



Field Trial Technical Report

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Riser Lifecycle Monitoring System for Integrity Management

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Abstract

The culmination of Phase 1 and Phase 2 of the Riser Lifecycle Monitoring System (RLMS) for Integrity Management project is a customer field trial test of the RLMS. A comprehensive technical report is described herein of the test results of a proof of concept (POC) of the RLMS successfully deployed, tested and decommissioned in a real-world operational environment in the Gulf of Mexico for a nine-week period.

The RLMS field test included five subsea sensing modules deployed by a remotely operated vehicle (ROV) controlled from the topside, with the lowest module located at a depth of 6,200 feet on the drilling riser string and the rest equally spaced towards the sea surface. The topside data acquisition system with the RLMS software collected processed data for a time period of 15 minutes every 1 hour and analyzed the riser health data in near real time from June 28, 2016 through August 24, 2016. Root-mean-square (RMS) acceleration values (ft/s²) and current speeds (knots) along the riser string are both measured and predicted. Baseline and high RMS acceleration and subsequent fatigue damage for individual riser joints are correlated with environmental and operational events.

The RLMS POC system has been demonstrated as a production tool on a marine drilling riser for (1) near real-time operational insights, and (2) riser life assessment for optimized riser inspection and maintenance planning. Novel aspects to this research program are field trial test results which demonstrate the long-range deep water communication, advanced machine learning techniques for fatigue damage estimation, ease of system deployment for the drilling contractor, and integrated system functionality of the RLMS on a drilling riser. Near real-time collection and display of key riser health data and analysis of said data to meaningful information were demonstrated.

1. RLMS Subsystems Development and Deployment

The RLMS system deployed in the field trial followed the initial system design requirements and technical approach described in the Phase I Final Report [1], and included the following technical elements/subsystems:

- **Subsea Sensing Modules** clamped on to a select number of riser joints and monitored the vibration, angular rate, and ocean current velocity at the specified joint locations. As part of each module, a long range acoustic transceiver provided near real-time tetherless sensor data transmission.
- **A Topside Data Acquisition System** deployed on the rig surface communicated with the subsea sensing modules, received the sensor data, and served as the physical host for the data processing and analysis, storage, and visual display.
- **RLMS Software** was also hosted in the topside system, and provided the software infrastructure for the analytics, database for data storage, and web-based user interface (UI) for data display.
- **Vibration and Fatigue Analytics** resided in the topside RLMS software system and calculated the fatigue damage and other parameters of interest for each riser joint.

Details on each of the subsystems are described in the following sections.

1.1 Subsea Sensing Module

For the RLMS field trial test, Sonardyne Inc. was selected as collaborator on the project to supply the subsea sensing system and acoustic telemetry for the subsea and surface communications. Sonardyne has been successful in delivering reliable and robust dynamic positioning products to the oil and gas offshore industry, and as such have deep technical and field experience in long range acoustic communications. The subsea sensing and acoustic subsystem from Sonardyne has specifications that met the requirements of the design of the RLMS system from Phase 1 of the project, and employs an architecture that was able to support further development of the RLMS.

The subsea sensing module subsystem deployed in the field was primarily based on the Sonardyne's Subsea Monitoring, Analysis and Reporting Transponder (SMART) unit [2], as seen in Figure 1, and followed the initial design criteria as listed below:

- **Near real-time condition monitoring and alerts** enabled by the acoustic transceiver were performed every hour in the field trial.
- The subsea sensing module, being a **Modular Platform**, integrated commercial off-the-shelf inertial measurement unit (IMU) as the motion sensor (accelerometer and gyroscope), and included serial interface for the additional current meter. It also provided processing capability for customized edge computation and analytics, acoustic communication, data storage and backup when acoustics not present, battery, and a maritized housing.
- **“Plug-and-go” and battery powered** units eliminated the requirement of auxiliary cabling, and minimized the impact to drilling operations.

- **Open Operating System (OS) environment** on the units allowed customized software applications for interfacing with the additional sensor, performing signal processing, and edge analytics.

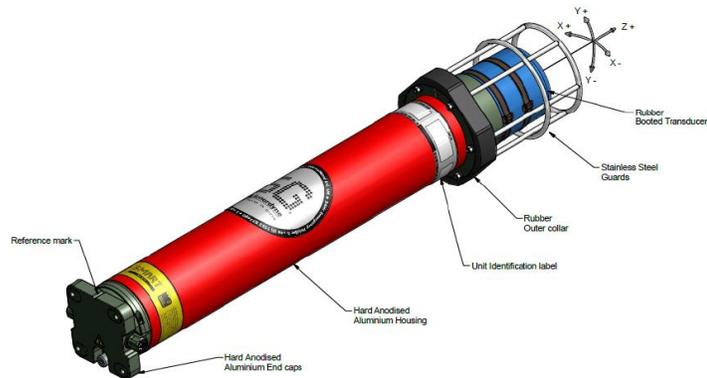


Figure 1. Sonardyne SMART unit.

The deployed subsea sensing modules were based on the modular design approach, and consisted of the key elements from the Phase I design including sensors and interface, microprocessor, memory, acoustic modem and transducer, and battery. Figure 2 shows the system architecture of the deployed subsea sensing modules. The subsea sensing module provides the following core functionality:

- Collected sensor data from an IMU sensor for acceleration and angular rate, and an external connected current meter for current velocity;
- Performed edge analytics to process the collected sensor data to generate time- and frequency-domain data features for the topside vibration and fatigue algorithms;
- Stored the raw and processed sensor data on the module for data backup;
- Updated the processed sensor data periodically via acoustic communication for fatigue analysis;

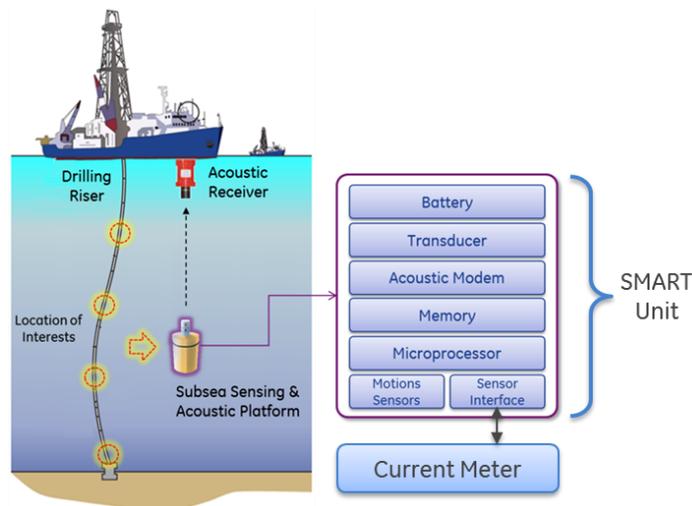


Figure 2. Subsea sensing module deployed architecture.

Sensing Elements

The subsea sensing modules deployed in the field trial consisted of an IMU sensor and a current meter. The IMU sensor has 6 degrees of freedom, and includes a triaxial accelerometer and a triaxial gyroscope that measures angular velocities. The IMU sensor is integrated inside the SMART unit, and data preprocessing is performed in the sensor. Specifically, the IMU performs a data down-sampling to convert the base sample rate of 4 kHz to a 250 Hz data through 16-tap moving average filter. The down-sampled data is then passed through 2 finite impulse response (FIR) anti-aliasing filters with a cutoff frequency at 3.6 Hz to generate the 10 Hz “raw” data which was logged and further processed by the SMART units. More details on the IMU data preprocessing can be found in the technical specifications provided by Sonardyne [3].

The current meter was connected to the SMART unit, and was the Nortek Aquadopp[®] Current Meter. The sensor provided current velocity data at 1 Hz, and data was collected and stored by the SMART unit via serial interface. The current meter measures the local current velocity for X, Y, and Z axis, which were set in the East North Up (ENU) reference frame relative to the earth.

Data Logging & Transmission Schedule

To conserve the usage of onboard battery of the subsea sensing module, the collecting, logging, and acoustic transmission of the sensor data were performed with a period of one hour. During each hour, the module started data sampling of the IMU sensor for about 15 minutes. At the same period, the module also started data collection of the Aquadopp current meter for a minute. The module then processed the collected IMU and current meter sensor data and generated the time and frequency domain features as described in the following section. Both the raw sensor data and the processed sensor data features were stored on the local data storage. At the end of the hour, the topside acoustic transceiver interrogated the subsea sensing module for data transmission, and the module sent the processed data features acoustically to the top. The module would retry once if the first transmission failed.

Edge Processing

The subsea sensing module performed sensor data processing at the edge to generate the time- and frequency-domain data features which were later used in the topside vibration and fatigue analysis for fatigue damage estimation. The distributed nature of the edge processing leveraged the computation resource on the module, reduced the power consumption of acoustic transmission by transmitting small processed data file, and hence extended the battery life. For each sensor channel, including the X, Y, and Z axis of the accelerometer, X, Y, and Z axis of the gyroscope, and the X, Y, and Z axis of the current meter, a mean and standard deviation were calculated in the time domain of the sensor data. The power spectral density was computed for the accelerometer and gyroscope, and the dominant frequency and

the corresponding amplitude were reported in the transmitted processed data file. Detailed description of these data features is listed in the technical specification from Sonardyne [3].

