ABSTRACT

One of the primary goals of riser monitoring is to build a database of measured riser behavior during different environmental conditions and compare against design predictions during each period. A comprehensive database of field measured riser response provides not only a dataset to benchmark riser performance but enables the calibration of design parameters for future risers. The calibrated set of design parameters would feedback to establish a more representative riser design process and provide greater confidence during future riser designs.

The following paper establishes a methodology to benchmark riser behavior against software predictions with applications specific to a steel catenary riser (SCR) suspended from a spar platform. Aspects and challenges dealing with processing of inclined sensors to derive global motions and operational effects are discussed and addressed. A demonstration of the methodology is presented using field measurements from a Gulf of Mexico deepwater SCR under storm conditions. The riser behavior of interest for this study is specifically the touchdown motions and stress but additional comparisons are made along the entire riser length.

INTRODUCTION

The structural response of a production SCR attached to spar in the Gulf of Mexico (GoM) is being monitored on a real-time basis. The SCR is fitted with a series of monitoring devices at key locations with the objective to provide field measurements for benchmarking of riser design software.

The ideal methodology to benchmark the riser design software is to drive the riser finite element analysis (FEA) model with measured vessel 6 degree-of-freedom (DOF) motions and compare predictions of riser response along the length against field measurements. However, following a benchmarking feasibility assessment, it has been determined that for seastates experienced to date at the spar platform, there is insufficient signal to noise ratio in vessel 6-DOF measurements to reliably drive the riser model. This is due to amplification in sensor error and noise during the rigid body motion transfer from the measurement location on deck to the vessel keel. A further discussion on this matter can be found in [4].

As a result of the above, an alternative riser benchmarking approach is to use the riser hang-off motions measured by the riser monitoring system to drive the riser model. The riser monitoring station consists of motion and strain measurements stations located near the hang-off and touchdown zone (TDZ) of the SCR, as shown in Figure 1. The distance of Devices 1 through 18 from the bottom of the pull tube are presented in Table 1. The motion measurement devices (INTEGRIPods) measure the riser acceleration in 3 directions and angular rates in 2 planes. The strain measurement devices (INTEGRISticks) measure bending strain in 2 planes.

The challenge of using the measurements for the purposes of benchmarking is that the coordinate system for each riser monitoring station is different as it depends on the local geometry of the riser at each location. As the riser model is driven using measured riser motions from the topmost riser monitoring station and the results compared against other monitoring stations along the riser length, it is critical that measurements from all monitoring stations are transformed to a single coordinate system.

The key objective of the work conducted in this paper is to develop a methodology for converting the local riser measurements at different locations into a global coordinate
system for comparing measured riser motions and stresses against those predicted from finite element analysis.

![Figure 1 – Location of Riser Monitoring System Devices](image)

<table>
<thead>
<tr>
<th>Device ID</th>
<th>Location Classification</th>
<th>Distance Along Riser from Bottom of Pull Tube (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hang-off</td>
<td>120</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>215</td>
</tr>
<tr>
<td>3</td>
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<td>19</td>
<td></td>
<td>254</td>
</tr>
</tbody>
</table>

![Table 1 – Distance of Monitoring Devices from Bottom of Pull Tube](image)

**PROBLEM DEFINITION**

As discussed above, it is necessary to transform the riser measurements from all the monitoring stations into a single coordinate system prior to performing any benchmarking. Riser motion response is captured by 3 accelerometers and two angular rate sensors housed inside a “motion bottle” assembly strapped onto the riser, as shown in Figure 2. Riser response recorded in the local coordinate system X-Y-Z is defined as the three accelerometer directions in a motion bottle. Right-hand rule is assumed for the accelerometer polarizations X-Y-Z. The X and Y accelerometers are oriented toward the radial and the tangential directions, respectively, with respect to the cross-section as shown in Figure 2. Z accelerometer of INTEGRIPods is aligned with the longitudinal axis of the SCR pointing upward, as shown in Figure 3. X and Y are within the SCR cross-section, while Z is perpendicular to the cross-section.

