VIBRATION-BASED DAMAGE DETECTION IN FLEXIBLE RISERS USING TIME SERIES ANALYSIS

Carlos RIVEROS¹, Tomoaki UTSUNOMIYA², Katsuya MAEDA³ and Kazuaki ITOH⁴

¹Student Member of JSCE, Dept. of Civil and Earth Resources Eng., Kyoto University (Katsura Campus, Nishikyo-ku, Kyoto 615-8540, Japan) E-mail: criveros@mbox.kudpc.kyoto-u.ac.jp
²Member of JSCE, Associate Professor, Dept. of Civil and Earth Resources Eng., Kyoto University (Katsura Campus, Nishikyo-ku, Kyoto 615-8540, Japan) E-mail: utsunomi@mbox.kudpc.kyoto-u.ac.jp
³Deep Sea Technology Research Group, National Maritime Research Institute (6-38-1, Shinkawa, Mitaka-shi, Tokyo 181-0004, Japan) E-mail: kmaeda@nmri.go.jp
⁴Marine Technology Research and Development Program, Marine Technology Center, JAMSTEC (2-15, Natashima-cho, Yokosuka 237-0061, Japan) E-mail: itohk@jamstec.go.jp

In this paper, a statistical pattern recognition method based on time series analysis is implemented in flexible risers. This method uses a combination of Auto-Regressive (AR) and Auto-Regressive with exogenous inputs (ARX) prediction models. The flexible riser model used in this paper is experimentally validated employing a proposed numerical scheme for dynamic response of flexible risers. A modal-based damage detection approach is also implemented in the flexible riser model and its results are compared with the ones obtained from time series analysis. The numerical results show that the time series analysis presented in this paper is able to detect and locate structural deterioration related to fatigue damage in flexible risers. Finally, considering the case study results presented in this paper, the presented AR-ARX prediction model works better than the modal-based damage detection method.

Key Words: flexible riser, damage detection, time series analysis, AR-ARX prediction model

1. INTRODUCTION

The oil production industry is gradually moving into deeper waters demanding accurate and reliable damage detection tools for offshore structures. One of the most important structural components needed for oil extraction in deep waters is the slender flexible pipe (riser), which is used to carry oil from the seabed to offshore facilities. Therefore, the flexible riser is currently receiving considerable attention by the research community due to its complex dynamic response and its economical impact when large structural degradation mainly caused by Vortex-Induced Vibration (VIV) affects its structural integrity. Recent advances in sensing technology are making possible the use of sensing systems to assess the current health state of civil structures; the main idea behind this approach is that measured modal parameters can be used to detect structural damage.

According to Rytter¹, a robust vibration-based damage detection system is divided into four levels: identification of damage that has occurred at a very early stage (Level I), localization of damage (Level II), quantification of damage (Level III) and prediction of the remaining useful life of the structure (Level IV). Although damage monitoring of civil structures has generated a lot of research over the past years, there is still a debate whether the measured deviations are significant enough to be a good indicator of structural degradation. It is widely recognized from sensitivity studies using finite element models and from in-situ tests of artificially damaged structures that the decrease of frequencies is often relatively low. Furthermore, although the local stiffness drop at a local damage site may be high, the global stiffness results in relatively small frequency changes, which can only be detected with precise measurement and identification procedures.
Vibration-based damage detection methods, which are able to locate and quantify structural damage, are based on the premise that the mass of a structure does not change appreciably as a result of structural damage. This assumption may not be true for offshore structures due to variation of structural mass or marine growth, which can cause uncertainty in the measured modal parameters. In addition, when an offshore structure is used to support tanks, the fluid in tanks can also vary its mass. Many studies have been conducted in this area showing that damage-induced frequency shifts are difficult to distinguish from shifts resulting from increased mass. Furthermore, structural damage usually causes changes in the order of the mode shapes; highlighting the importance of identifying a mode shape as well as its corresponding resonant frequency to accurately track its changes, which is not easy considering the adverse marine conditions commonly affecting offshore structures.

An innovative approach to assess the current health state of a structure is the statistical analysis of its measured vibration data. This approach offers several advantages over existing modal-based damage detection methods. Modeling errors and modal identification limitations are avoided in this approach making it more attractive and affordable for the development of a vibration-based damage detection framework for flexible risers.

In this paper, a numerical scheme to predict the dynamic response of flexible risers is implemented in a flexible riser model and its results are validated using experimental data. This riser model is then used to implement a modal-based damage detection approach. This approach was selected based on previous comparative studies where the best performance of this approach is demonstrated. Modal identification data is obtained from impulse response synthesis followed by system identification and structural damage detection. Finally, a time series analysis procedure is implemented in the flexible riser model and its results are compared with the ones obtained from the modal-based damage detection approach.

2. NUMERICAL SCHEME FOR DYNAMIC RESPONSE OF FLEXIBLE RISERS

A numerical scheme to simulate the VIV response of flexible risers was developed by Riveros et al.\(^2\). The Finite Element Method (FEM) was used in conjunction with the quasi-steady model\(^3\) to predict the transverse response of flexible risers taking into consideration the main features of the VIV process. One of the main advantages of the proposed numerical scheme is its relatively simplicity when compared with numerical schemes that involve the computation of the fluid forces using Computational Fluids Dynamics (CFD). A 35-meter riser model was used to experimentally validate the numerical scheme proposed by Riveros et al.\(^2\). Good agreement was observed in those comparisons.