Power Consumption

The power consumption of the subsea sensing module is a function of the data collection, processing, and acoustic transmission, as detailed in the Phase I report [1] of the program. In the RLMS field trial, a 100-Ah Lithium battery was used for each module, and the battery life estimate for the SMART unit was plotted in Fig. 3 for two different acoustic telemetry schemes (TS3 and TS5). TS5 is a faster telemetry scheme than TS3, and the unit transmits the same amount of data for a shorter period of time and hence consumes less power. Either scheme combining the above edge processing would extend the battery life of the unit to more than 90 days which was the requirement of the field trial.

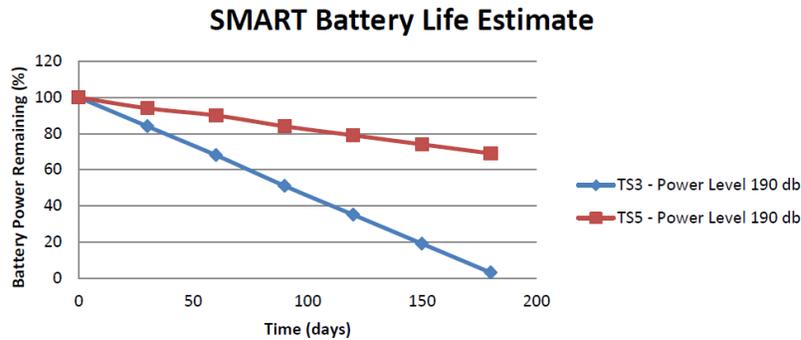


Figure 3. SMART unit battery life estimation.

Deployment

The subsea sensing modules were remotely deployed onto selected drilling riser joints by a ROV using a two-part clamping system. The clamping system consists of two elements, as shown in Figure 4: (1) a clamping element which was directly clamped onto an auxiliary line of a riser joint, and has a bucket that allows the other sensing element to form a firm link with the clamping element; (2) a sensing element which half-enclosed the SMART unit and the current meter and could be deployed to the bucket to join the clamping element. During the field trial, the clamping elements were installed manually onto the auxiliary line of each of the selected riser joints, and the sensing elements were docked into the corresponding clamping elements by a ROV after the entire riser string was deployed. Figure 5 shows the docking of the subsea sensing module inside the sensing element into the bucket of the clamping element by a ROV.

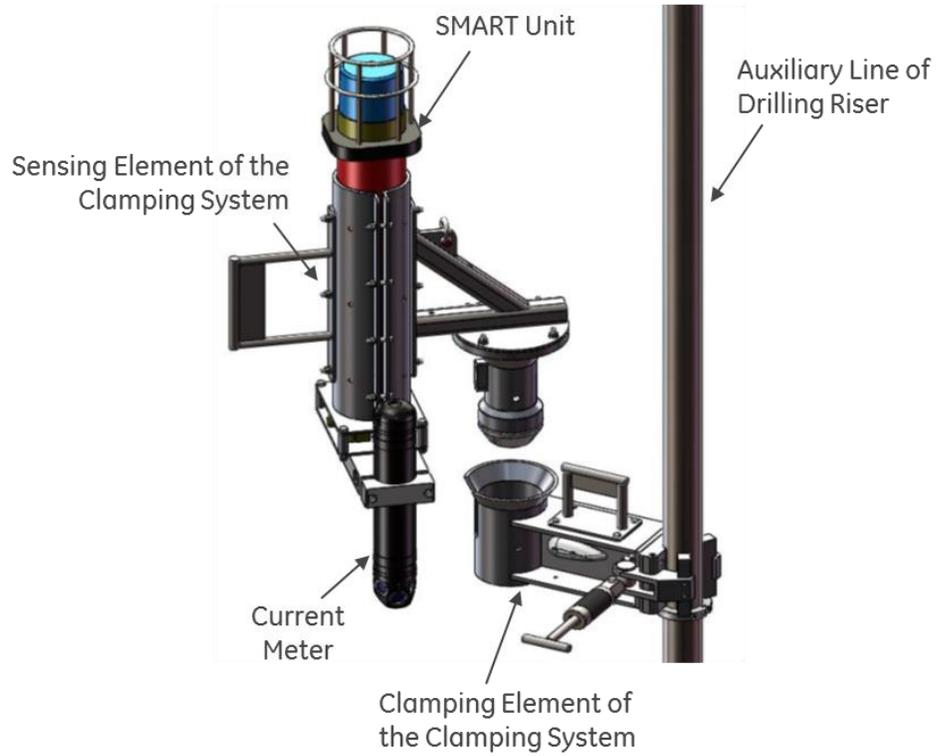


Figure 4. Illustration of the two-part clamping system for the deployment of the subsea sensing module.

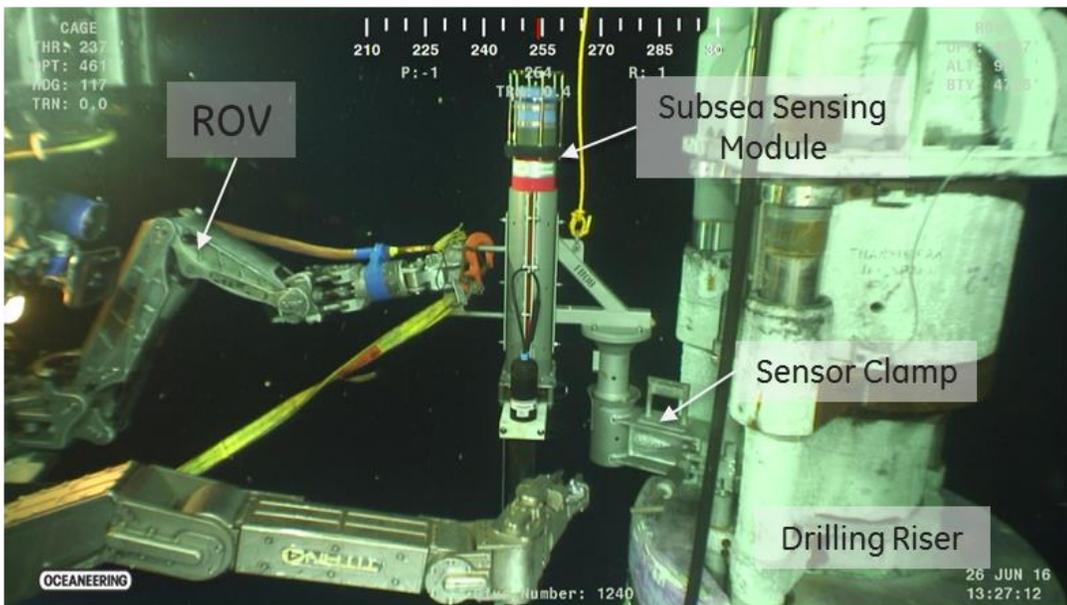


Figure 5. Deployment of the sensing element with the subsea sensing module to the clamping element by a ROV.

1.2 Topside Data Acquisition System

The topside data acquisition system was deployed on the drilling rig platform surface. It consists of an acoustic receiver dunker which communicates with the subsea sensing modules and receives the sensor data, a topside acoustic receiver supporting assembly providing the physical infrastructure for holding the dunker at the right depth under the sea surface, and a surface computer and associated electronic components for controlling the acoustic receiver, as well as serving as the physical host for the data processing and analysis, storage, and visual display. The surface computer also has the capability to be connected through the rig or third-party network for transmitting data back onshore for remote monitoring and diagnosis. In the field trial, the data at the surface computer was stored locally. Figure 6 shows the topology of the topside data acquisition system.

The topside receiver supporting assembly, as seen in Figure 7, holds the acoustic receiver dunker using a pneumatic winch which is secured to a deployment frame. A storage reel is also attached to the frame to provide secondary retention for the dunker. A jib crane extends the dunker over the side of the rig. Figure 7 also shows the deployment of the topside data acquisition system in the field trial.

