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Vibration analysis for the determination of modal parameters of steel catenary risers based on response-only data

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ABSTRACT

Modal analysis is one of the most preferred method in the structural engineering community to investigate vibration characteristics. When dealing with response-only data of specific operating conditions, this method could be useful to characterize its dynamic behavior. It could also be used for damage detection, and damping estimation, among others. However, existing methods are not yet robust enough to be used in a daily basis for any kind of structures; thus, numerical simulations must be carried out to investigate the performance of existing and newly developed methods.

In the case of deepwater risers, they present highly nonlinear dynamic behavior due to large displacements of the floating structure. Under these circumstances it is convenient to identify the dynamic behavior of operational risers due to the variability of environmental conditions.

This paper presents a comparative study to determine modal parameters (periods and mode shapes) of a Steel Catenary Riser (SCR) taking into account only output data of acceleration records. Two methods are used to identify the operational frequencies of a riser, the Frequency Domain Decomposition Method (FDDM) and the Conventional Spectral Analysis Method (CSAM). This work takes into account the output response obtained through numerical simulations at various points along the riser. The identified and the theoretical parameters show good agreement.

1. Introduction

The structural response of marine structures, such as risers, depends on the randomness of environmental conditions. Due to this fact, the identification of the overall performance during its lifespan is a complex problem because the riser will be changing its original characteristics like tension and vertical–horizontal position in every operational (normal conditions) and extraordinary events (extreme weather conditions).

In order to estimate damping characteristics, modal parameters or another information that allow to identify the dynamic behavior of a structure the some numerical methods can be used. However, the problem arises when one is trying to monitor the behavior of a riser in operation. Then identification methods are needed to estimate these parameters of an existing system.

One preferred identification method among structural engineers is the modal analysis. This method could aid on health monitoring activities. Several works have been performed with this objective on real operating risers around the world, but there is no public access to the techniques used for the determination of dynamic properties [1]. In the academic front, research has been published where response data of risers and umbilicals has been used to understand their behavior in VIV analysis [2–7].

Modal parameter estimation for health monitoring reasons, based on structural response data, has been studied in a great amount of works, both for land structures as well as in some cases for offshore structures [8–12]. However, only a handful of researchers have focused on the study of the behavior of risers based on output-only data records. In this regard, it is important to evaluate the applicability of existing methodologies in order to characterize the dynamic behavior of risers based solely on output data records.

In many modal-based methods the structure needs to be excited with a prescribed forcing signal. In many cases, particularly for offshore structures, it is difficult or even unfeasible to force a particular excitation on the structure. In this sense, a method capable of using ambient excitation is clearly desirable [8].

Spectral analysis is very useful to identify modal parameters of structures. Many authors have focused their studies on structural linear dynamic behavior [13–16]. However, it is important to acknowledge the presence of uncertainties and nonlinearities during the identification process. Some uncertainties are due to a lack of knowledge concerning the physical laws which govern the