The proposed numerical scheme uses the model presented in Eq. (1) to represent the in-line motion of a structure under the action of fluid flow.

\[
\begin{align*}
&m_0 \ddot{x}_i + 2m_0 \zeta_0 \omega_0 \dot{x}_i + k_{x_i} x_i = \rho S C_m U_i \\
&\quad - \rho S C_d \dot{x}_i + \frac{1}{2} \rho D C_d (U_i - \dot{x}_i) [U_i - \dot{x}_i] 
\end{align*}
\] (1)

where \(m_0\) is the mass of the structure per unit length, \(x_i\) is the relative displacement of the structure, \(\zeta_0\) is the damping coefficient, \(\omega_0\) is the natural frequency of the structure without fluid surrounding it and \(k_{x_i}\) is the stiffness parameter related to the physical properties of the structure. The density of the surrounding fluid is denoted by \(\rho\), the cross-sectional area of the displaced fluid by \(S\), the steady velocity of the fluid in the in-line direction acting on the surface of the structure is defined by \(U_i\), and \(D\) is defined as the characteristic length (e.g. diameter of the riser). The three force parameters correspond to the widely recognized approach proposed by Morison et al.\(^3\). The mean drag coefficient is denoted by \(C_d\), the added-mass coefficient by \(C\), and the inertia coefficient is defined by \(C_m = C_{i+1.0}\).

(1) The quasi-steady model

The analytical representation of the transverse (lift) force is incorporated into the numerical scheme by using the quasi-steady procedure presented by Obasaju et al.\(^4\). This model is used in conjunction with the left-hand side of the Eq. (1) to represent the cross-flow response of a structure using the corresponding stiffness parameter and the relative displacement of the structure in the cross-flow direction. The quasi-steady procedure assumes that regular shedding of vortices produces a sinusoidal force (transverse lift force), which is proportional to the square of the in-line maximum velocity as shown in Eq. (2).

\[
F_L(t) = \frac{1}{2} \rho U_0^2 D C_{\text{lift max}} \sin(2 \pi t \omega L + \psi) \quad (2)
\]

where \(F_L\) is the lift force per unit length of the structure, \(U_0\) is the relative in-line maximum velocity, \(C_{\text{lift max}}\) is the maximum lift coefficient, \(\omega L\) is the dominant frequency and \(\psi\) is the phase angle.
(2) Numerical implementation

The numerical solution of the differential equation governing the static and dynamic behavior of a flexible riser, presented in Eq. (1), is carried out using the Finite Element Method (FEM). The commercial software ABAQUS is used to assemble the FE model of the riser and the ABAQUS/Aqua capability is used to input the in-line hydrodynamic forces to the riser.

The riser is then idealized as an assembly of 2-node cubic pipe elements using the Euler-Bernoulli beam theory. The main idea behind this procedure is that using multiple beam elements to compose the flexible riser allows the element cubic shape functions to more closely fit the actual shape function of a nonlinear beam, thus improves the simulation accuracy.

Due to the inherently nonlinear behavior of the riser response, a nonlinear time-domain method is selected. A static stress analysis is performed in order to apply the self-weight of the riser. As a result, the geometric nonlinearity is included during this step. The dynamic response of the riser is computed using the direct-integration method, during this step the quasi-steady model is incorporated into the proposed numerical scheme using an in-house FORTRAN subroutine developed by Riveros et al.

3. MODAL-BASED DAMAGE DETECTION APPROACH

The modal-based damage detection approach proposed in this paper consists of three steps; in the first step, ambient excitation sources are employed to extract the free response behavior of a riser, which is used in the second step to obtain its modal information and finally, by comparing the obtained modal parameters of the healthy and damaged states of the riser, a deterministic damage detection algorithm locates damaged sites. These methods are described in the following sections.

(1) Impulse response synthesis from ambient measurements

Farrar and James found that if an unknown excitation is a white-noise random process, the cross-correlation function between two response measurements would have the same form as the free response of the structure. This method is known as the Natural Excitation Technique (NExT) and it is very important due to physical limitations to calculate the magnitude of the exciting forces during an ambient excitation test. This statement, therefore, allows us to use fluid forces to excite a flexible riser and obtain its free response.

(2) System identification

The use of accurate modal information for system identification will lead to reliable damage detection results. The most commonly used system identification methods are the extended Kalman Filters, the Polyreference time domain method, the multivariate Auto-Regressive and Moving Average (ARMA) model, the Q-Markov COVER algorithm, and the Eigensystem Realization Algorithm (ERA).

In this paper, ERA is selected for system identification. This algorithm has been successfully used during the last two decades for several researchers showing good performance due to its ability to handle measurement data corrupted by noise and indicators that allow quantification of the obtained modal parameters.

The mathematical formulation of the ERA uses the Hankel matrix, which is formed using the response vector obtained from synthesized free-response. The generalized Hankel matrix consisting of Markov’s parameters is constructed as shown in Eq. (3).

\[
\begin{bmatrix}
Y(k) & \ldots & Y(k+s-1) \\
Y(k+1) & \ldots & Y(k+s) \\
\vdots & \ddots & \vdots \\
Y(k+r-1) & \ldots & Y(k+r+s-2)
\end{bmatrix}
\]

where \([Y(k)]\) is the Markov’s parameter obtained from structural impulse response at \(k\)th time step. The number of columns and rows are represented by \(r\) and \(s\), respectively. The Hankel matrix is then evaluated for the \([H(0)]\), and a singular value decomposition technique is performed as shown in Eq. (4).

\[
[H(0)]=[P][D][Q]^T
\]

The diagonal matrix \([D]\) contains singular values that correspond to structural modes. However, small singular values are likely to appear in the diagonal values of the matrix \([D]\). Therefore, this diagonal matrix is condensed in order to retain the largest \(N\) singular values and then minimize the effect of computational modes. The matrices \(P\) and \(Q\) are square and unitary. The matrices \(D_N, P_N,\) and \(Q_N\) are obtained without considering computational modes. The basic ERA’s theorem states that, if the dimension of any minimal realization is \(N\), then the triplet shown in Eq. (5) is the minimum realization.
\[
[R] = [E_p] [P_N] [D_N]^{1/2}
\]
\[
[A] = [D_N]^{1/2} [P_N] [H(1)] [Q_N] [D_N]^{-1/2}
\]
\[
[B] = [D_N]^{1/2} [Q_N] [E_q]
\]

where \( E_p \) is defined as \([[[1] \ 0 \ ... \ 0]]\)^T, and \( E_q \) is defined similarly. The unknown matrix \( A \) contains the eigenvalues and modal damping values of the structure and the matrix \( R \) is used for the transformation of the corrupted eigenvectors, in the state space matrix, to the physical states model.