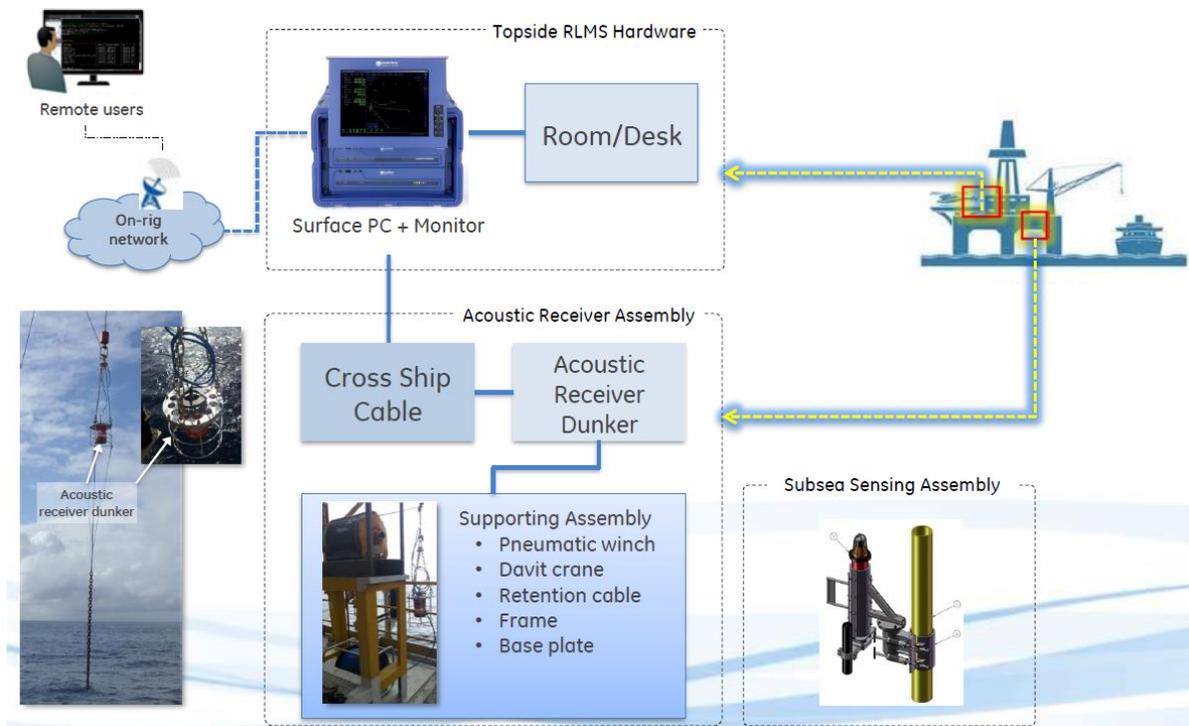


Figure 6. Topside data acquisition system topology.

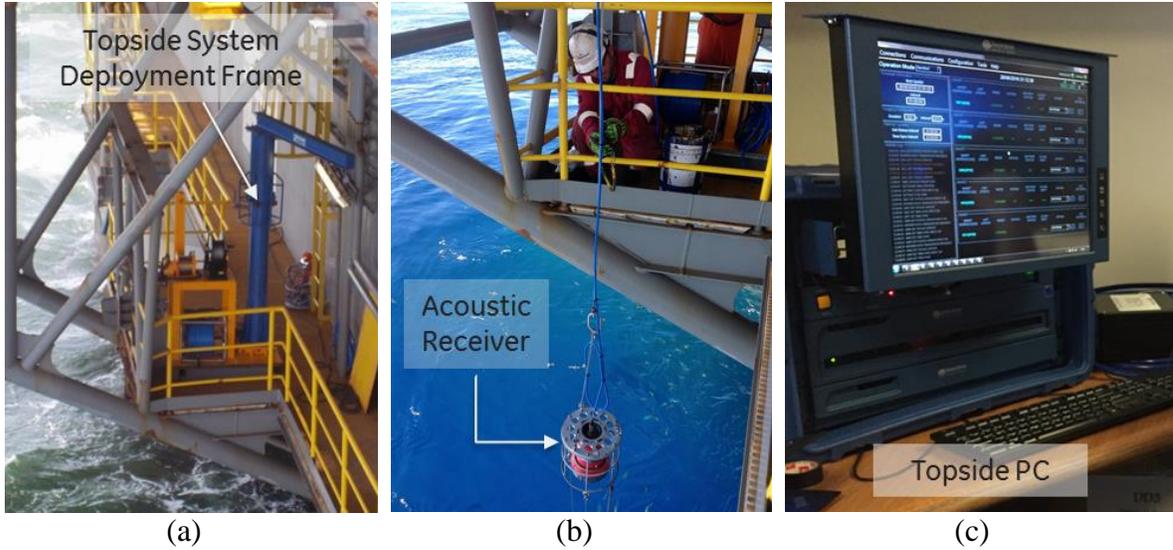


Figure 7. Topside data acquisition system. (a) Supporting assemble & deployment frame; (b) Acoustic receiver; (c) Topside computer.

1.3 RLMS Software

The RLMS Software resides in the surface computer of the topside data acquisition system, and provides the infrastructure for receiving the sensor data, running the riser fatigue estimation algorithms and analytics, storing data in the database, and displaying sensor data and fatigue estimation via web-based UI. Figure 8 shows a high level architecture of the RLMS software.

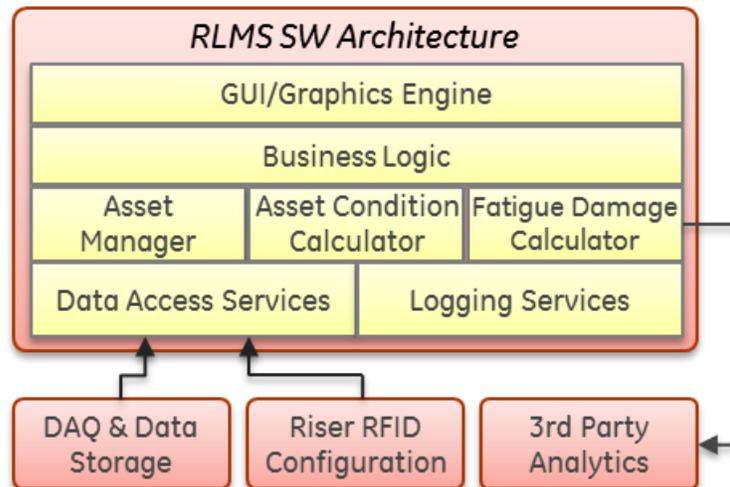


Figure 8. RLMS software architecture.

Architecturally Significant Requirements

To ensure a proper design of the software architecture of the RLMS system, a set of significant requirements, as shown in Table 1 were followed during the design and development process.

Table 1. Architecturally significant requirements.

Type	Architecturally significant requirement (ASR) (sorted by priority)
Constraint	Limited or no remote connectivity to the field test site.
Constraint	Windows 7 OS requirement imposed by the Shear7 product (damage calculation analytics) as well as by the possibility of using Sonardyne's Sensor Computer that runs on Windows 7.
Quality attribute	Availability. Due to the remote connection constraints (i.e. inability to fix the system often), this quality attribute is of the highest priority so the system is functioning when needed.
Quality attribute	Testability. In order to ensure maximum availability, each components of the system need to be tested as much as possible during the development process. Additionally, overall (or at least major portion) system needs to be tested automatically.
Quality attribute	Monitorability. Due to the remote connection constraints, the system should be able to collect enough information in order for the team to analyze analytics results as well as analyze the health status of the software system.
Quality attribute	Portability. Because it is unclear where parts of the system will be deployed, it is important to have an ability to distribute individual parts of the system to different computers that potentially can run different OS.
Quality attribute	Interoperability with GE's SeaLytics™.
Quality attribute	Scalability. This is not as significant requirement because the number of sensors is not expected to increase dramatically.
Quality attribute	Extensibility is an ability of the system to easily accommodate changes to its software. This is not as significant requirement, however, it is expected that future incremental changes to the system should not require complete refactoring of the system.
Quality attribute	Security. Because of the prototype nature of the system there will be minimal security features in this system.

UI for Field Trial

The RLMS software provides a web-based UI during the field trial for the rig operators to view and access the sensor data, as well as the fatigue damage estimation. The following Figures 9 through 12 show examples of the UI. Further development of the UI will be continued after the program.

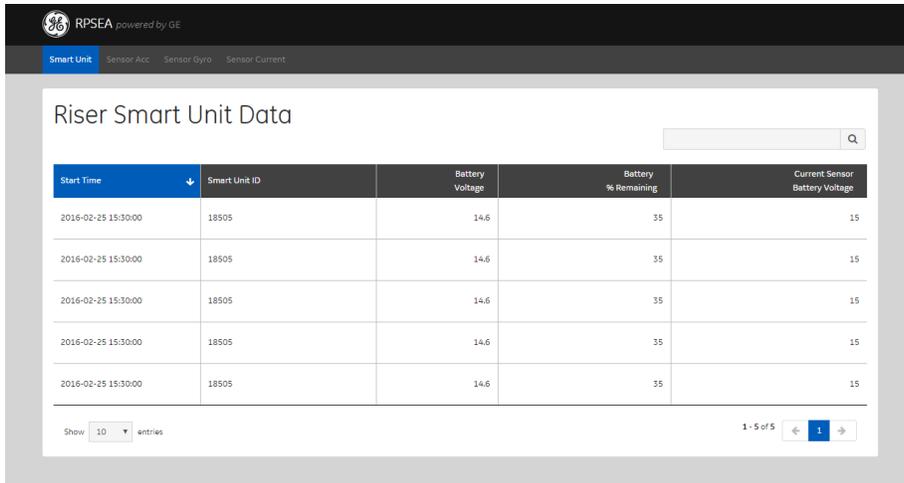


Figure 9. SMART unit status.

