5th International Conference on
Structural Health Monitoring of Intelligent Infrastructure (SHMII-5) 2011
11-15 December 2011, Cancún, México

NUMERICAL STUDY ON THE OPTIMAL POSITION OF SENSORS FOR MODAL PARAMETER EXTRACTION IN SCR

V.F. Hernández Abraham Escuela Superior de Ingeniería y Arquitectura-IPN, México	R. Rodríguez Rocha Escuela Superior de Ingeniería y Arquitectura-IPN, México
F.J. Rivero Ángeles SEISMIC Ingeniería y Construcción, S.A. de C.V, México	A.O. Vázquez Hernández Instituto Mexicano del Petróleo, México

ABSTRACT: Steel Catenary Risers (SCR) are subject to vessel movements, wave, wind, current and tidal forces, also the SCR are subject to the movement of water particles of wave and current. Current can provoke vortex-induced vibrations during their lifetime that could provoke fatigue damage in the riser. The fatigue damage on welds may depend on the dynamic behaviour of the riser. In oil industry is important to evaluate the probability of damage since failure of a single crack could cause serious environmental, safety and cost problems. The reason is because risers have no high structural redundancy, and failure of one weld could result in failure of the whole system.

In order to apply Structural Health Monitoring (SHM) of these structures the identification of modal parameters are needed. Also, accuracy in damage detection depends on the number of sensors and their position along the riser. For this reason, a numerical study on the optimal location of sensors in welded SCR is presented for the purpose of modal parameter identification.

Modelling of the riser is based on Finite Element Method involving nonlinear behaviour of the system and structure-fluid interaction. Acceleration records from several locations along the riser are processed utilizing the Frequency Domain Decomposition Method to obtain frequencies and mode shapes. These identified parameters are compared to the theoretical values for intact and damage condition of the risers in several sea states cases. Conclusions about the number of sensors and their location are stated. Results demonstrate the feasibility of the proposed methodology that will be useful for future SHM studies.

Corresponding author's email: vhernandeza0902@ipn.mx, rrodriguezr@ipn.mx, f.rivero@seismic.mx, ovazquez@imp.mx

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[1] Escuela Superior de Ingeniería y Arquitectura-IPN, D.F, México
[2] SEISMIC Ingeniería y Construcción, S.A. de C.V, D.F, México
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1 INTRODUCTION

Extraction of petroleum in deep waters has resulted in the extensive use of long steel cylindrical structures. The typical examples include risers, tendons, mooring lines and pipeline. These structures in the hostile marine environment need to be in constant monitoring to evaluate the damage due to degradation effects as corrosion and fatigue.

The ocean environment might change dramatically during the life of the riser, it is difficult to accurately predict its fatigue life before installation. Thus, it is extremely important to understand the fatigue damage history of the risers and provide an estimate of the remaining life span before failure due to fatigue. There is also a concentrated effort from the regulatory bodies to ensure the health and safety of the marine installations by regular visual and automated monitoring. For monitoring activities it is always convenient to use a minimal number of sensors for modal parameter identification due to the high cost of the same.

In this paper the optimal number and position of sensors along the riser for modal parameter extraction is studied. Results are discussed and recommendations are stated demonstrated the feasibility of the proposed methodology.

2 FREQUENCY DOMAIN DECOMPOSITION METHOD

Modal parameters from the dynamic response of the riser will be computed using the frequency domain decomposition (FDD) method proposed by Brincker et al. (2000) where the relationship between the unknown excitation $x(t)$ and the measured response $y(t)$ can be expressed as follows:

$$[Gyy(f)] = [H(f)][Gxx(f)][\overline{H}(f)]^T \quad (1)$$

Where $Gxx(f)$ is the power spectral excitation matrix of order r x r; r is the number of records of input; $Gyy(f)$ it is the power spectral response matrix of order q x q; q is the number of records of response. $[H(f)]$ is the frequency response function matrix of order q x r. The upper dash indicates complex conjugate and T the transpose.