(3) Structural damage detection

The Damage Index (DI) method\(^{12}\) is adopted here for damage detection. This method has been extensively used in previous damage detection studies showing its best performance over other existing damage detection methods (Farrar and Jauregui\(^{13}\) and Barroso and Rodriguez\(^{14}\)). The DI method was developed by Stubbs et al.\(^{12}\) to detect the existence and location of damage in a structure and is based on the assumption that strain energy stored in damaged regions will decrease after the occurrence of damage. The damage index, \( \beta_i \), is estimated by the change of the curvature of a particular mode shape, which is related to mode strain energy changes at location \( j \), \( \beta_j \) is then defined in Eq. (6).

\[
\beta = \frac{\int_a^b [\psi_{ij}^* (x)^2] \, dx + \int_0^l [\psi_{ij}^* (x)]^2 \, dx}{\int_a^b [\psi_{ij}^* (x)^2] \, dx + \int_0^l [\psi_{ij}^* (x)]^2 \, dx}
\]

(6)

where \( \psi_{ij}^* \) and \( \psi_{ij}^{**} \) are the second derivatives of the \( i \)th mode shape before and after the occurrence of damage, respectively. \( L \) is the length of the beam element in which damage is being evaluated, and \( a \) and \( b \) are the limits of this beam element. The damage index for the selected mode shapes is obtained by adding the individual contribution of the damage index of each of the selected mode shapes.

The damage index procedure can be summarized as follows: (1) calculate the mode shapes amplitudes for the nodes where sensors are located; (2) estimate the amplitudes of the mode shapes for the nodes where no sensors are located by interpolating the instrumented nodes using cubic-spline functions; and, (3) take a second derivative of the interpolation function at each node. Finally, treating \( \beta_i \) as a realization of a normally distributed random variable \( \beta \), a normalized damage index is computed as shown in Eq. (7).

\[
Z_j = \frac{\beta_j - \bar{\beta}}{\sigma_\beta}
\]

(7)

where \( \bar{\beta} \) and \( \sigma_\beta \) are the mean and standard deviation of the damage index, respectively. The \( i \)th sub-structure is defined as damaged when \( Z_i > 2 \), which corresponds to a hypothesis testing with 95% confidence level. The DI method is implemented in this paper using the graphical user interface DIAMOND developed at Los Alamos National Laboratory (Doebbling et al.\(^{15}\)).

4. AR-ARX PREDICTION MODEL

Sohn et al.\(^{16}\) presented a comprehensive report providing an overview of existing damage detection methods. The main conclusion that can be drawn from this report is that modal-based damage detection methods usually require large amount of high-quality data and considerable number of sensors strategically located, requirements that are almost impossible to meet in the field. Therefore, the research community has been recently exploring the use of pattern recognition approaches to tackle the problem of reliable damage detection when vibration data are measured at limited locations.

Sohn et al.\(^{17}\) developed an AR-ARX prediction model, which is solely based on signal analysis of measured vibration data. This model has been successfully implemented in various damage detection problems as reported by Sohn et al.\(^{17}\). The mathematical derivation of the model begins by using standardized time signals as shown in Eq. (8).

\[
x(t) = \frac{x(t) - \mu_x}{\sigma_x}
\]

(8)

where \( x(t) \) is the standardized signal of the initial signal \( x(t) \) at the time step \( t \) and \( \mu_x \) and \( \sigma_x \) are the mean and standard deviation of \( x(t) \), respectively. The next step consists on the construction of AR(p) models for each sensor channel. One of the damage identification features that is proposed in this paper involves the use of the coefficients of the AR(p) models. Therefore, a computationally efficient stepwise least squares algorithm for the estimation of AR(p) parameters is used herein in conjunction with the AR-ARX model proposed by Sohn et al.\(^{17}\).
An AR model using the Yule-Walker method as proposed by Sohn et al.\(^{(17)}\) is then replaced by the ARfit algorithm proposed by Neumaier and Schneider\(^{(18)}\). This algorithm computes the model order, \(p_{opt}\), that optimizes the order selection criteria using a QR factorization of a data matrix to evaluate, for a sequence of successive orders, the model order and to compute the parameters of the AR(\(p_{opt}\)) model. Then, the AR(\(p_{opt}\)) model can be represented as shown in Eq. (9).

\[
x(t) = \sum_{j=1}^{p_{opt}} \phi_{ij} x(t-j) + \varepsilon_x(t) \quad (9)
\]

Once the AR(\(p_{opt}\)) model has been constructed, the residual error of the model, \(\varepsilon_x(t)\), is computed by subtracting the data obtained from the AR(\(p_{opt}\)) model from the standardized signal, \(x(t)\). The AR(\(p_{opt}\)) coefficients, \(\phi_{ij}\), will later be used to locate damaged sites. Finally, the residual error, \(\varepsilon_x(t)\), is employed in the construction of the ARX model as shown in Eq. (10) by assuming that this residual error, defined by the difference between the measured and the predicted values obtained from the AR model, is mainly caused by an unknown external input.

\[
x(t) = \sum_{i=1}^{a} \alpha_i x(t-i) + \sum_{j=1}^{b} \beta_j \varepsilon_x(t-j) + \varepsilon_x(t) \quad (10)
\]

where \(\varepsilon_x(t)\) is the residual error after subtracting the ARX(\(a,b\)) model from the standardized signal, \(x(t)\). Similar results are obtained for different values of \(a\) and \(b\) as long as the sum of \(a\) and \(b\) is kept smaller than \(p_{opt}\) as reported by Sohn et al.\(^{(17)}\). The residual errors from the healthy state are defined as \(\varepsilon_x(t)\) and the residual errors after the occurrence of structural damage are defined as \(\varepsilon_y(t)\). Finally, using the standard deviations of \(\varepsilon_x(t)\) and \(\varepsilon_y(t)\), the ratio, \(\sigma(\varepsilon_x) / \sigma(\varepsilon_y)\), is then defined as the first damage sensitivity feature. A threshold value for this ratio must be computed using measured vibration data obtained from different operational conditions. Therefore, a value of this ratio larger than the computed threshold value indicates the occurrence of damage (Level 1). The standard deviation of the Mahalanobis squared distance between healthy and damaged AR(\(p_{opt}\)) coefficients is then used to locate structural damaged sites as shown in Eq. (11).

\[
D = \sigma(\phi^d_{ij} - \phi^h_{ij})^T s^{-1}(\phi^d_{ij} - \phi^h_{ij}) \quad (11)
\]

where \(\phi^d_{ij}\) are the AR(\(p_{opt}\)) coefficients from the damaged state, \(\phi^h_{ij}\) are the mean values from the healthy state and \(s\) is the covariance matrix of \(\phi^h_{ij}\). The Mahalanobis squared distance is independent of the scale of the AR(\(p_{opt}\)) coefficients. Therefore, vibration data collected at the sensor channel closest to the location of the structural damage would have the largest values of \(D\). The proposed AR-ARX prediction model uses two damage sensitivity features, \(\sigma(\varepsilon_x) / \sigma(\varepsilon_y)\) and \(D\), to identify and locate structural damage, respectively.

5. FLEXIBLE RISER MODEL

The experimental model presented by Senga and Koterayama\(^{(19)}\) is used herein. This model has a length of 6.5 m, Young’s modulus of 8.847 MPa, outer diameter of 0.0225 m, inner diameter of 0.093 m and a weight in water of 3.489 N. The riser model is simply supported at its top end and is excited at its top end by a sinusoidal forced oscillation motion with amplitude of 0.1 m and forced oscillation period of 8 sec.

Fig. 1 depicts the riser’s geometry, where the \(x\)-axis is defined in the direction of the forced oscillation motion. The coordinate system is then defined using the \(z\)-axis in the direction of the riser’s axis.
The forced oscillation experiments were carried out in an experimental tank of 65 m long, 5 m wide and 7 m deep. There is no horizontal water velocity component ($U=0$). Ten CCD cameras were used to measure the motion of the riser model; each pair of cameras is arranged at the same level in the $x$-$y$ direction. For the numerical implementation of the vibration-based damage detection approaches, sensors are located where CCD cameras are placed. Two additional sensors were located at points 3 and 5 as shown in Fig.1. Acceleration records are collected at sensor locations in $x$-axis and $y$-axis.

(1) Finite element model

The numerical scheme developed by Riveros et al.\(^2\) is implemented in the riser model presented by Senga and Koterayama\(^{19}\). The FE model is assembled using 21 pipe elements. One cylindrical element is used for the bottom weight. A geometric non-linear procedure is used to load the riser by its self-weight and the bottom weight during the static step; then, the drag force and the fluid inertia load are applied to the riser during the dynamic step. The hydrodynamic coefficients were obtained from experiments conducted by Koterayama and Nakamura\(^{20}\), and the maximum lift coefficients were obtained from Sanghafian et al.\(^{21}\).

The model is sinusoidally excited at Reynolds numbers (Re) up to 2000 and Keulegan-Carpenter (KC) numbers up to 28. This regime is named the third vortex ($22 \leq \text{KC} \leq 30$) by Obasaju et al.\(^4\). In this regime three full vortices are formed during each half cycle and three vortex pairs convect away from the cylinder during a complete cycle. Experimental studies had shown that the dominant frequency is four times the in-line oscillating frequency. In this numerical implementation, the in-line maximum velocities for each of the 21 pipe elements are used to compute dominant frequencies.

Another important parameter to be considered in the quasi-steady model is the beta parameter ($\beta=\text{Re}/\text{KC}$), because several experimental studies have shown that the maximum lift coefficient depends on the beta parameter at low KC numbers ($\text{KC} \leq 15$), but in the third vortex region can be assumed without loss of accuracy that the maximum lift coefficient only depends on the KC number at low Reynolds numbers ($\text{Re} \leq 14200$) as reported by Senga and Koterayama\(^{19}\).

The FE model is initially excited without considering the transverse (lift) force, during this stage the in-house FORTRAN subroutine computes the maximum displacements and velocities at all nodes. A time increment of 0.01 sec. is used during the dynamic step. The KC numbers and the maximum lift coefficients for all sections are calculated using the

maximum displacements and velocities computed in the previous stage. The procedure to calculate the phase angle is based on the time difference between the time required for each section of the FE model to achieve its maximum displacement and the required time at the top end to achieve the same condition.

The in-house FORTRAN subroutine computes and applies the transverse (lift) force to each element of the FE model using the quasi-steady model. In-line and transverse response results were found to be good agreement with the experimental data provided by Senga and Koterayama\(^{19}\).