A global coordinate system U-V-W is defined using heave, surge and sway directions of the riser, with heave vertically pointing upward, surge horizontally toward vessel, and sway horizontally perpendicular to riser plane. The relation between the local coordinate system X-Y-Z and the global coordinate system U-V-W is shown in Figure 4 and Figure 5. As the riser geometry varies from one monitoring station location to the other, it is necessary to transform measurements from each riser monitoring station into the global coordinate system. A methodology is developed to identify and track the relative positions between the local and global coordinate systems based on previous work with 3D sensors suspended on a cable to measure P- and S-wave signals along a borehole [1].
METHODOLOGY FOR COORDINATE TRANSFORMATION

All riser response measurements are in local coordinate system X-Y-Z. Three directions accelerations are measured in X, Y and Z directions, while the angular rates are measured about X and Y axes, assuming zero angular rate about riser Z (or torsional) axis. All the acceleration measurements have g-contamination, which is defined as the undesired component of acceleration due to gravity, or g, because the accelerations due to stationary motions should have zero mean. Most low frequency drifts or calibration errors can be filtered or corrected.

At nominal orientation, all sensors in a monitoring station “display” readings equal to their corresponding mean values. The resultant of the three mean accelerations (X, Y and Z) is equal to the acceleration due to gravity, or g, because the accelerations due to stationary motions should have zero mean. The tilt angle θ of the Z-axis with respect to vertical can be calculated by assuming only g-contamination contributes to the resultant acceleration at the nominal orientation, as illustrated in Figure 7. Vertical vector OP indicates the resultant acceleration R, while \(X_0\), \(Y_0\) and \(Z_0\) denote mean values of X, Y and Z accelerations, respectively. Given the resultant \(R = \sqrt{X_0^2 + Y_0^2 + Z_0^2}\), the tilt angle θ measured in the global coordinate system can be solved from

\[
\cos \theta = \frac{Z_0}{R} \quad \text{or} \quad \theta = \text{sign}(Z_0) \arccos \frac{Z_0}{R}
\]

The factor \(\text{sign}(Z_0)\) in the above equation is applied for generality, considering that the motion bottle might be inverted and aligned with the longitudinal axis of the SCR pointing downward. Usually a negative \(Z_0\) value indicates Z-accelerometer directing downward as positive g-force is measured in upward direction.
Assuming the riser is in a vertical plane, the twist angle $\psi$ between X-axis of the motion bottle and the SCR top dead center line can be obtained from Figure 8, or
\[
\tan \psi = \frac{Y_0}{X_0} \quad \text{or} \quad \psi = \arctan(2Y_0, X_0).
\]
The twist angle $\psi$ is measured in local coordinate system X-Y-Z.

The correlation between the local and global coordinate systems is achieved by two forward transformations starting from global coordinate system. First, rotate the global coordinate system U-V-W about the global V-axis by angle $\theta$, as shown in Figure 9. The coordinate system after the rotation is termed $U_1$-$V_1$-$W_1$, where the $V_1$-axis is identical to V-axis, while $W_1$-axis coincides with the local Z-axis. $U_1$ and $V_1$ axes are within the SCR cross section. Then, rotate $U_1$-$V_1$-$W_1$ system about the $W_1$-axis by angle $\phi$ as shown in Figure 10, where
\[
\phi = \frac{\text{sign}(Z_0) + 1}{2} \pi - \psi \quad \text{or} \quad \phi = \frac{\text{sign}(Z_0) + 1}{2} - \arctan(2Y_0, X_0).
\]
Angle $\phi$ is measured in $U_1$-$V_1$-$W_1$ system. The second rotation results in $U_2$-$V_2$-$W_2$ system, which coincides with the local coordinate system X-Y-Z.

Similarly, two reverse transformations rotating from the local coordinate system X-Y-Z and ending up with the global system U-V-W yield the same result, except that the rotation angles of the reverse transformation are the invert values of the forward transformation.