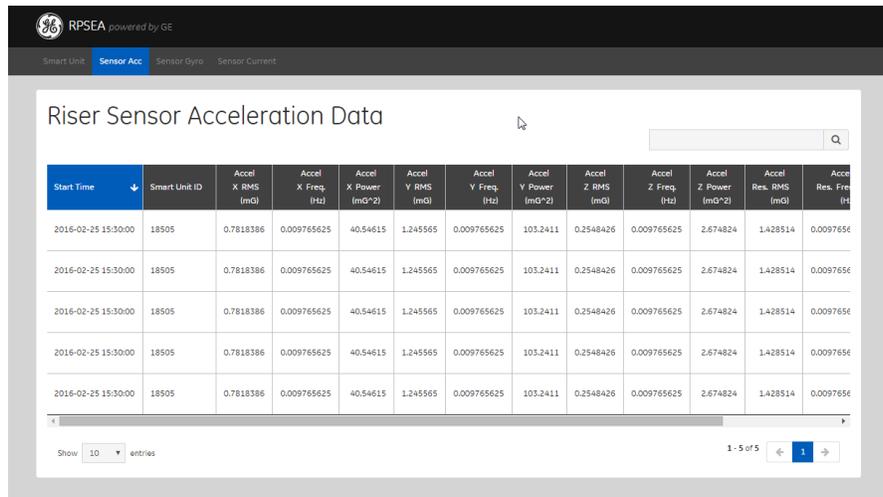


Figure 10. Accelerometer sensor data.

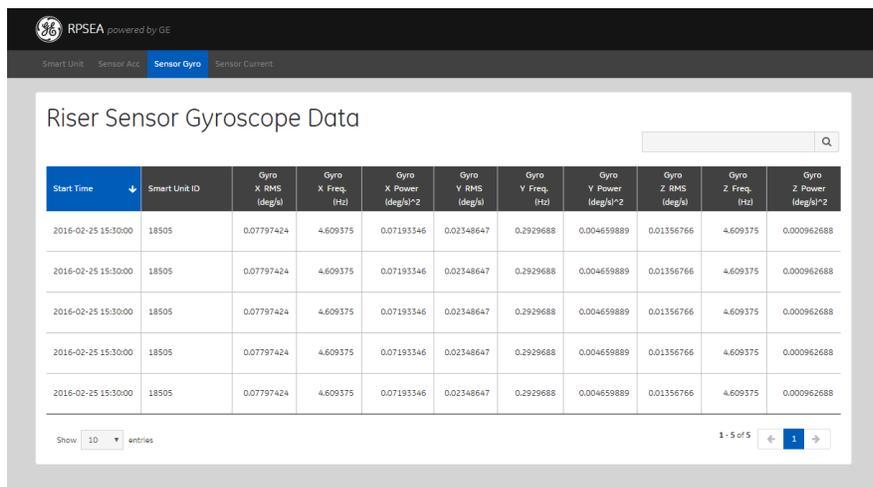


Figure 11. Gyroscope sensor data.

RPSEA powered by GE

Smart Unit | Sensor Acc | Sensor Gyro | **Sensor Current**

Riser Sensor Current Data

Start Time	Smart Unit ID	Current X SD (mm/s)	Current X Mean (mm/s)	Current Y SD (mm/s)	Current Y Mean (mm/s)	Current Z SD (mm/s)	Current Z Mean (mm/s)	Current Res. Dir. (deg)	Current Res. Mag. (mm/s)
2016-02-25 15:30:00	18505	181	-36	181	25	255	-14	145.2222	46.01087
2016-02-25 15:30:00	18505	181	-36	181	25	255	-14	145.2222	46.01087
2016-02-25 15:30:00	18505	181	-36	181	25	255	-14	145.2222	46.01087
2016-02-25 15:30:00	18505	181	-36	181	25	255	-14	145.2222	46.01087
2016-02-25 15:30:00	18505	181	-36	181	25	255	-14	145.2222	46.01087

Show 10 entries 1 - 5 of 5

Figure 12. Current sensor data.

1.4 Vibration and Fatigue Analytics

The RLMS is subjected to severe and prolonged undersea currents. These currents can result in vortex-induced vibrations (VIV) in which the riser vibrates in a direction perpendicular to the dominant current direction. VIV are main source of fatigue damage to the risers. Fatigue damage can also occur due to surface waves and inline vibrations of the risers but the vibration and fatigue analytics developed here predicts only the fatigue damage caused by VIV. The fatigue damage is calculated using neural networks and SHEAR7. SHEAR7 is the offshore industry's leading software tool for the prediction of VIV. It takes current speed as inputs along with riser configuration and geometric and material properties.

The fatigue damage analysis workflow used in this generic riser life-cycle reliability methodology is shown in Figure 13. The workflow can be broadly divided in three steps, the first being *Inputs* which consists of riser configuration (modal data from the global riser analysis), and the measured accelerometer data. The second step is *Analysis* which consists of generating the transfer function (algorithm) for as-built configuration, calculating the fatigue damage along the drilling riser, and updating the database and UI with damage rates and remaining useful life. The third step is *Output* which consists of recommendations for inspecting particular riser segments in case of a significant event, such as a VIV occurrence, or unanticipated discrepancies in load sharing in the riser system, such as on the wellhead. Recommended actions from the RLMS advisory system may involve, for example, swapping riser segments in low-fatigue portions of the riser string with ones from the high-fatigue regions for the subsequent drilling campaign. Such operations changes could result in extension of the inspection and maintenance period.

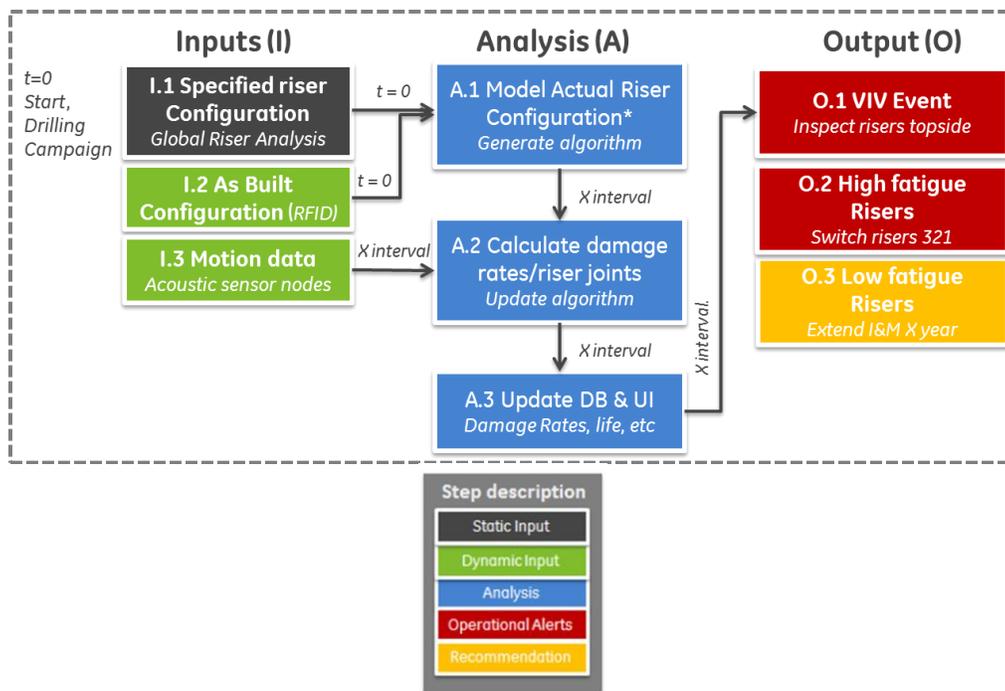


Figure 13. Fatigue damage analysis workflow

In Step A.2, a neural network model, combined with an optimization algorithm, is used to develop transfer functions that will estimate the ocean current velocities along the length of the marine drilling riser. The inputs to the neural network model are current intensities, and the outputs of the model are acceleration features at locations along the riser string where the sensor nodes containing motion sensors are attached. An optimization algorithm is used to match predicted acceleration from the neural network model with measured acceleration features in order to back-calculate the current intensities. The current intensities are then input into SHEAR7 to estimate fatigue damage rates. When a new riser configuration is specified, neural network models are automatically run by generating a space-filling design of experiments (DOE) that covers a wide range of current profiles and current intensities representative of the flows that occur in the geographical regions in which upcoming drilling campaigns will be conducted. The data set for the DOE is split into three parts: one for training the neural network model, one for cross-validation and tuning of the model's internal parameters, and one for validation. The neural network models include the effects of the specific riser geometry, material properties, top-tension levels, and mud weights.

The neural network model discussed in the previous section calculates acceleration features at each sensor location on the riser string based on current intensities, which are initially unknown. Periodically, acceleration data is collected from accelerometers located along the riser string, and the acceleration features are calculated. A constrained optimization problem is performed that minimizes the sum of the squares of the differences between the predicted and the measured acceleration features: Step A.2 (see Figure 14). This process yields a set of current intensities at the sensor locations that would result in the observed acceleration features. Once the current intensities are known, the SHEAR7 code is run to calculate stresses and damage rates for each component in the riser string. Damage increments are then calculated by assuming constant damage rates during the period of time over which the sensor data was taken (typically a duration on the order of minutes). The total damage for each component is updated and entered into a database.

