OPTIMIZATION OF SENSOR PLACEMENT TO CAPTURE RISER VIV RESPONSE

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ABSTRACT  
Riser VIV response due to ocean current loading is a complex phenomenon governed by both the hydrodynamic and structural properties. In order to obtain better understanding of the global riser VIV response and assist in the improvement of riser VIV design, riser monitoring is being increasingly used.

An optimization technique to identify the number of sensors required and the sensor locations for monitoring riser VIV fatigue is presented. The optimization technique has been developed using modal decomposition and linear regression. The paper explains why monitoring at selected locations with limited instrumentation is sufficient to capture global riser response.

The principles and methods of using multiple measurement quantities in the optimization technique are also presented along with the adopted methodology, limitations and key conclusions.

INTRODUCTION  
Deepwater exploration and production poses a significant design challenge for drilling, production and export risers. VIV response in deepwater is a widely observed phenomenon which can cause significant fatigue damage to the riser. The critical fatigue damage location constantly changes with different excited modes of response. Therefore, it is not possible to simply monitor the critical fatigue location(s). Also, the state of the art VIV analysis tools use VIV models that are calibrated against small scale model tests. Due to uncertainty in the global VIV response of a riser in service, a significant level of conservatism is introduced in to the riser VIV fatigue analysis.

Full-scale riser data is therefore required to understand global riser VIV response, validate the VIV models used in analysis tools and reduce/justify the safety factors used for design.

Full scale measurements of a riser typically employ motion sensors such as accelerometers and angular rate sensors, and strain measuring devices. The measurements at select locations along the riser need to be correlated together to understand the riser response along the whole length of the riser. In designing the monitoring system it is necessary to determine the number of measurements required and suitable instrument locations. This paper describes an optimization technique to obtain the number of sensors required and the required placement of the sensors along the riser.

The main emphasis is on addressing the extent of instrumentation array and the spatial distribution of sensors required for achieving sufficient spatial resolution. Typically the response shape captured at the discrete monitoring locations is interpreted using a modal decomposition method and assuming a stationary response, [1], [2]. A linear regression based method is developed to identify and minimize the error in the response interpretation based on the measurements at discrete locations.

Riser response is commonly measured using accelerometers and strain sensors. Often both the measurements are used in combination to capture the response and provide a cost-effective monitoring solution. The method used to incorporate multiple measurement quantities in the linear regression analysis is also presented.

NOMENCLATURE  
m = Number of modes considered for the assessment  
n = Number of sensors used
\(a\) = base functions containing the analytical modal information such as shapes, slopes or curvatures  
\(p\) = index representing mode number excited  
\(q\) = index representing mode number used for the best-fit  
\(l\) = number below which it is considered low modes  
\(h\) = number above which it is considered high modes  
\(A_{i,j}\) = Mode shape of \(j^{th}\) mode at \(i^{th}\) sensor location  
\(\kappa_{i,j}\) = Mode curvature of \(j^{th}\) mode at \(i^{th}\) sensor location  
\(\lambda_{p,q}\) = Best fit amplitudes of mode \(q\) through mode \(p\)  
\(CI\) = Modal clarity index  
\(\rho_l\), \(\rho_m\), \(\rho_h\) = weights considered for low, middle and high mode numbers  
\(S\) = scale factor matrix used as weighting functions for combining different types of measurements

**MEASUREMENTS AND DATA LOGGING METHODS**

The data logging methods that are currently in industry practice are stand-alone and real-time monitoring. For stand-alone monitoring systems the sensors are powered by batteries and the measurements are stored locally. For real-time monitoring systems the power to the sensors is provided via hardwired links from the rig power supply and the data streamed back to the top-side data acquisition system. Both the methods of data logging have certain advantages and disadvantages, as discussed by Pei et al, [3] and Podskarbi et al, [4].

Typical measurement devices used for monitoring riser dynamics are motion sensing devices such as accelerometers, angular rate sensors, inclinometers, and strain measurement devices. The parameters such as shapes and curvatures along the riser can be derived from the measurements to provide meaningful data on riser VIV response. The state of the art analysis techniques used to interpret the measured VIV response is discussed by Thethi et al, [5].

**SENSOR PLACEMENT CONSIDERATIONS**

The principle behind the sensor placement is to have sufficient spacial extent of the sensors and spacing between the sensors to capture the entire modes of riser response expected. The sensor array can be distributed along the whole riser or clustered in to groups near the areas of interest. The spacial extent of the sensor array should capture at least a quarter wave length of the lowest mode number of interest, as shown in Figure 1, and must provide sufficient measurement points to distinguish between higher mode numbers.