The first step in using the FDD method is to estimate the power spectral response matrix. This computed matrix is called $[\hat{}Gyy\ (f)]$ and operates at discrete frequencies $f = fp$, where p is a discrete series for each frequency domain. $[\hat{}Gyy\ (f)]$ can be estimated as:

$$[\hat{G}yy(f)] = [\overline{Y}(f)]^T [Y(f)] \quad (2)$$

where $[Y(f)]$ the transformed response in the frequency domain for each frequency value f. Subsequently, the power spectral matrix of eq. (2) decomposes as:

$$\left[\hat{G}\,yy(f)\right] = [U_p][S_p][U_p]^T \quad (3)$$

where $[U_p]=[\ \{u_{p1}\},\{u_{p2}\},\ldots,\{u_{pn}\}]$ is a matrix containing singular vectors or mode shapes $\{u_{pk}\}$, and $[S_p]$ is a diagonal matrix composed of singular values s_{pk}. Then these singular values are plotted with respect to frequency f and maximum values are observed corresponding to vibration frequencies of the system.

3 MODAL ASSURANCE CRITERIA

Correlation of mode shapes has been always a difficult task. Element by element comparison approach for a pair of vectors may lead to unreasonable results if the differences between some corresponding elements of the two vectors are large. Literature recommends comparison between modal parameters using the Modal Assurance Criteria (MAC). The function of the MAC is to provide a measure of consistency (degree of linearity) between estimates of a modal vector. This provides an additional confidence factor in the evaluation of a modal vector from different excitation locations or different modal parameter estimation algorithms, According Allemang et al. (1982) this can be computed as:

$$MAC(u,v) = \frac{(u \bullet v)^2}{(u \bullet u)(v \bullet v)} \quad (4)$$

where u and v are the mode vectors to be compared and • represents the dot product operation.

MAC considers zero values as having no consistent correspondence and one means a consistent correspondence. Thus, if the modal vectors under consideration truly exhibit a consistent, linear relationship, the modal assurance criterion should approach to unity correspondence may be considered reasonable.

4 EXAMPLE

A finite element mathematical model of the riser was developed using commercial software called FLEXCOM, Marine Computation Services Ltd (2008), for riser dynamics and analyzed nonlinearly in the time domain. The inside diameter of the SCR is 0.2286m at 1800m depth with 2720 elements of 1m long each. A flexible joint at the top side was considered.

According to Rivero (2009), soil properties and sea state data are shown on Table 1 and 2 respectively, where Hs and Tp are wave height and peak period respectively.

Table 1. Soil properties

Property (SI Units)	Value
Seabed stiffness	35, 850.0
Lateral seabed stiffness	3,585.0
Suction stiffness	358.5

Table 2. Sea state data.

Hs (m)	Tp (s)	Return period (years)
4.4	9.1	25

15 acceleration records were measured at vertical coordinates (sensors) 0, 19.834, 71.39, 142.274, 211.984, 311.434, 421.16, 591.051, 687.076, 881.206, 1077.095, 1254.331, 1432.164, 1610.423 and 1788.005 (Figure 1), too according to Rivero (2009).

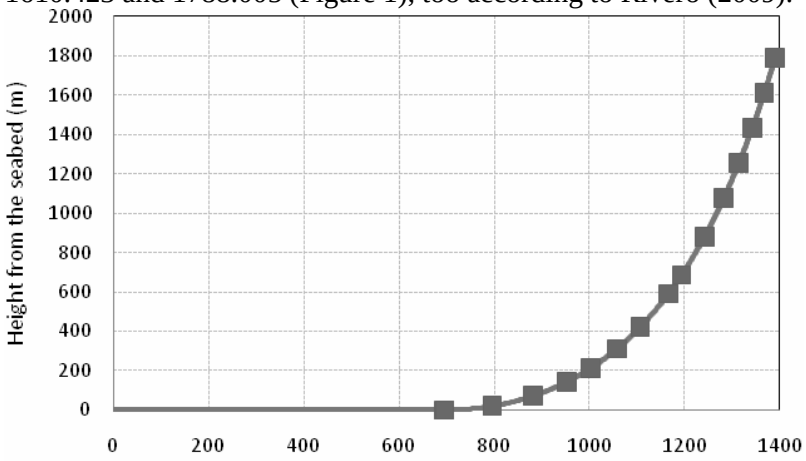

Figure 1. Sensor position. [1].