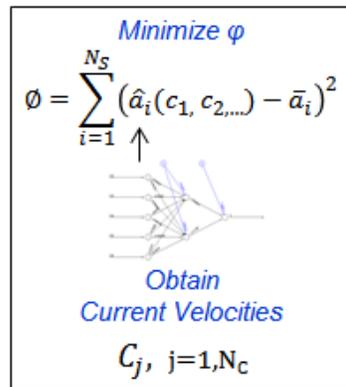


Figure 14. Calculation of Current Intensities in Data-Matching

Verification of the methodology of fatigue damage calculation is summarized in Figure 15. To verify the transfer function and the optimization algorithm described above, a typical current velocity profile was first created (Step 1). Next, the RMS acceleration and damage rates at each sensor location (total 9 sensors) were calculated in SHEAR7 using the current

profile (Step 2). The neural network model was then used to predict the RMS acceleration at each sensor location (Step 3). The optimization algorithm was then used to minimize the sum of squares of the differences between the actual and predicted RMS accelerations to obtain the predicted current velocity profile (Step 4). That profile was then run through SHEAR7 to generate predicted damage rates (Step 5). Verification of the method is contingent on good agreement between the actual and predicted damage rates, which agreed to within 10% for the dozen verification cases that were considered.

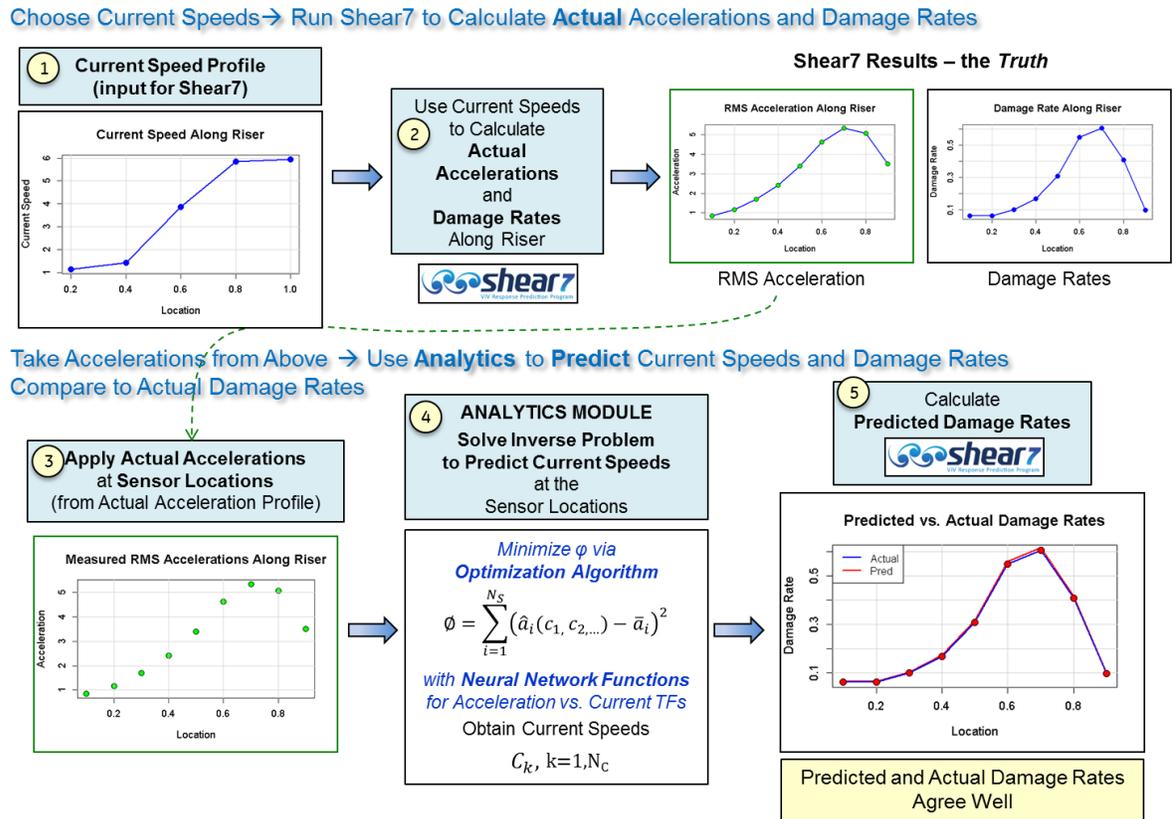


Figure 15. Methodology to Verify Fatigue Damage Calculation

2. Data Analysis and Results

The five sensors were placed at locations listed in Table 2. Sensor 1 being the bottommost sensor and sensor 5 the topmost.

Table 2. Sensor location and depth.

Sensor ID	Depth (ft)
1	6,066
2	4,728
3	3,125
4	1,422
5	345

The processed data for a time period 15 minutes measured every 1 hour is shown in the subsequent figures from June 26, 2016 through August 4, 2016. Examples of the processed sensor data are shown in the following Figures 16 through 20. The RMS acceleration is in ft/s^2 . The acceleration values are small with maximum being 0.115 ft/s^2 . Relatively high accelerations are seen on July 11th and July 12th. There is missing topside processed sensor data in Figure 16 for July 3, 2016 through July 9, 2016 and July 16, 2016 through August 2, 2016. The first gap was due to troubleshooting with the topside acoustic transceiver and the second data gap was because the power level was not set high enough on the lowermost beacon at 6,066 ft. Raw sensor data was obtained from the sensors to fill these gaps but not available for analysis at the time of this report. Beacons 2 through 5 performed satisfactory at the low power setting and hence more data during the period of July 16, 2016 through August 2, 2016.

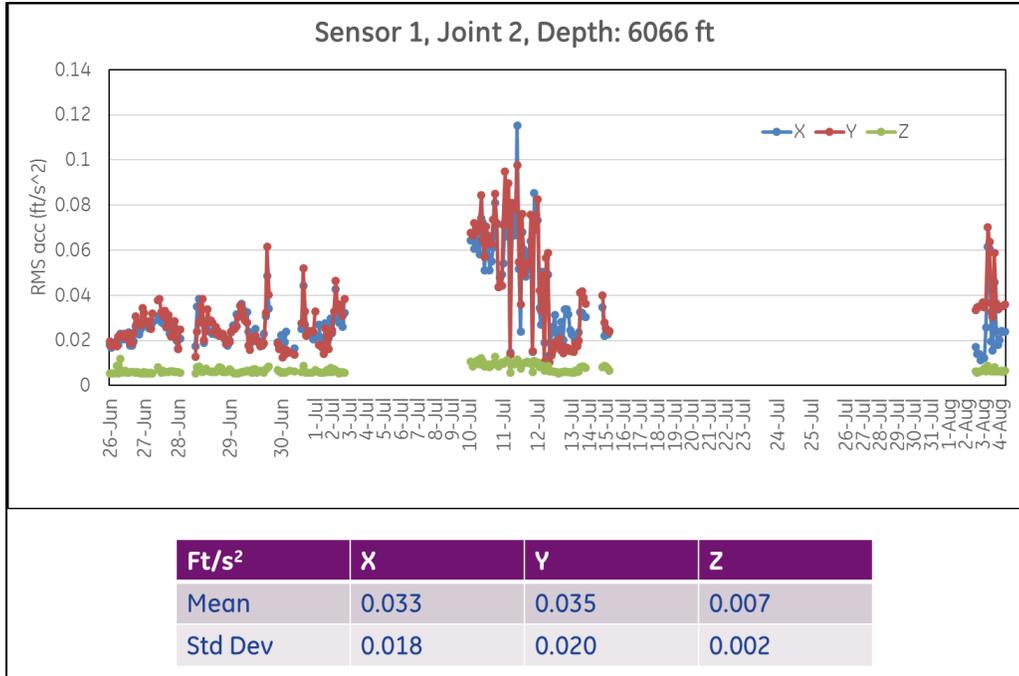


Figure 16. Example processed sensor data for sensor unit 1.