(2) Damage scenarios

The VIV analysis of a flexible riser is still challenging due to the fact that the riser can be excited along its length in different modes and at different frequencies leading to a modal response dominated by mode interference, multi-mode response, mode switching and frequency dependence of the added mass. Furthermore, the resonant type VIV, when the vortex shedding frequency approaches, or is coincident with, a natural frequency of the riser, produces considerable transverse oscillations of the riser. Therefore, VIV may cause severe fatigue damage to flexible risers.

One of the main economical constraints for deep-water oil production is related to the design of risers for large safety factors on fatigue damage, which has been found to occur indiscriminately, and with the same magnitude, along the in-line and cross-flow directions as reported by Trim et al.\(^{22}\). Therefore, in this paper structural damage is associated with fatigue damage.

Hinge connections are used initially to represent six damage scenarios and are inflicted node-by-node for each of the instrumented locations as shown in Fig.1. The mechanism of the hinge connection is numerically represented by a zero-moment node. Thus, the rotational degree-of-freedom is released allowing the elements that limit the hinge connection to rotate freely relatively to the zero-moment node. Only intermediate locations are considered. Therefore, hinge connections at sensor locations 2, 3, 4, 5, 6, 7 are used. Table 1 shows the proposed damage scenarios and corresponding locations of the hinge connections.

<table>
<thead>
<tr>
<th>Damage Scenario</th>
<th>DS1</th>
<th>DS2</th>
<th>DS3</th>
<th>DS4</th>
<th>DS5</th>
<th>DS6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of the hinge</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 1 Damage Scenarios.
The acceleration records of the riser in its healthy state (HS) are collected only at instrumented locations as shown in Fig.1. A time step of 0.01 sec. and a total duration of 24 sec. are used for all the signals in the healthy and damaged states of the riser. Under normal operational conditions the healthy state characterization of the dynamic response of a flexible riser may show deviations that must be considered in order to build the baseline condition of the flexible riser. Because of the inherently limitations of any numerical simulation approach, in this paper the baseline condition is defined invariant and is constructed using the experimentally validated response previously presented.

Although acceleration records are collected in the in-line and cross-flow directions, only in-line response is considered in this paper for the implementation of the vibration-based damage detection approaches. The main reason is that the VIV process is still not well understood and is extremely complex exhibiting rapid and unpredictable shifts when its response is stationary. Furthermore, although the sheared flow generating the VIV process can be considered steady, the cross-flow response is mainly non-stationary.

6. SIMULATION RESULTS

To evaluate the performance of the two proposed vibration-based damage detection approaches, numerical simulations are performed using a limited number of structural responses to simulate the use of measurements from sensors. The acceleration records at these locations, obtained during the steady state response of the flexible riser, are used for the analysis. The simulation results obtained from the two proposed approaches are presented in the following sections.

(1) Modal-based damage detection results

The first step in the implementation of the proposed modal-based damage detection approach is the calculation of free vibration records from the loading excitation process. NExT is used to estimate impulse response functions from the acceleration records. The reference channel used to calculate the cross-correlation corresponds to sensor 3. Free vibration records calculated from NExT are then used for system identification using ERA. Only one mode can be identified considering the value of the forced oscillation period, which is identifiable for a Nyquist frequency equals to a half of the sampling frequency (50 Hz). 40 columns and 200 rows were used to compute the Hankel matrix. Tables 2 and 3 show the identified modal parameters for the healthy state (HS) and the six damage scenarios.

Finally, the DI method is used to locate damage. For the implementation of the DI method the riser is divided into 13 segments; the length of each segment is approximately 0.5 m. Table 4 shows the damage detection results for the six damage scenarios. Bold numbers indicate the location of the hinge for each of the damage scenarios and therefore it is expected that the damage index, presented in Eq. (7), shows the existence of structural damage for these locations. It can be seen from Table 4 that none of the damage scenarios is correctly identified. The required confidence level of 95% is not achieved, but there is a clear tendency in DS1, DS2, DS3 and DS6 to identify the location of the hinge with a lower confidence level. In the case of DS4 and DS5 the DI method failed to locate damage.

| Table 2 Identified Modal Parameters (HS, DS1, DS2, DS3). |
|---|---|---|---|
| Freq. (Hz) | HS | DS1 | DS2 | DS3 |
| Sensor 1 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| Sensor 2 | 0.9604 | 0.9667 | 0.9601 | 0.9646 |
| Sensor 3 | 0.7872 | 0.8147 | 0.7904 | 0.8117 |
| Sensor 4 | 0.5289 | 0.5933 | 0.5467 | 0.5920 |
| Sensor 5 | 0.2407 | 0.3346 | 0.2841 | 0.3338 |
| Sensor 6 | -0.0041 | 0.1028 | 0.0425 | 0.1060 |
| Sensor 7 | -0.2092 | -0.0923 | -0.1532 | -0.0962 |
| Sensor 8 | -0.3216 | -0.2120 | -0.2745 | -0.2158 |

| Table 3 Identified Modal Parameters (HS, DS4, DS5, DS6). |
|---|---|---|---|
| Freq. (Hz) | HS | DS4 | DS5 | DS6 |
| Sensor 1 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| Sensor 2 | 0.9604 | 0.9585 | 0.9613 | 0.9582 |
| Sensor 3 | 0.7872 | 0.7875 | 0.7943 | 0.7880 |
| Sensor 4 | 0.5289 | 0.5464 | 0.5555 | 0.5503 |
| Sensor 5 | 0.2407 | 0.2505 | 0.2667 | 0.2864 |
| Sensor 6 | -0.0041 | -0.0036 | 0.0291 | 0.0433 |
| Sensor 7 | -0.2092 | -0.1843 | -0.1843 | -0.1634 |
| Sensor 8 | -0.3216 | -0.3213 | -0.3213 | -0.2989 |