In order to study the number optimal of sensors and their position for modal parameter extraction 50 analyses, varying the number of sensors from 15 to 3 and their position, moving away at the ends and concentrated in the center, were performed. Of these analyses, modes and periods were calculated according by FDD and associated to the values theoretical, through with value highest of MAC and the error for periods less than 10%. Not all of them are show in this paper.

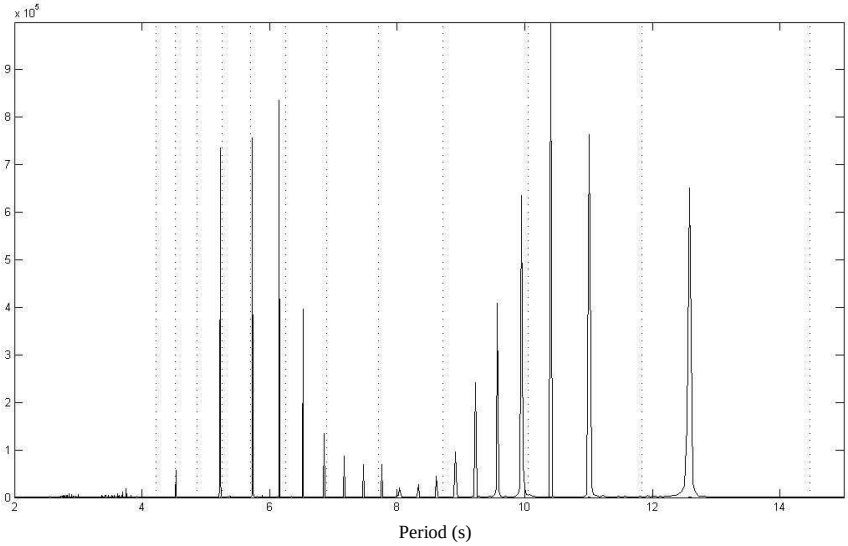

Figure 2. Singular values according to the FDD.

Figure 2 shows the singular values according to the FDD method when 15 sensors were utilized. A dotted line indicates theoretical periods.

Applying the MAC method for 15 sensors was compared the modes shapes computed with the theoretical. Figure 3 shows the low mode shape (mode 12) and the high mode shape (mode 28) founded. Table 3 shows that for the mode shape 12 shows that the error period is low and in the MAC is more than 50%, however, according to Figure 3, the configuration for this mode is similar.

As well as for the 28 shows that the period error is low and the MAC is higher. This is justified since the period of the FDD for this mode is 4.53 s. and as observed in Figure 2 and as shown in Table 3 the period is very close to the theoretical with value 4.52 s., so the same in Figure 3 shows the similarity of the modal behavior for this mode shape.

Table 3. Theoretical and computed modes using 15 sensors.

Associated mode shapes	FDD period (s)	Theoretical period (s)	Relative error (%)	MAC
8	12.54	14.47	13.29	0.59
12	9.92	10.05	1.29	0.48
16	8.02	7.71	4.01	0.45
20	6.14	6.25	1.72	0.37
24	5.72	5.25	9.01	0.35
28	4.53	4.52	0.19	0.74