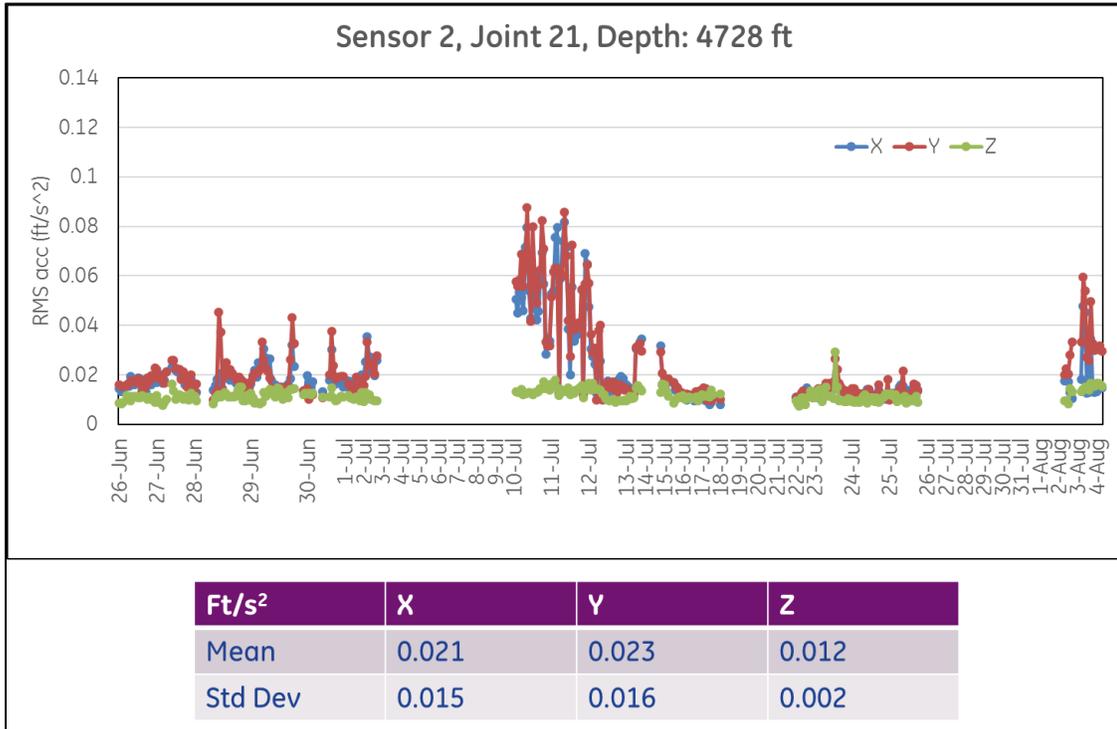


Figure 17. Example processed sensor data for sensor unit 2.

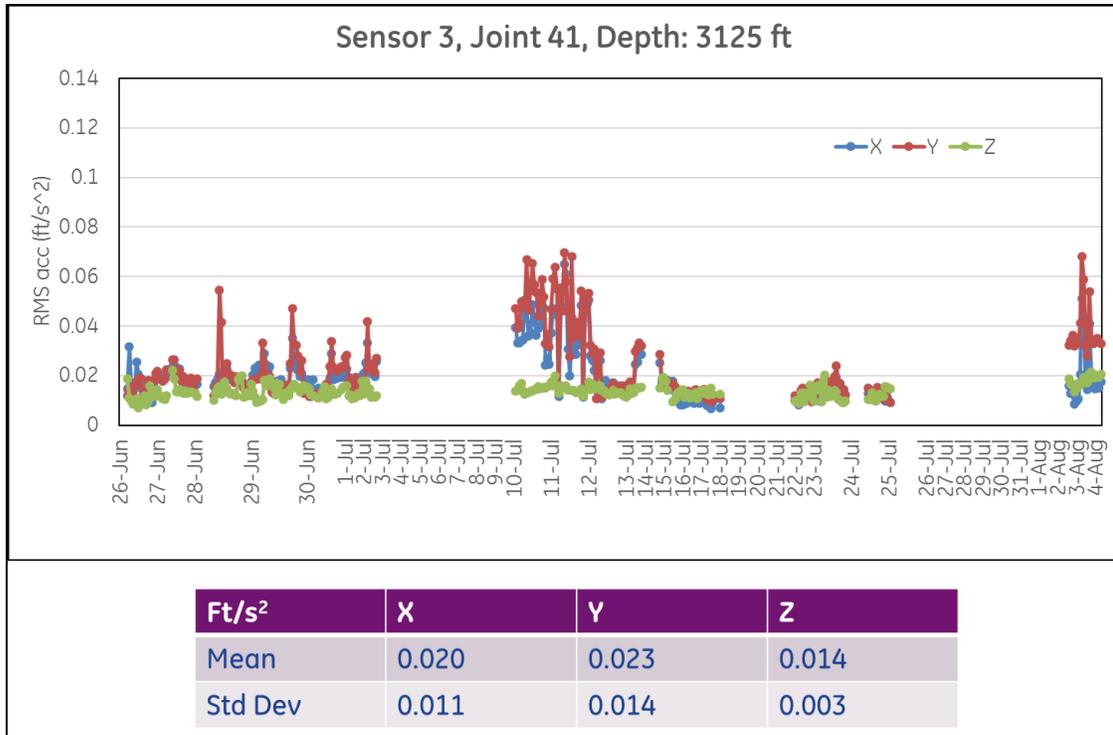


Figure 18. Example processed sensor data for sensor unit 3.

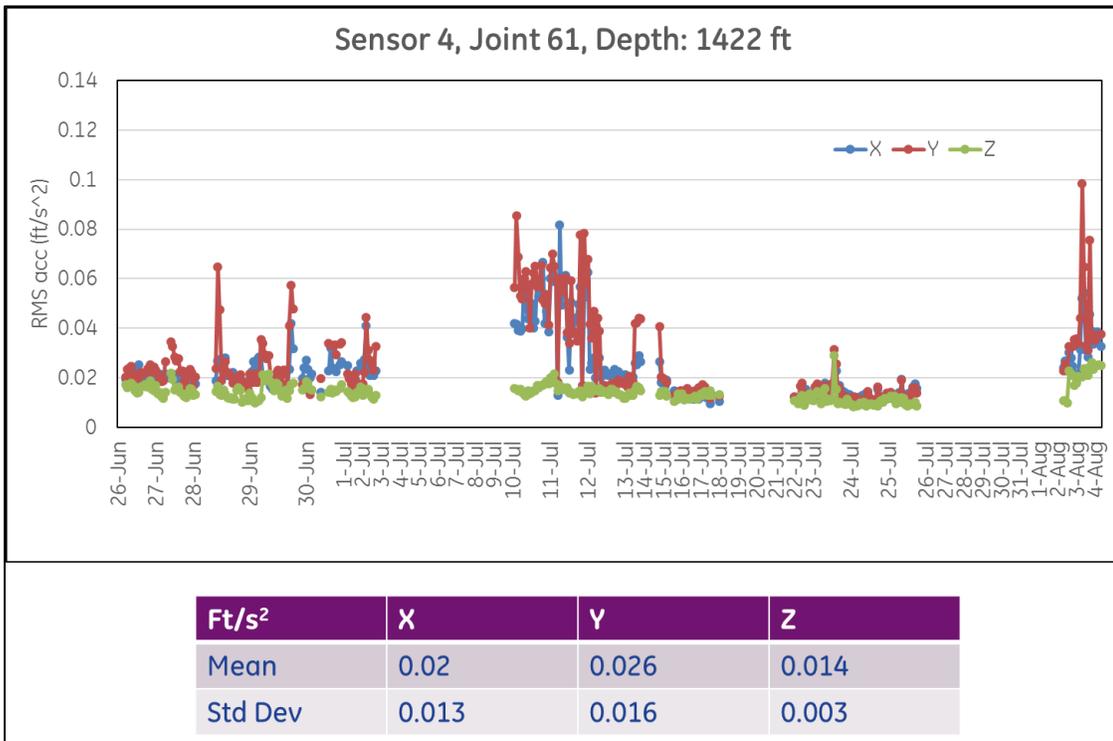


Figure 19. Example processed sensor data for sensor unit 4.

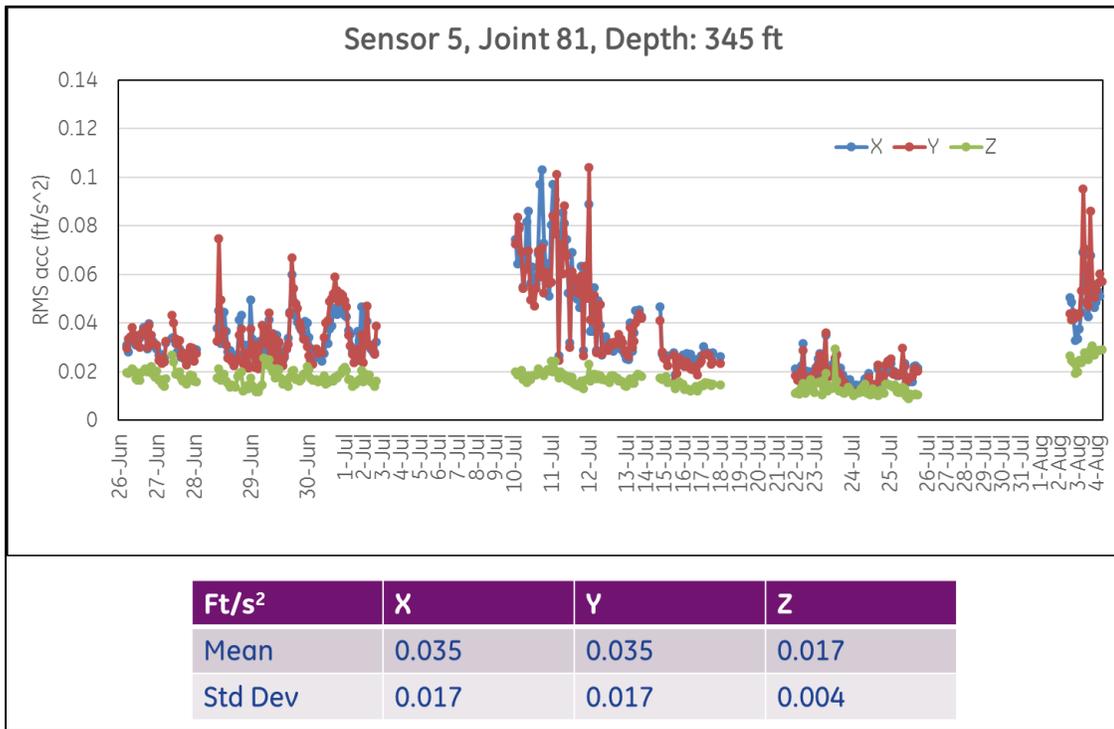


Figure 20. Example processed sensor data for sensor unit 5.