| Table 4 Damage Detection Results (Damage Index Method). |
|---|---|---|---|---|--- |
| Depth (m) | DS1 | DS2 | DS3 | DS4 | DS5 | DS6 |
| 6.5-6.0 | 1.86 | 0.35 | 0.24 | 0.03 | 0.36 | -0.33 |
| 6.0-5.5 | 0.77 | 0.85 | -0.72 | -0.12 | 0.02 | -0.41 |
| 5.5-5.0 | -1.07 | 1.22 | -1.88 | -0.29 | -0.46 | -0.35 |
| 5.0-4.5 | 0.01 | 0.11 | -0.33 | 0.35 | 0.46 | -0.37 |
| 4.5-4.0 | 1.38 | -0.54 | 1.35 | 1.02 | 1.47 | -0.25 |
| 4.0-3.5 | 0.26 | -0.13 | 0.29 | 0.22 | 0.25 | -0.08 |
| 3.5-3.0 | -1.02 | -1.05 | -0.39 | -0.04 | 0.68 | -1.65 |
| 3.0-2.5 | -0.51 | -0.68 | -0.45 | 0.67 | 1.04 | -1.09 |
| 2.5-2.0 | 0.26 | 0.83 | -0.42 | 1.36 | 0.42 | 0.88 |
| 2.0-1.5 | 0.44 | 1.33 | -0.50 | 0.93 | 0.06 | 1.81 |
| 1.5-1.0 | 0.05 | 0.61 | -0.17 | -0.32 | -0.57 | 1.65 |
| 1.0-0.5 | -0.85 | -0.84 | 0.97 | -1.59 | -1.56 | 0.69 |
| 0.5-0.0 | -1.60 | -2.07 | 2.03 | -2.21 | -2.18 | -0.50 |
There is only one inflection point located in between sensors 5 and 6. At these locations the hinge connection does not considerably affect the dynamic response of the riser after damage. It can partly explain why the DI method failed to identify cases DS4 and DS5. It can also be observed from Table 2 that the location of the inflection point moves to a different location as a result of structural damage.

The simulation results show that for all damage scenarios the variations of the identified mode shapes, as a result of damage, are not large enough to be detected by the DI method. Although structural damping was not included in the numerical simulations, the hydrodynamic damping induces a non-proportional damping to the riser model. One of the main limitations of any modal-based damage detection approach is that progressive structural damage is a non-stationary phenomena. Furthermore, measured vibration data are also influenced by a non-stationary effect related to the unavoidable variations during normal operational conditions.

Lucor et al.\textsuperscript{23}) performed full-scale experiments for riser modal identification. A main feature of riser modes, as described by Lucor et al.\textsuperscript{23}), is that they are complex showing variations in amplitude and phase along the length of the riser and are mainly a mixture of traveling and standing waves. According to Lucor et al.\textsuperscript{23}), the amount of energy input to a specific region of a riser is a function of the local Strouhal frequency. This amount of energy is then carried away to be dissipated to a different region of the riser, where the local Strouhal frequency is different and the fluid force resists the traveling wave, providing a damping force.

The frequency content of the in-line response is usually lower than the cross-flow response. Higher modes may produce better damage detection results, but considering the cross-flow response, which has a frequency content approximately four times higher that the in-line response in the riser model presented in this paper, its results may not be realistic for damage detection, because in sheared flows local response from one region may dominate the total response of a flexible riser by disrupting the excitation process in other regions (Lucor et al.\textsuperscript{23}).

(2) AR-ARX prediction model results

The acceleration records are standardized according to Eq. (8). Then, the AR-ARX model is implemented for all the signals obtained from the previous step at each sensor channel. The first damage sensitivity feature, \( \sigma(e_y)/\sigma(e_x) \), is then used to identify the occurrence of damage (Level I). The threshold value selected for this study is 1.0.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>DS1</th>
<th>DS2</th>
<th>DS3</th>
<th>DS4</th>
<th>DS5</th>
<th>DS6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor 1</td>
<td>1.000</td>
<td>0.992</td>
<td>0.983</td>
<td>1.001</td>
<td>0.981</td>
<td>1.000</td>
</tr>
<tr>
<td>Sensor 2</td>
<td>0.952</td>
<td>1.083</td>
<td>1.440</td>
<td>1.004</td>
<td>1.289</td>
<td>1.041</td>
</tr>
<tr>
<td>Sensor 3</td>
<td>1.105</td>
<td>1.302</td>
<td>1.489</td>
<td>1.028</td>
<td>1.508</td>
<td>1.215</td>
</tr>
<tr>
<td>Sensor 4</td>
<td>1.298</td>
<td>1.369</td>
<td>1.846</td>
<td>1.248</td>
<td>1.484</td>
<td>1.247</td>
</tr>
<tr>
<td>Sensor 5</td>
<td>1.189</td>
<td>1.071</td>
<td>1.329</td>
<td>1.346</td>
<td>1.019</td>
<td>1.003</td>
</tr>
<tr>
<td>Sensor 6</td>
<td>0.903</td>
<td>0.940</td>
<td>0.905</td>
<td>0.960</td>
<td>1.088</td>
<td>0.910</td>
</tr>
<tr>
<td>Sensor 7</td>
<td>1.014</td>
<td>0.983</td>
<td>1.154</td>
<td>0.973</td>
<td>1.157</td>
<td>1.170</td>
</tr>
<tr>
<td>Sensor 8</td>
<td>0.981</td>
<td>0.870</td>
<td>0.988</td>
<td>1.029</td>
<td>1.058</td>
<td>0.911</td>
</tr>
</tbody>
</table>

It is important to highlight that it is necessary to define a threshold value for each sensor channel under normal operational conditions, because some regions of the riser are more sensitive to structural damage than the others. Therefore, when new measured vibration data, in the damage state, are collected, one or more sensor channels may indicate significant deviations due to an abnormal structural condition while other sensor channels may indicate that the riser has not suffered structural damage. The results of the first damage sensitivity feature, \( \sigma(e_y)/\sigma(e_x) \), for the six damage scenarios, are presented in Table 5.

