpretation.

The configuration changes anticipated during the flowline launch, towing to site and installation operations require that the monitoring data be obtained almost continuously. Hence a near-continuous monitoring duration of 10 minutes recorded every 30 minutes is chosen to capture the monitoring data during the anticipated duration of this towing and installation activity. The event logs during this operation are also collected in order to correlate the changes in the condition against the measurements. However, during the in-service operations, the design driver is the flowline response to both extreme environment loading and daily seastate loading causing fatigue. The recording intervals for the loggers are determined as a trade off between the battery life and the resolution of the data required to interpret the flowline strength and fatigue response. The logging duration of 10 minutes is sufficient to determine the long-term wave and VIV loading cycles, and a logging interval of every 3 hours is chosen to adequate to capture the extreme storm events. The selected logging duration and cycle can collect data for about 9 months in one monitoring campaign.

The loggers are retrieved using an ROV deployed from the field support vessel at the end of the monitoring campaign to retrieve the data from the memory cards for post-processing and serviced for the next monitoring campaign.

The data processed into fatigue damage usage provides an indication of severity of the response, identifies components to target during inspections, and provides an estimate of the remaining fatigue life of the components.

CONCLUSIONS

The design challenges of various mid-water flowline configurations are discussed. Of concern are the stress and fatigue issues in the flowlines, especially at end terminations, due to environmental loading and vessel motions and the flow assurance concerns.

An integrity monitoring strategy for mid-water flowlines is developed to address the design concerns. An effective integrity management program consists of both direct monitoring and inspection schemes. The monitoring system should capture the failure mechanisms that cannot be inspected, and the loading source of the failure mechanisms. The monitoring parameters should be based on the design predicted strength/fatigue concerns, and any deviations from the design assumptions during fabrication and installation phases. The monitoring parameters required to capture the mid-water flowline response includes environmental conditions, vessel motions, flowline motions and configuration, corrosion, and material degradation.

An integrity management strategy for mid-water flowlines is presented with a case study of such a program recently implemented for a bundled flowline installed in South East Asia.

A strategy of combining monitoring and inspections is proven to be beneficial in terms of reducing costs through optimized IMR schedules, improving operational efficiency and assuring integrity. Such an integrity management strategy has also paved the way for improving operator confidence in mid-water flowline systems and reduces any conservatism for future designs.

NOMENCLATURE

ADCP	Acoustic Doppler Current Profilers
CFD	Computational Fluid Dynamics
DGPS	Differential Global Positioning System
FE(A)	Finite Element (Analysis)
FPSO	Floating Production, Storage and Offload
KPI	Key Performance Indicator
ROV	Remotely Operated Vehicle
VIV	Vortex Induced Vibrations

REFERENCES

[1] Alvim, R. A., Elman, P., 2008, "Feasibility Assessment of a Mid-Water Transfer System", Paper No. OTC-19350, *Proc. Offshore Technology Conference* (OTC 2008), Houston, Texas, United States, 5-8 May 2008.

[2] Rampi, L., Lavagna, P., 2006, "TRELLINE – A Cost Effective Alternative for Oil Offloading Lines (OOLs)", Paper No. OTC-18065, *Proc. Offshore Technology Conference* (OTC 2006), Houston, Texas, United States, 1-4 May 2006.

[3] Lemoël, M., Brown, P., Jean, P., Shepheard, B., 2008, "Design of the World's 1st Gravity Actuated Pipe (GAP) for Murphy's Kikeh Deepwater Development, East Malaysia", Paper No. OMAE2008-57533, *Proc. ASME 27th International Conference on Offshore Mechanics and Artic Engineering* (OMAE 2008), Estoril, Portugal, 15-20 June 2008.

[4] Morin, P., Jean, P., Melis, C., Helle, Y., Shepheard, B., 2008, "Preparation and Execution of the GAP Surface Tow", Paper No. OMAE2008-57541, *Proc. ASME 27th International Conference on Offshore Mechanics and Artic Engineering* (OMAE 2008), Estoril, Portugal, 15-20 June 2008.

[5] Lim, T. K., Natarajan, S., Falconer, P., 2009, "Deepwater Riser and Subsea Integrity Management Strategy", *Proc. 7th Deepwater Technology Asia 2009*, Kuala Lumpur, Malaysia, 26-27 October 2009.

[6] Det Norske Veritas, 2008, "Riser Integrity Management", DNV Recommended Practice DNV-RP-F206, April 2008.

[7] Tognarelli, M., Yin, F., Campbell, M., Achanta, V., 2009, "benchmarking of Shear7V4.5: Comparisons to Full-Scale Drilling Riser VIV Data and Legacy Analyses", Paper No. OMAE2009-79442, *Proc. ASME 28th International Conference on Offshore Mechanics and Artic Engineering* (OMAE 2009), Honolulu, Hawaii, United States, 31 May-5 June 2009.

[8] Thethi, R., An, P., 2008, "Performance Monitoring of Deepwater Risers", Paper No. OMAE2008-57018, *Proc. ASME 27th International Conference on Offshore Mechanics and Artic Engineering* (OMAE 2008), Estoril, Portugal, 15-20 June 2008.

[9] Natarajan, S., Howells, H., Deka, D., Walters, D., 2006, "Optimization of Sensor Placement to Capture Riser VIV Response", Paper No. OMAE2006-92366, *25th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2006), Hamburg, Germany, 4-9 June 2006.

[10] Cook, H., Dopjera, D., Thethi, R., Williams, L., 2006, "Riser Integrity Management for Deepwater Developments", Paper No. OTC 17891, *Proc. Offshore Technology Conference* (OTC 2006), Houston, Texas, United States, 1-4 May 2006.

[11] American Petroleum Institute, 1998, "Design of Risers for Floating Production Systems (FPSs) and Tension-Leg Platforms (TLPs)", API Recommended Practice 2RD, First Edition, 1 June 1998.

[12] Beynet, P., Shilling, R., Campbell, M., Tellier, E., Howells, H., 2008 "Full Scale VIV Response Measurements of a Drill Pipe in Gulf of Mexico Loop Currents", Paper No. OMAE2008-57610, *Proc. ASME 27th International Conference on Offshore Mechanics and Artic Engineering* (OMAE 2008), Estoril, Portugal, 15-20 June 2008.

[13] Tognarelli, M., Taggart, S., Campbell, M., 2008, "Actual VIV Fatigue Response of Full Scale Drilling Risers: With and Without Suppression Devices", Paper No. OMAE2008-57046, *Proc. ASME 27th International Conference on Offshore Mechanics and Artic Engineering* (OMAE 2008), Estoril, Portugal, 15-20 June 2008.