Spatial aliasing is an effect of insufficient sampling of the data along the length of the riser and as a result the measurements at the discrete locations cannot be uniquely correlated to the original shape, as shown in Figure 2. Measurement data should be sampled at least two per wavelength of the highest mode of response required to capture.

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![Figure 1 – Illustration of Sensor Array Extent Required](image1)

![Figure 2 – Example of Spacial Aliasing](image2)

For deepwater risers a broad range of modes are expected to be excited due to VIV. To monitor using sensor arrays distributed along the whole length would require at least as many sensors as the highest mode expected. This could prove to be expensive.

As an alternative, sensors may be clustered together in arrays near the top, middle or bottom of the riser depending on the region of greatest interest and can capture a broad range of excited modes with a minimum number of sensors. In addition, locating a cluster distant from the main cluster enables calibration of the modal response derived from the main cluster of sensors.

The spacing of loggers within each cluster determines the discrete data points available to interpret the riser response. The logger locations need to be optimized to maximise the accuracy with which modal contributions can be identified and minimise
the potential for modal confusion, up to the highest mode expected.

SENSOR PLACEMENT APPROACH

The basic approach is to consider several feasible sensor arrangements and assess the relative merit between the arrangements. For a typical deepwater riser monitoring program different sensor arrangements with the following parameters are considered:

1. Sensor arrays in clusters and spread along the whole riser;
2. Location of the clusters - top, middle and bottom;
3. Spacing between sensors;
4. Number of sensors.

Typical sensor arrangements considered for a typical drilling riser monitoring program is shown in Figure 3. Any installation constraints and accessibility to monitor particular locations along the riser should be considered before generating several sensor arrangements.

![Drilling Riser Monitoring Sensor Arrangements](image)

**Figure 3 – Sensor Arrangements Considered for Deepwater Drilling Riser Monitoring**

The arrangements are evaluated by a linear regression method based on the principles of modal decomposition. The method predicts the accuracy in capturing entire range of modes expected due to VIV, based on the discrete measurement data points along the riser, with the modes adjacent to the excited mode of response.

The motion and strain measurements obtained can be converted to shapes and curvatures respectively to represent the modal response from the measurements. The derived quantities at the sensor locations can then be compared against the analytical response shapes and curvatures.

The phase of response between adjacent sensors is not considered for stand alone monitoring systems because the clock synchronization between sensors is unlikely to be adequate.

An index called the modal clarity index is used to determine the extent of spatial aliasing between any two modes. The distinction between the interpreted response at the discrete locations and the modes adjacent to the excited mode of response is defined as modal clarity. Modal clarity index is calculated as the sum of the square of the difference between any mode number \( n \) as measured by the sensor at the sensor locations and the best fit of mode number \( m \). An illustration of the modal clarity index is given in Figure 4. The objective is to determine the sensor locations that maximize the clarity between adjacent modes of response.

![Modal Clarity Index Definition](image)

**Figure 4 – Illustration of Modal Clarity Index**

For the range of modes of interest, a modal clarity matrix is determined whose terms represent the modal clarity indices. The mathematical details are discussed in the next section. The modal clarity matrix obtained for a particular sensor arrangement is condensed to an index called configuration clarity index, which represent the measurement clarity for the entire range of modes. The configuration clarity indices are calculated for all the sensor arrangements considered and the arrangement with the highest clarity is chosen.

PLACEMENT METHODOLOGY

A matrix \([\alpha]\) is constructed such that each column represents normalized modal information such as shapes, slopes or curvatures at each sensor location as basis functions. The modal information can be obtained from finite element analysis or by assuming sinusoids. Mode shapes or slopes should be used if motion sensors such as accelerometers or angular rate sensors are used for monitoring. For strain sensors, modal curvatures are used as basis functions.

The phase information is ignored by taking the absolute modal amplitudes for stand-alone monitoring. The basis function matrix \([\alpha]\) represent the basis functions at \( n \) sensor
locations and \( m \) modes, and has dimensions of \( n \times m \). A matrix \([\alpha]_{j}\) is the basis function for the \( j \)th mode.

\[
[\alpha] = \begin{bmatrix}
A_{1,1} & \cdots & A_{1,m} \\
\vdots & \ddots & \vdots \\
A_{n,1} & \cdots & A_{n,m}
\end{bmatrix}_{n \times m}
\]  

(1)

where,

\( A_{i,j} \) is the basis function of \( j \)th mode at the \( i \)th sensor location.