Figure 8 – Cross-Section of SCR and Motion Bottle

The forward transformation can be presented in matrix format as $R_0(\theta, \phi)$:
\[
R_0(\theta, \phi) = \begin{bmatrix}
\cos \theta & 0 & \sin \theta \\
0 & 1 & 0 \\
-\sin \theta & 0 & \cos \theta
\end{bmatrix}
\begin{bmatrix}
\cos \phi & -\sin \phi & 0 \\
\sin \phi & \cos \phi & 0 \\
0 & 0 & 1
\end{bmatrix},
\]
where $\theta$ and $\phi$ are measured with respect to the fixed coordinate system of each rotation. It is applied to the left side of the local coordinates to obtain global coordinates. For example, the mean values in the local coordinate system are converted to the global coordinate system by the following equation:
\[
\begin{bmatrix} U_0 \\ V_0 \\ W_0 \end{bmatrix} = R_0(\theta, \phi) \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}.
\]
For the reverse transformation, the above equations remain true but the reference for $\theta$ and $\phi$ is the rotating coordinate system at each rotation. The forward and reverse formations give the same $\theta$ and $\phi$ values with opposite signs.

METHODOLOGY FOR MOTION BENCHMARKING

The motion bottle orientation continually changes under dynamic wave or VIV loading, and its measurements at a specific time step are based on the local coordinate system at that time step. Hence the measurements of the motion bottle at time $t = T$ is with the coordinate system at time $t = T-1$ as reference and the measurements of the motion bottle at time $t = T+1$ is with respect to the orientation of the motion bottle at time $t = T$. For benchmarking of riser response, it is necessary to have the location of the motion bottle at every time instant with respect to a constant global coordinate system. For example, acceleration measurements in a series of local coordinate systems cannot be integrated directly, but can be integrated into velocity or displacement time series after the measurements are converted into a global coordinate system.
Coordinate system transformations using Euler angles, including Tait–Bryan angles are found in [2][3]. For example, Z-Y-X convention representing yaw-pitch-roll rotation sequence can be applied to the measured data in that the angular rates are relatively small and the error caused by the subjective sequence of X, Y and Z angular rates is negligible. In fact, the X, Y and Z angular rates are measured simultaneously without any subjective sequence. A vector convention as shown in Figure 11 is proposed for this work. Suppose the measured X, Y and Z angular rates correspond to rotation angles $\alpha$, $\beta$ and $\gamma$, respectively. The initial plane OAB has a normal vector OP. After the plane OAB rotates about X-axis by angle $\alpha$ and simultaneously about Y-axis by angle $\beta$, the plane OAB moves to location OCD with a normal vector OQ. This rotation is equivalent to a rotation with a yaw angle $\xi$ about Z-axis and then a tilt angle $\zeta$ about line of nodes OM. OM is the intersection of planes OAB and OCD.

Application of simple geometry gives the equivalent yaw angle $\xi$:
$$\tan \xi = \frac{\tan \beta}{\tan \alpha}, \text{ or } \xi = \arctan 2(\tan \beta, \tan \alpha),$$
and equivalent roll angle $\zeta$:
$$\tan^2 \zeta = \tan^2 \alpha + \tan^2 \beta.$$

The transformation matrix for rotations $\alpha$ and $\beta$ is
$$R(\alpha, \beta) = R(\alpha, \beta)R(\xi, \zeta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \xi & -\sin \xi \\ 0 & \sin \xi & \cos \xi \end{bmatrix} \begin{bmatrix} \cos \zeta & -\sin \zeta \\ \sin \zeta & \cos \zeta \end{bmatrix} \begin{bmatrix} \cos \xi & -\sin \xi \\ \sin \xi & \cos \xi \end{bmatrix} \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}.$$

In addition to roll angle $\alpha$ about X-axis and pitch angle $\beta$ about Y-axis, the yaw angle $\gamma$ about Z-axis is also included. The vector convention is thus the transformation matrix for rotations $\alpha$, $\beta$ and $\gamma$:
$$R(\alpha, \beta, \gamma) = R(\xi, \zeta + \gamma).$$