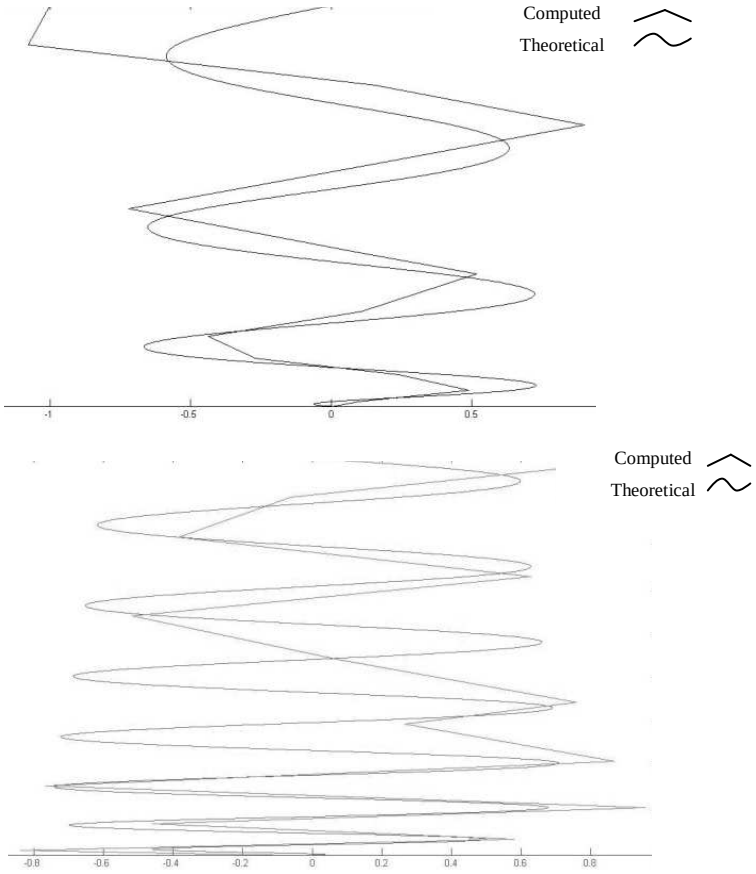

Figure 3. Theoretical and identified mode shapes 12 (up) and 28 (down)

Figure 4 shows the number of sensors used with respect to a lower error associated with observed periods for modes shapes detected. Where 6 modes shapes of 10 all of which are less than 10% error period can be detected with 4 to 10 sensors, i.e., an efficiency of 0.6, but for 5 and 7 sensors may be include 2 modes, with this has to be the best efficiency with a value of 0.8 in this number of sensors.

In the range of 4-7 sensors there is no variation in the error, i.e. it has a linear behavior, and with 8 sensors there is a clear fluctuation of error associated with the number of tests that was identified with this number of sensor.

For the 8 mode no matter how many of sensors in the range of 6-10, the association is neglected because, as shown in Figure 2, period calculated with reference to theoretical has a significant gap so it sees no correspondence. But not so for mode 28 which also has a constant error regarding the number of sensors but its error and MAC are very close to zero and unity respectively and can be justified as in Figure 2, the correspondence of the period is very close.

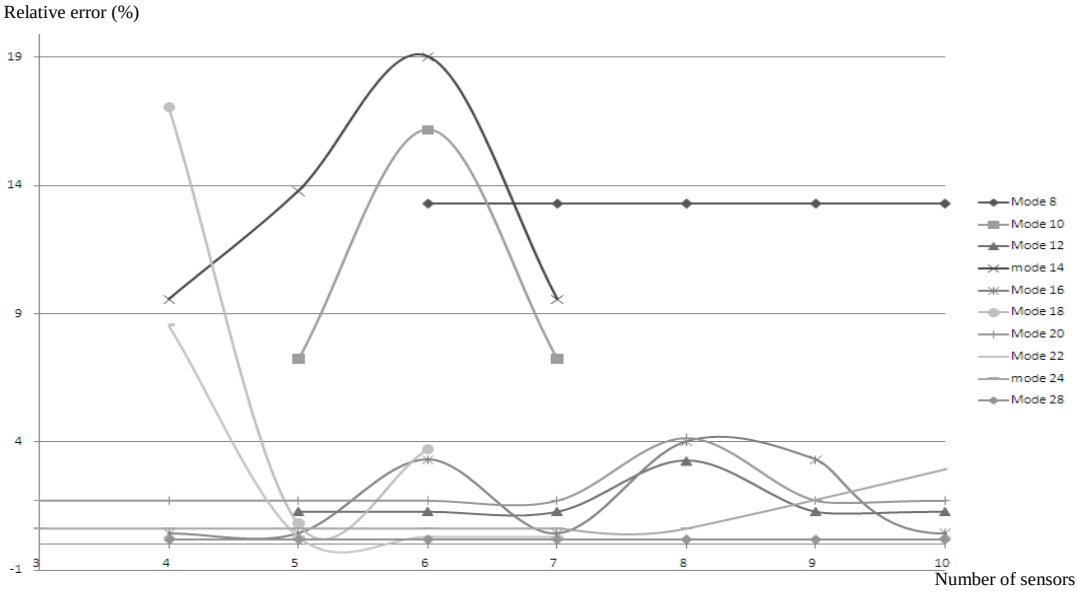

Figure 4. Number of sensors vs. Period error (%).