In Table 5, sensor 4 shows the largest deviations in the calculation of the first damage sensitivity features for four damage scenarios. Sensor 3 and 5 are also sensitive to damage scenarios DS5 and DS4, respectively. On the other hand, sensor 6 is almost insensitive to any damage scenario due to its proximity to the inflection point, but locations of the inflection points are extremely important in the area of structural health monitoring due to the fact that an abnormal response in this region may be automatically related to structural damage. Furthermore, these regions are almost insensitive to environmental conditions, which, in some cases, induce large variations in the measured vibration data and therefore false identification of structural damage.

The second step in the proposed AR-ARX prediction model is the calculation of the second sensitivity feature, \( \sigma(e_y)/\sigma(e_x) \), which is related to the location of structural damage (Level II). The order of the AR model using the ARfit algorithm was 10 and a ARX(10,10) model was selected for all damage scenarios. In Table 6, the calculation of the second sensitivity features for all damage scenarios is presented.

It can be seen from Table 6 that structural damage is correctly located for five damage scenarios, only the case DS3 is not located properly. Nevertheless, the value of the second sensitivity feature for the real location of damage in DS3 shows a small deviation from the maximum values obtained from sensor channels 5, 6 and 7.
The numerical results presented in Tables 6 and 7 show that structural damage was identified and located using the proposed damage sensitivity features. In order to study the sensitivity of the presented AR-ARX prediction model to identify and locate structural damage, when the hinge connection due to fatigue is created in nodes where sensors are not located, three additional damage scenarios are defined using Fig.1. The proposed damage scenarios are DS7, DS8 and DS9 having hinge connections at depths of 3.5 m, 2.5 m and 1.5 m, respectively. The numerical results for the three additional damage scenarios are presented in Table 7.

The numerical results presented in Table 7 show that the first damage sensitivity feature indicates the occurrence of damage especially at locations of sensors 4, 5 and 6. The location of damage in these damage scenarios is not related to a single sensor location, the inflicted damage may affect a region of the riser, which in some cases can not be measured by only one sensor channel highlighting the importance of having a dense array of sensors for continuous damage monitoring implementations. Finally, a comparative study is presented in this paper using the previously defined six damage scenarios, but instead of using hinge connections, structural damage is modeled as a 10% stiffness reduction of elements at locations defined in Table 8. The node locations of the damaged elements are expressed in meters. Then, the reduction of stiffness in an element length of 0.217 m represents the formation of the hinge connection at its initial stage.

### Table 6 Second Damage Sensitivity Feature Results.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>DS1</th>
<th>DS2</th>
<th>DS3</th>
<th>DS4</th>
<th>DS5</th>
<th>DS6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.826</td>
<td>3.204</td>
<td>1.669</td>
<td>3.822</td>
<td>1.664</td>
<td>3.825</td>
</tr>
<tr>
<td>2</td>
<td>7.507</td>
<td>5.933</td>
<td>4.726</td>
<td>6.494</td>
<td>5.180</td>
<td>5.943</td>
</tr>
<tr>
<td>3</td>
<td>6.744</td>
<td>6.089</td>
<td>3.873</td>
<td>5.765</td>
<td>4.735</td>
<td>5.402</td>
</tr>
<tr>
<td>4</td>
<td>5.692</td>
<td>4.609</td>
<td>4.992</td>
<td>5.772</td>
<td>4.717</td>
<td>5.088</td>
</tr>
<tr>
<td>5</td>
<td>5.499</td>
<td>4.830</td>
<td>4.998</td>
<td>5.774</td>
<td>4.739</td>
<td>5.341</td>
</tr>
<tr>
<td>6</td>
<td>5.933</td>
<td>5.433</td>
<td>5.007</td>
<td>5.961</td>
<td>5.837</td>
<td>6.054</td>
</tr>
<tr>
<td>7</td>
<td>5.410</td>
<td>5.149</td>
<td>5.288</td>
<td>5.535</td>
<td>5.410</td>
<td>6.706</td>
</tr>
<tr>
<td>8</td>
<td>5.717</td>
<td>5.231</td>
<td>4.381</td>
<td>6.480</td>
<td>5.011</td>
<td>6.097</td>
</tr>
</tbody>
</table>

### Table 7 Damage Detection Results (Cases DS7, DS8 and DS9).

<table>
<thead>
<tr>
<th>Sensor</th>
<th>DS7</th>
<th>DS8</th>
<th>DS9</th>
<th>DS7</th>
<th>DS8</th>
<th>DS9</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.995</td>
<td>0.978</td>
<td>0.998</td>
<td>3.808</td>
<td>1.481</td>
<td>3.820</td>
</tr>
<tr>
<td>2</td>
<td>1.113</td>
<td>0.849</td>
<td>1.329</td>
<td>6.978</td>
<td>4.631</td>
<td>7.035</td>
</tr>
<tr>
<td>3</td>
<td>1.187</td>
<td>0.749</td>
<td>1.482</td>
<td>6.500</td>
<td>4.051</td>
<td>6.327</td>
</tr>
<tr>
<td>4</td>
<td>1.094</td>
<td>0.933</td>
<td>1.575</td>
<td>6.214</td>
<td>5.469</td>
<td>6.316</td>
</tr>
<tr>
<td>5</td>
<td>1.018</td>
<td>1.396</td>
<td>1.254</td>
<td>6.065</td>
<td>3.979</td>
<td>6.594</td>
</tr>
<tr>
<td>6</td>
<td>1.216</td>
<td>1.096</td>
<td>0.959</td>
<td>6.274</td>
<td>4.256</td>
<td>6.287</td>
</tr>
<tr>
<td>7</td>
<td>0.983</td>
<td>0.939</td>
<td>1.109</td>
<td>6.106</td>
<td>3.907</td>
<td>6.998</td>
</tr>
<tr>
<td>8</td>
<td>0.999</td>
<td>1.095</td>
<td>0.975</td>
<td>6.518</td>
<td>4.685</td>
<td>7.349</td>
</tr>
</tbody>
</table>