Examples of the resultant current speed measurements from the Aquadopp current profiler are shown in Figures 21 through 25.

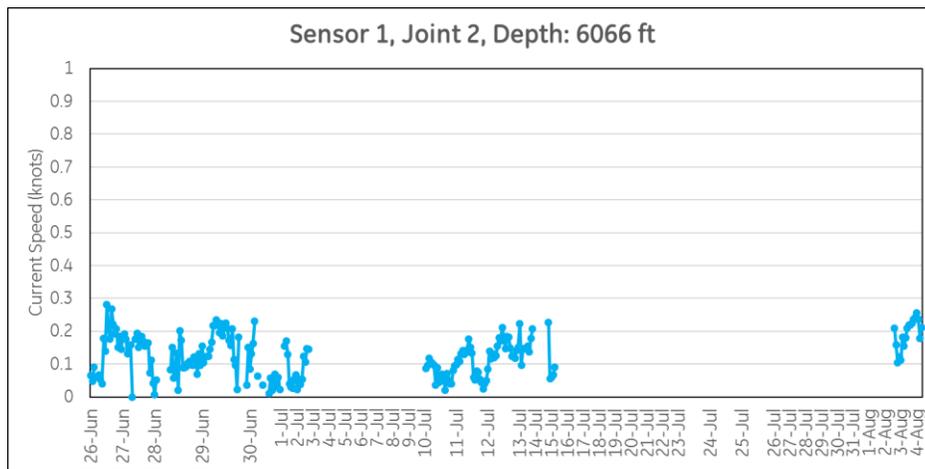


Figure 21. Example current sensor data for sensor unit 1.

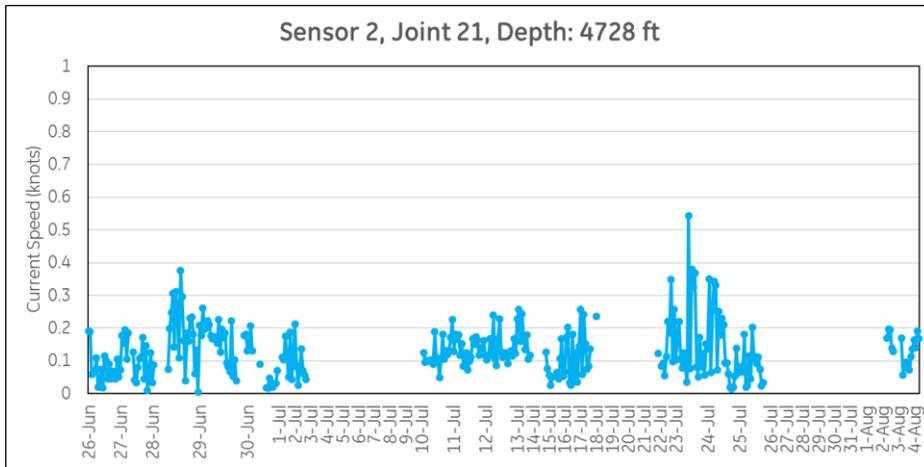


Figure 22. Example current sensor data for sensor unit 2.

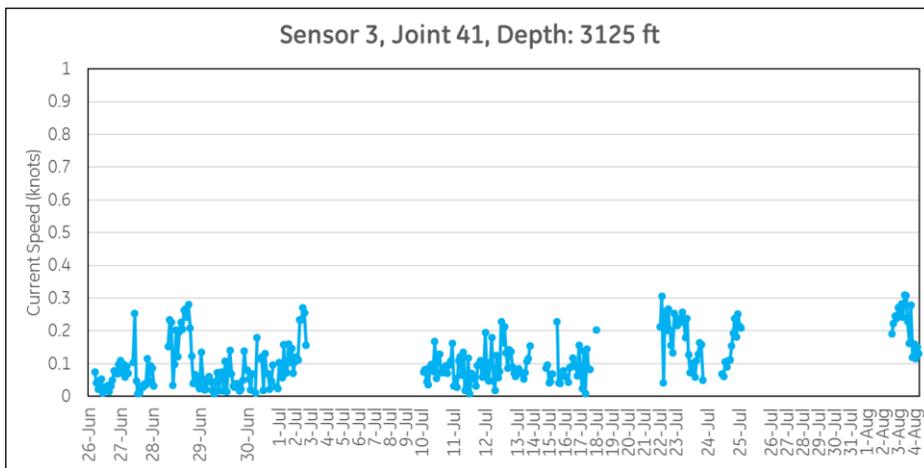


Figure 23. Example current sensor data for sensor unit 3.

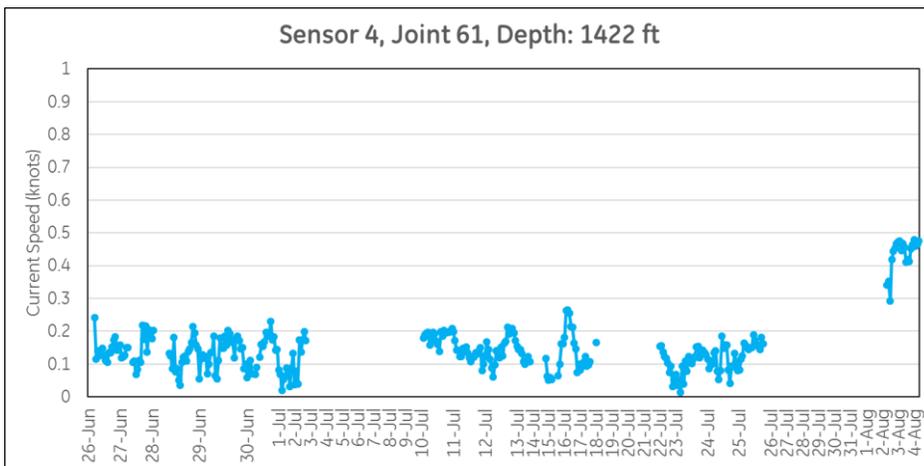


Figure 24. Example current sensor data for sensor unit 4.

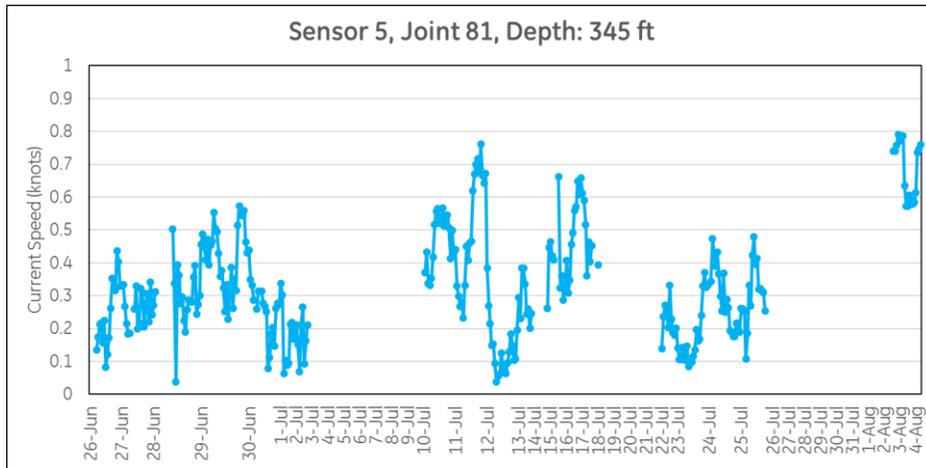


Figure 25. Example current sensor data for sensor unit 5.