Assuming the \( p \)th mode is excited, the best fit amplitude for each mode in the entire range of modes is calculated using a least squares method. A matrix \([\lambda_{p,q}]\) represents the best fit of amplitudes from mode \( q \) through mode \( p \).

The pseudo inverse solution for the system of equations \([A]\{X\} = [B]\) can be written as,

\[
\{X\} = ([A]^{T}[A])^{-1}[A]^{T}[B]
\]  

(2)

Similarly, the best fit amplitude of \( p \)th mode \([\alpha]_{p}\) to the \( q \)th mode \([\alpha]_{q}\) is given by,

\[
\lambda_{p,q} = \frac{\sum_{i=1}^{n} \alpha_{p,i} \alpha_{q,i}}{\sum_{i=1}^{n} \alpha_{q,i}^{2}}
\]  

(3)

The modal clarity indices are calculated as the difference between the excited mode \( p \) and the best fit of mode \( q \). This is obtained as shown,

\[
CI_{p,q} = [\alpha_{p} - \lambda_{p,q} \alpha_{q}]^{T} [\alpha_{p} - \lambda_{p,q} \alpha_{q}]
\]  

(4)

The dimension of modal clarity matrix \([CI]\) is \( m \times m \). A sample plot of an ideal modal clarity matrix is shown in Figure 5. The clarity indices are shown for modes excited along the X axis and the modes interpreted along the Y axis. The modal clarity index is 0 for best fit of mode \( p \) with mode \( p \). The off-diagonal values represent the extent to which the adjacent modes can be confused with the excited mode. The clarity should be higher with the adjacent modes. For modal response components farther apart can be distinctly identified based on response frequencies in the frequency domain.

\[\text{Figure 5 – Example Ideal Modal Clarity Matrix Plot}\]

The clarity indices thus obtained are condensed to provide a representative index for that particular sensor arrangement. An index called configuration clarity index, \( CCI \), is calculated as the root mean square value of the average modal clarity indices with the adjacent modes. The derivation of the \( CCI \) is given in Table 1.

The clarity indices can be calculated in different mode ranges of interest such as low, middle and high response modes. Depending on the objective of the monitoring program, clarity indices for low, mid or high mode numbers can be weighted accordingly while calculating \( CCI \).

\[
\text{Table 1 – Configuration Clarity Index Definition}\]

\begin{center}
\begin{tabular}{|c|c|}
\hline
Parameter & Definition \\
\hline
Average Clarity Index (\( ACI_{p} \)) & \frac{\sum_{q=2}^{q+2} \text{ModalClarityIndex}_{p,q}}{5} \\
\hline
Low Modes Clarity Index (\( LMCI \)) & \sum_{p=1}^{l} ACI_{p} \\
\hline
Mid Modes Clarity Index (\( MMCI \)) & \sum_{p=d}^{h} ACI_{p} \\
\hline
High Modes Clarity Index (\( HMCI \)) & \sum_{p=h}^{m} ACI_{p} \\
\hline
Configuration Clarity Index (\( CCI \)) & \sqrt{\left(\rho_{L}^{2}LMCI\right) + \left(\rho_{M}^{2}MMCI\right) + \left(\rho_{H}^{2}HMCI\right)^{2}} \\
\hline
\end{tabular}
\end{center}

\textbf{EXAMPLE OF MODAL CLARITY ASSESSMENT}

A total of 73 motion sensor arrangements are considered for a typical Gulf of Mexico SCR, as shown in Figure 6. The
fatigue critical locations for an SCR are located near the touch down point (TDP) and at the SCR hang-off location. Therefore, 2 clusters of motion sensors, one near the top and the other towards the touch down zone are considered.

The 73 configurations considered include different spacing between motion sensors, numbers of sensors used and the location of the clusters near the hang-off and touch down zones.

Configuration clarity values, $CCI$, for all the 73 configurations assessed using the methodology described above are shown in Figure 7. $CCI$ values for 50, 100 and 1000 motion sensor configurations converge to a value of 3.05.

The $CCI$ plot shows that increase in spacing to 80ft and 100ft between motion sensors does not provide significant improvement in the modal clarity. Configurations with motion sensor clusters towards the middle of the riser provide modal clarity higher than 3.0. The shapes of the adjacent modes are clearly distinguishable when sensors are clustered towards the middle of the riser, as shown in Figure 8.