### Table 8 Damage Scenarios at Initial Stage.

<table>
<thead>
<tr>
<th>Damage Scenario</th>
<th>DSA</th>
<th>DSB</th>
<th>DSC</th>
<th>DSD</th>
<th>DSE</th>
<th>DSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper node of damaged element</td>
<td>6.5</td>
<td>5.5</td>
<td>4.5</td>
<td>3.5</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Lower node of damaged element</td>
<td>6.283</td>
<td>5.283</td>
<td>4.283</td>
<td>3.283</td>
<td>2.283</td>
<td>1.283</td>
</tr>
</tbody>
</table>

Table 8 shows the distances, measured from the top end of the riser, corresponding to the upper and the lower nodes that limit the damaged elements. The damage detection results from the damage scenarios at their initial stages are presented in Tables 9 and 10. It can be seen from Table 9 that the first sensitivity feature has values closer to the previously defined threshold value. Sensors 4, 5 and 6 do not clearly indicate the occurrence of damage in contrast to the numerical results considering hinge connections. There is a large deviation in the presented values of DSA, which may be caused due to its proximity to the top end of the riser model.

In Table 10, only the damage scenario DSA is correctly located showing that the occurrence of damage presented in Table 9, showing large deviation in its values, is correctly linked to the second sensitivity feature. The damage results presented in Table 10 show that the remaining damage scenarios are not correctly identified.
The modal-based damage detection approach suffers from limitations related to the correct identification of the mode shapes as previously explained. The simulation results presented in this paper show that the proposed modal-based approach could not identify with acceptable level of confidence the existence of structural damage as shown in Table 4. On the other hand, the presented AR-ARX prediction model is independent of the aforementioned problems related to modal identification in risers and therefore is solely based on measured vibration data. The simulation results presented in Table 5 show that it is possible to have at least one sensor channel sensitive enough to identify the occurrence of structural damage. Table 6 shows that additional information related to the location of damage, which is extremely useful for work site inspection prioritization, can be obtained from the presented AR-ARX model.

Finally, the undesirable non-stationary effect related to progressive damage is avoided by the AR-ARX prediction model as shown in Tables 9 and 10, where the structural damage at its initial stage is not reported for most of the damage scenarios. Therefore, false damage identification, which is also of concern for its economical implications, is therefore partially avoided. A threshold value obtained from measured data at different operating conditions can tell the owner when a significant deviation of the measured vibration data collected in real time significantly deviate from normal operational conditions, which is extremely useful for health integrity of riser’s systems.

7. CONCLUSIONS

The numerical implementation of two vibration-based damage detection approaches on a flexible riser model was presented. A numerical scheme for dynamic response of flexible risers developed by the authors was used to obtain the dynamic response of the flexible riser model under different structural conditions. The healthy condition of the flexible riser model was experimentally validated.

The modal-based damage detection approach presented in this paper consists of three widely recognized methodologies namely NExT, ERA and the Damage Index method. The main objective of this implementation was to show the limitations of the modal approach when it is used in flexible risers. The main difficulties arise from variation of the structural mass, non-stationary response in the cross-flow direction and hydrodynamic damping.

The Damage Index method could locate the damage scenarios presented in this paper with a low confidence level. However, it was impossible to locate structural damage when it was inflicted near the inflection point. The use of the higher modes was avoided in order to present more realistic results, because the VIV process is still not well understood involving non-stationary response and a self-regulation process.

A statistical pattern recognition method based on time series analysis was used to show a more attractive approach for flexible risers. Acceleration records were collected at location of sensors and analyzed in order to obtain the two damage sensitivity features presented in this paper. Six damage scenarios were studied, the first damage sensitivity feature was able to indicate the occurrence of damage and the location of five damage scenarios was correctly identified for the second sensitivity feature.

Three additional damage scenarios were used to show the ability of the proposed statistical-based approach. The occurrence of damage was identified. However, the location of damage was spread into a larger identified region. Finally, the initial stages of the proposed damage scenarios were simulated by reducing the stiffness of short elements located in sensor regions. Although damage was not clearly identified, the stability of the proposed statistical-based approach was demonstrated.

A flexible riser involves many challenges due to its complex nonlinear behavior. The numerical scheme for dynamic response of flexible risers presented in this paper was developed in order to be used in damage detection studies. Other approaches may be extremely computationally demanding when several damage scenarios have to be simulated as in the study case presented in this paper, mainly those approaches involving the calculation of the fluid forces using Computational Fluid Dynamics (CFD).

Several issues need further study. The use of acceleration records for vibration-based damage detection may involve serious limitations for practical implementations. Vandiver(24) presented a comprehensive analysis of the main challenges related to instrumented marine risers. Basically, the use of accelerometers introduces a gravitational error component into the signals. On the other hand, other alternatives such as strain gages are expensive and difficult to install and calibrate.

This study shows a practical statistical-based approach for continuous damage monitoring of flexible risers. The AR-ARX prediction model can be easily incorporated in full-scale instrumentation projects if a reliable baseline condition of the flexible riser is provided. The statistical treatment of the proposed damage sensitivity features must be considered in order to improve the presented statistical-based damage detection approach.
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