Using the analytics, the current speed generating the accelerations at each sensor location is predicted and used as an input to SHEAR7. SHEAR7 then outputs the fatigue damage rate along the length of the riser. The damage rate of 0 means no damage at all and damage rate of 1 means failure. The cumulative damage rate is calculated for all days and shown in the form of bar chart in Figure 26. The vertical axis on the figure shows joint numbers and horizontal axis shows the fatigue damage on a scale of 0 to 1, where 0 is no fatigue and 1 is failure. The neural network is trained using Shear 7 acceleration predictions for cross-flow vibrations. The resultant of the X and Y measured RMS acceleration is used to predict the current profile. Shear7 version 4.7 has added pure-inline fatigue calculation option but in most cases it assumes that the cross-flow response dominates the fatigue. Combined cross-flow and inline motion is only seen in uniform flow. The pure in-line VIV will be taken into account in the subsequent versions of the analytics for the RLMS system. The measured currents are not taken into account in this version of the RLMS system since current measurements may not be available in future. The measured current data during field trial has provided a good training data set to train the next version of the neural network model.

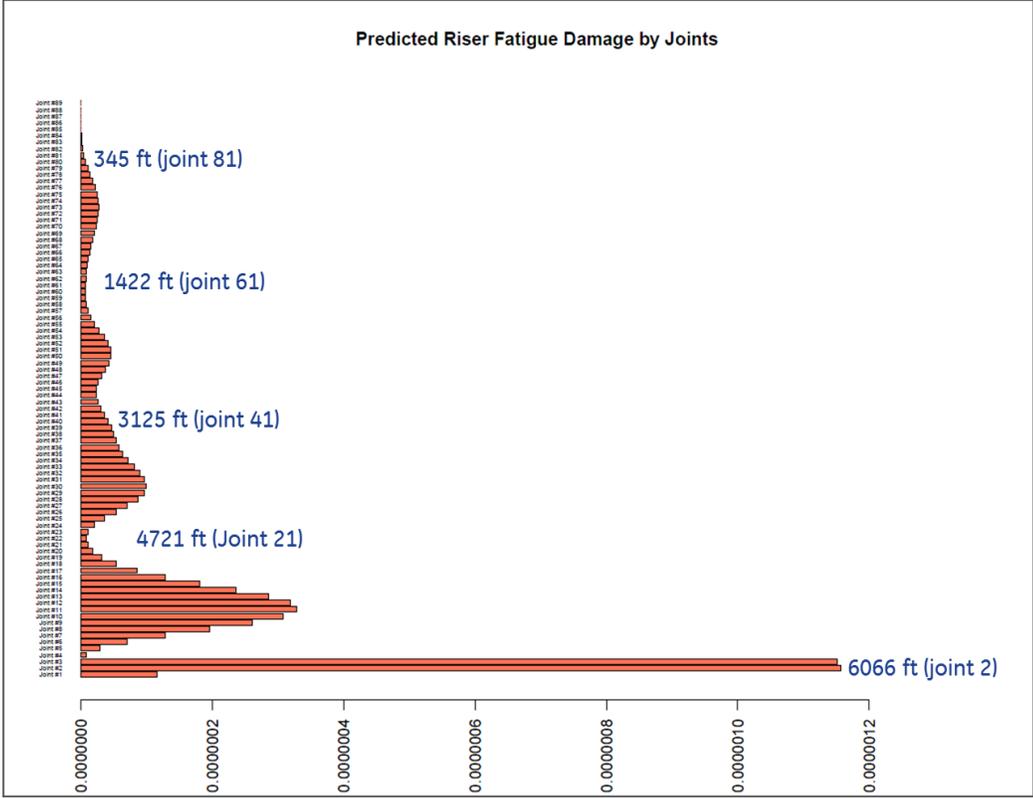


Figure 26. An example of the predicted riser fatigue damage by joints.

The predicted riser displacement corresponding to the predicted current profile for an instance in time is shown in Figure 27.

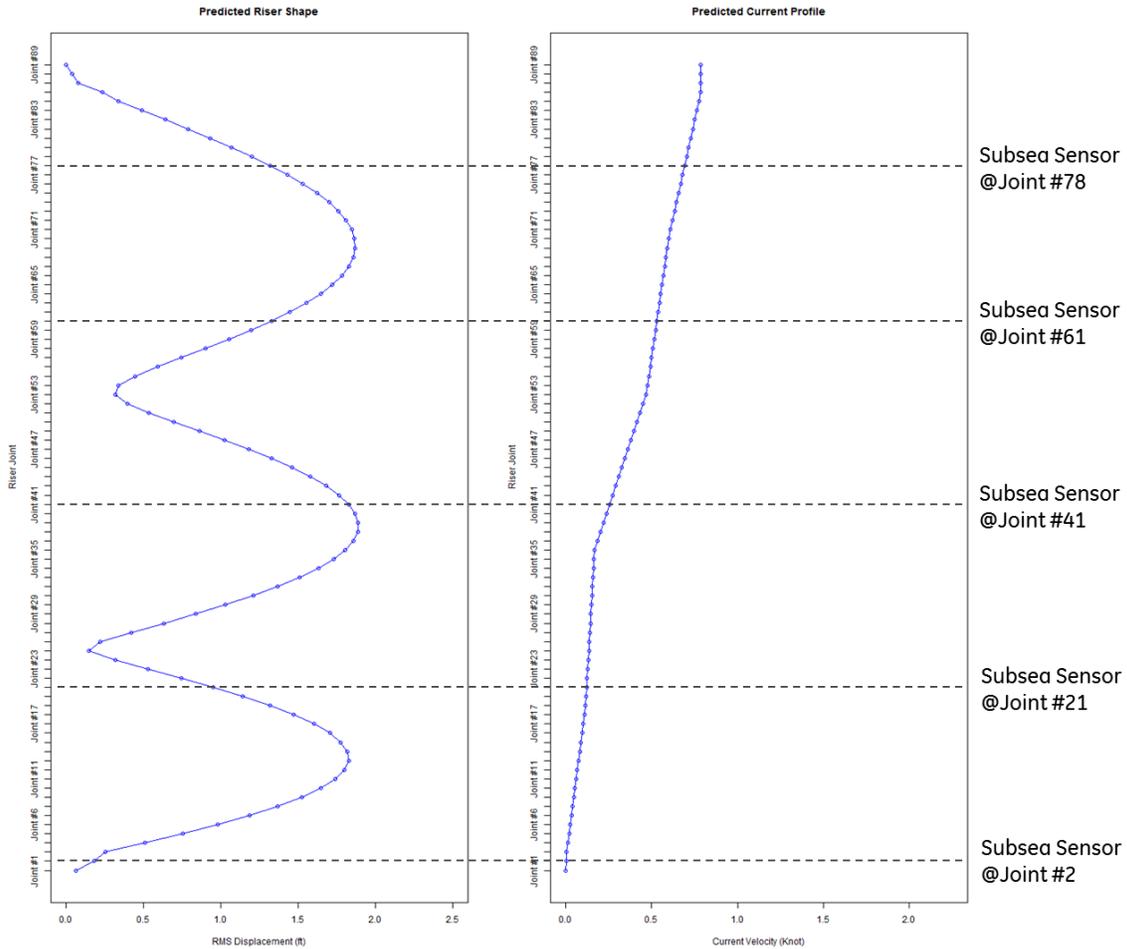


Figure 27. An example of predicted riser displacements vs. predicted current profile.

The vibration and fatigue analytics thus predict the fatigue damage in the riser joints due to VIV. Since the current speeds measured and predicted were small, the fatigue damage predicted was not significant during the nine-week duration of the RLMS field trial test.

Future work will require enhancements to improve the RLMS model for fatigue prediction. Such effort includes enhancing the boundary conditions of the riser model, namely at the top and bottom of the string near the upper and lower flex joints. Fatigue damage in this model is primarily from VIV due to fundamental frequencies, the effect of higher harmonics was not taken into account in the current version of Shear7. The latest version of Shear7 has been introduced with higher harmonics threshold and factor which would be incorporated in the improved model; damage from wave and motion vessel are not included in the scope of this work but will be included in future efforts.

3. Conclusions

A POC of the RLMS system has been tested in the field on a drilling rig in the Gulf of Mexico for a nine-week period to demonstrate system functionality, including (1) near real-time collection and display of key riser health data and (2) analysis of this data to meaningful information. Five subsea sensing modules were deployed by a ROV controlled from the topside, with the lowest module located at a depth of 6,200 feet on the drilling riser string and the rest equally spaced towards the sea surface. The topside data acquisition system with the RLMS software collected processed data for a time period of 15 minutes every 1 hour and analyzed the riser health data in real time from June 28, 2016 through August 24, 2016. RMS acceleration values (ft/s^2) and current speeds (knots) along the riser string are both measured and predicted. Baseline and high RMS acceleration and subsequent fatigue damage for individual riser joints are correlated with environmental and operational events.

Novel aspects to this research program are field trial test results which demonstrate the long-range deep water communication, advanced machine learning techniques for fatigue damage estimation, ease of system deployment for the drilling contractor, and integrated system functionality of the RLMS on a drilling riser.

In summary, the RLMS POC has been demonstrated as a production tool in a real-world environment on a marine drilling riser for (1) near real-time operational insights, and (2) riser life assessment toward optimized riser inspection and maintenance planning.

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- [1] RPSEA RLMS Phase I Final Report, Subcontract 11121-5402-01
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