Figure 9 shows the modal clarity matrix plot for the configuration with the highest clarity. The clarity indices are shown for modes excited along the X axis and the modes interpreted along the Y axis. The off-diagonal values represent the extent to which the adjacent modes can be confused with the excited mode. Modes 5 and above can be clearly distinguished from the adjacent modes. Similarly, for the low mode numbers except for mode 4 response, the chosen sensor arrangement provides high clarity. Spatial aliasing occurs with the 5th adjacent mode for modes greater than 5, which can be clearly distinguished by the corresponding response frequencies.

Figure 6 – Motion Sensor Arrangements Considered for a Typical GoM SCR

Figure 7 – Configuration Clarity Indices for a Typical GoM SCR

Figure 8 – Mode Shapes of a Typical GoM SCR

Figure 9 – Modal Clarity Matrix Plot – Recommended Configuration
COMBINING MULTIPLE MEASUREMENTS

The instrumentation can involve multiple measurement quantities such as motion and strain sensors. Different measurement quantities can be used together to interpret the riser response. The linear regression approach described in the previous sections is adapted to use different measurement quantities.

Assuming accelerometers and strain sensors are used, the basis function matrix \( [\alpha] \) contains normalized mode shapes at the accelerometer locations, and curvatures at the strain sensor locations.

\[
[\alpha] = \begin{bmatrix}
A_{1,1} & \ldots & A_{1,m} \\
\vdots & & \vdots \\
A_{n,1} & \ldots & A_{n,m} \\
\kappa_{1,1} & \ldots & \kappa_{1,m} \\
\vdots & & \vdots \\
\kappa_{s,1} & \ldots & \kappa_{s,m} \end{bmatrix}_{(n+m)xm}
\]  

(5)

where,

\( A_{i,j} = \) Mode shape of \( j^{th} \) mode at \( i^{th} \) sensor location

\( \kappa_{i,j} = \) Modal curvature of \( j^{th} \) mode at \( i^{th} \) sensor location

In order to combine two measurement quantities of different type and magnitudes a scale factor is used, as described by Kaasen et al. [4]. The scale factor matrix is a diagonal matrix whose elements are the inverse square root of the maximum base function for each mode.

\[
S = \begin{bmatrix}
\max(\alpha_1) \quad & \max(\alpha_m) \\
\cdots & \cdots \\
\max(\kappa_1) & \max(\kappa_m)
\end{bmatrix}_{m \times m}
\]  

(6)

The pseudo inverse solution for the system of equations \([A] \{X\} = [B]\) with a scale factor matrix can be written as,

\[
\{X\} = ([A]^T[S][A])^{-1} [S][A]^T[B]
\]  

(7)

Similarly, the best fit amplitude \( \lambda_{p,q} \) of \( p^{th} \) mode \([\alpha]_p\) to the \( q^{th} \) mode \([\alpha]_q\) is given by,

\[
\lambda_{p,q} = \frac{\sum_{i=1}^{n+m} \alpha_{p,i} \alpha_{q,i} S_{i,i}}{\sum_{i=1}^{n+m} \alpha_{q,i}^2 S_{i,i}}
\]  

(8)

The modal clarity indices are calculated as the difference between the excited mode \( p \) and the best fit of mode \( q \). This is obtained as shown,

\[
CI_{p,q} = \left[ \alpha_p - \lambda_{p,q} \alpha_q \right]^T[S] \left[ \alpha_p - \lambda_{p,q} \alpha_q \right]
\]  

(9)

CONCLUSIONS

Full-scale riser data is required to understand the global riser VIV response and verify VIV prediction tools. The numbers and positions of instruments required to measure response need to be carefully selected to ensure that the response is satisfactorily captured while avoiding excessive expense. An optimization technique to identify the number of sensors required and the sensor locations is described. The method uses modal decomposition and linear regression analysis techniques. In addition, a method to incorporate measurements of different types in the optimization method is described.

The modal clarity method described is applicable for all the monitoring programs for which the data interpretation is based on the principle of modal decomposition. Accurate prediction of modal information such as shapes, slopes and curvatures can provide best results. The sensor installation and accessibility constraints should be considered to ensure optimum solution.

The optimization method has been applied to various deepwater riser monitoring programs to define sensor placement requirements. The data thus collected on various drilling risers provides a valuable basis for the calibration of VIV analysis tools and rationalization of design methods, [2].

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REFERENCES