Figure 5 shows the number of sensors used on the largest observed value of MAC for each detected mode. It can be observed that a higher order mode shapes in the MAC behavior are almost linear in the range of 4-7 sensors and with values near or greater than 0.9. Thus for values greater than 7 sensors a higher error value can be observed in the correlation mode.

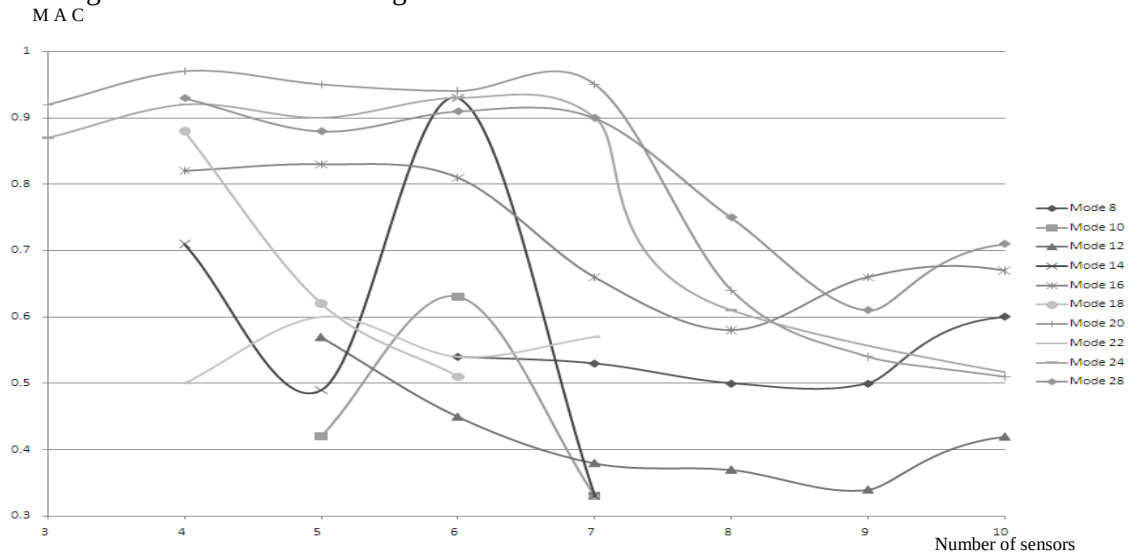

Figure 5. Number of sensors vs. MAC.

Table 4 shows modal parameters extracted using five sensors (sensor number 2, 7, 8, 9, 14) minimum number which was detected with best results. It is observed that the number of modes and periods is equal to the number of sensors used; data are considered optimal because unlike other data with the same number of sensors this analysis reported the highest number of modes shapes associated to theoretical values and high MAC values and small error period. It can be observed than all error values are smaller than 10% which is engineeringly adequate.

Table 4. Optimal data

Associated mode shapes	FDD period (s)	Theoretical Period (s)	Relative error (%)	MAC

12	10.98	10.05	9.25	0.66
16	7.45	10.05	-1.29	0.79
20	6.14	7.71	-4.01	0.92
24	5.22	6.25	-1.72	0.89
28	4.53	5.25	-0.19	0.82

5 CONCLUSION

In this paper the Frequency Domain Decomposition method was utilized to extract modal parameters from acceleration records of a riser. It is concluded, for this particular structure, that maximum number of mode shapes with error values smaller than 10% were identified with a minimum number of sensors equal to 5.

The better results in obtaining modal parameters were observed when having a concentration of sensors in the middle of riser and a minimum number requested of sensors near the ends.

The presented methodology showed adequate results for modal extraction of risers and future Structural Health Monitoring studies will be carried out.

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