The nominal orientation is regarded as the start point of all the subsequent concatenated motions. The coordinate conversion from local measurements X-Y-Z to global coordinate system U-V-W at time step $i$ depends on all previous steps of motion, and can be expressed as

$$\begin{bmatrix} U_i \\ V_i \\ W_i \end{bmatrix} = R_{0}(\theta, \varphi)R_{i}(\alpha_1, \beta_1, \gamma_1)R_{i}(\alpha_2, \beta_2, \gamma_2)\ldots R_{i}(\alpha_i, \beta_i, \gamma_i) \begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix}.$$

After all the time steps of a measured acceleration time series are converted to the global coordinate system U-V-W, the $g$-contamination is removed from the heave component W to obtain the accelerations due to riser motions. The global accelerations without $g$-contamination at time $t$ are:
$$\begin{bmatrix} U_i \\ V_i \\ W_i \end{bmatrix} = \begin{bmatrix} U_i \\ V_i \\ W_i - g \end{bmatrix}.$$

The velocity and displacement time series can therefore be integrated from the global acceleration series in either time or frequency domain.

A riser model is built for finite element analysis to predict riser behavior and compare with measurements. The riser model is driven using the global hang-off motions calculated at the Device 1 location. The analysis predictions of riser accelerations at riser monitoring system locations are used to benchmark the design software by comparing against corresponding device measurements. The software benchmarking for riser accelerations is conducted at both Hang-off and TDZ locations.

RESULTS

The measurements for testing the methodology are selected from a Dec 2009 storm, when the spar platform measured significant wave heights in excess of 17ft. To demonstrate the need for the above benchmarking methodology, the measured raw Z accelerations at hang-off and TDZ are compared in Figure 12. It is observed that the measurements do not correlate in Phase and as the orientation of the monitoring stations is different along the length of the riser, motions in X, Y or Z direction do not correspond to the same global direction.
Using the derived benchmarking methodology, the calculated results of rotated riser hang off motions in surge/sway and heave direction are shown in Figure 13. Excellent correlation is observed between all devices providing confidence in the methodology.

![Figure 13: Calculated Hang-off motions using the derived methodology](image)

A final check is performed, similar to Figure 12, where riser accelerations from the hang-off are compared against each other after transformation. Time domain correlation is shown in Figure 14 where phase synchronization is observed. Due to the nature of an SCR behavior, the heave amplitudes are not identical, which is to be expected. A frequency domain comparison is shown in Figure 15, which also reveals correlation in frequency content between both devices.

![Figure 14: Comparison of transformed Hang-off and TDZ measurements in the global coordinate system.](image)

![Figure 15: Fast Fourier transformation of transformed heave measurements of Hang-off and TDZ.](image)

The SCR benchmarking is carried out by comparing response time traces between the predictions from design software and actual measurements. The coordinate system transformation methodology described in the previous section is used to generate SCR 6DOF motions near riser hang-off location during storm periods. The generated riser hang-off motions are used to drive the SCR FEA model to obtain response predictions along the length which are benchmarked against actual measurements.

Sample SCR response time traces at the TDZ obtained from software are compared against measurements in Figure 16 wherein good correlation is observed between analysis predictions and field measurements thereby validating the benchmarking methodology. The results of the SCR benchmarking are discussed in detail in [5].
CONCLUSIONS

An effort to benchmark full-scale SCR response predictions with field measurements has been initiated. The vessel measurements alone are inadequate to provide adequate data for riser analysis to benchmark riser response on a spar, hence a methodology is developed to allow benchmarking using riser motions measured close to the SCR hang-off location. The presented methodology reliably transforms local riser motions in any coordinate system into global coordinate system. The methodology eliminates g-contamination in sensor measurements and also corrects for errors in measured riser motions due to angular rotations in the riser surge and sway axis. The methodology has been applied to real time field measurements to illustrate its effectiveness. In addition, sample results from the SCR benchmarking have been displayed as an example of the usability of this technique to reduce uncertainties in future riser designs and to better understand the global behavior of an SCR from a spar.

REFERENCES