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Nomenclature

f	frequency response in Hertz
f_k	frequency of vibration of the system for the kth mode
$\mathbf{g}_y(f)$	autospectral density function of a signal y for positive frequencies
k	number of modes of the structure
q	number of records of response
r	number of records of input
$\mathbf{s}_y(f)$	autospectral density function of a signal **y**
$\mathbf{tf}_{yo}(f)$	transfer function of the signal **y**
u_{pk}	system mode shapes
$x, \dot{x}, \ddot{x}$	displacement, velocity and acceleration of the floating body
$\mathbf{y}(f)$	Fourier transform of a signal **y** in terms of the frequency f
A_k	kth residual matrix of the response spectral matrix of order $q \times q$
$Ab(w)$	hydrodynamic added mass of the floating body in the six 6 degrees of freedom
$B(w)$	potential damping of the floating body in the six 6 degrees of freedom
C	hydrostatic restoring coefficients of the floating body in the six 6 degrees of freedom
$F(w)$	harmonic excitation wave forces due to incident waves in the floating body in the six 6 degrees of freedom
F_0	linear excitation force complex amplitude per wave height
$Gxx(f)$	power spectral excitation matrix of order $r \times r$
$Gyy(f)$	power spectral response matrix of order $q \times q$
$\widehat{G}yy(f)$	power spectral response matrix
Hs	significant wave height
$\mathbf{I}$	unit matrix
$\mathbf{K}$	stiffness matrix of the riser
$\mathbf{M}$	structure mass matrix of the riser
Mb_{jk}	generalized mass coefficients of the floating body in the six 6 degrees of freedom
RAO(w)	Response Amplitude Operators
$Sn(w)$	wave sea spectrum
$S_R(w)$	responses spectrum is a given sea state condition
S_p	diagonal matrix composed of singular values s_p
U_p	matrix containing singular vectors or mode shapes
Tp	spectral peak period
Tz	zero crossing period
$Y(f)$	transformed response in the frequency domain for each frequency value f
α_k	negative of the real part of the pole
ζ_k	kth modal participation vector
λ_k	kth pole or singular value
$\lambda\lambda_i$	ith Eigen value
ς	wave height
φ_k	kth the vibration mode
w	wave frequency in rad/s
$\mathbf{\Delta}$	Eigen value diagonal matrix of the riser
$\mathbf{\Phi}$	eigenvector or mode shape vector

behavior of a physical component. It is possible to reduce this epistemic uncertainty with a combination of more detailed experimental observations and improvement of the physical models [17–26]. The work herein does not take into account this kind of uncertainty.

On other hand, marine risers are also subject to randomness of sea states (wave, wind, current and other environmental loads) that will provoke changes of the vertical configuration of riser such as shifts in the touchdown point, mean tension and total suspended length. Also there is nonlinear behavior due to the intermittent contact between soil–pipe interaction behavior in the touchdown zone.

In addition, for the purposes of design, natural mode shapes are calculated without external forces driving the dynamic behavior. Yet, the physical riser is always subject to environmental loads which excite some modes more than others at different times; thus, it is possible that the modal combination might not be so accurate.

Consequently, in order to study the dynamic non-linear behavior of risers, it is important to consider the response of the riser under certain load conditions that represent critical or typical operational behaviors. These load conditions are regularly defined in a small number of cases due to high computational costs in which the process of analysis and design of risers incur.

In this study, five sea state conditions are used to show the variability of the behavior of a steel catenary riser, and to compare two modal parameter estimation methods, based on response-only data (structural response in the time domain) calculated through numerical simulations at various points along the riser. These methods are: Conventional Spectral Analysis and Frequency Domain Decomposition.

Both methods provide acceptable results compared with theoretical natural frequencies. In the methodology used herein was able to identify the modes of vibration of the riser, depending on the type of sea state conditions. These methods can be used to characterize and map the riser behavior during its lifetime, they also could be used in fatigue analysis or for monitoring structural objectives, not covered by this work. The aim in the near future is to develop a robust detection system to obtain a methodology to characterize riser behavior.

2. Methods for the identification of modal parameters based on response data

2.1. Conventional Spectral Analysis Method (CSAM)

This method is used to identify modal parameters of a structure using its dynamic response. According to Bendat and Piersol [27], the autospectral density function of a signal **y** for positive frequencies is defined as:

$$\mathbf{g}_y(f) = 2\mathbf{s}_y(f) \tag{1}$$

where $\mathbf{s}_y(f)$ is the autospectral density function of a signal **y** defined as:

$$\mathbf{s}_y(f) = \mathbf{y}^*(f)\mathbf{y}(f) \tag{2}$$

where $\mathbf{y}(f)$ is the Fourier transform of a signal **y** in terms of the frequency f.

The asterisk indicates the operation of complex conjugate.

On the other hand, when a structure is subject to an excitation, Eq. (1) it will present some maximum value, either due to the excitation frequency or to the frequencies of the system. In order to determine the mode shapes corresponding to each identified vibration frequency of the structure, it is necessary to calculate the transfer functions from Eq. (1) and the signal from the excitation level (in the case of a riser this reference level is the fairlead position) as: