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Viscoelastic axisymmetric structural analysis of flexible pipes in frequency domain considering temperature effect

Junpeng Liu, Murilo Augusto Vaz*

Ocean Engineering Program, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil

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ABSTRACT

Structural damping induced by material viscoelasticity in flexible risers may generate a non-ignorable effect on the global dynamic analyses. This paper presents an analytical model in frequency domain which is capable of predicting the structural viscoelastic behavior of flexible risers subjected to axisymmetric harmonic loads. In this model, the influence of temperature is taken into consideration, as well as the viscoelastic material properties, which are represented by Prony series. Shift factor as a function of temperature is observed through a series of experimental data. The material constants in Prony series are obtained through Levenberg-Marquardt curve-fitting method. This model yields an evident non-linear relationship between force and axial strain, posing a noticeable hysteresis loop. The loop circumscript area can be accurately calculated as the dissipated energy used for obtaining the axial structural damping. A case study is presented to illustrate the model application and it is found that the axial strains are inversely proportional to the frequency regardless of temperature. Furthermore, both axial strain and dissipated energy are seen to be dramatically affected by the interaction of frequency and temperature, but no strict law can be found.

1. Introduction

Flexible risers have around 40 years history of successful performance in offshore oil and gas industry. However, as deep-water development expands, the design challenges increase, especially on predicting mechanical behavior due to its structural complexity from helical components combined with cylindrical layers [1]. Several kinds of configurations can be chosen based on environmental, economic and operational conditions, of which the most common used type is the free hanging catenary configuration. Once the configuration is decided, global analysis for the riser system is carried out by means of specialist software to study the maximum top tension and curvature, which are related to the riser ability to resist extreme operational conditions and accumulated fatigue damage in its service life. A correct damping assessment is very important for the system design in ultra deep-waters, otherwise the utilization of free hanging catenary risers may be compromised. Damping mechanism from the bending moment versus curvature hysteretic behavior is important especially near the areas of high curvature variations such as at the touch down zone and at the very top area near the bend stiffener. This energy dissipation mechanism is well studied and its formulation has been incorporated in most global dynamic software. During this process, structural damping induced by polymeric material under oscillating load generates a non-negligible impact for

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* Corresponding author.
E-mail address: murilo@oceanica.ufrj.br (M.A. Vaz).

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an accurate result of global analysis as discussed by Silveira et al. [2]. In order to capture the amount of structural damping, mechanical analysis of flexible pipes, consubstantiated by mechanical tests, has to be carried out.

Over the past 30 years, a comprehensive study of the mechanical behavior of flexible pipes has been undertaken, and one of the major concerns in this topic is related to axisymmetric analysis, which allows description of the riser behavior under internal and external pressures, axial tension and torque. The first work to explore the mechanics of a straight flexible pipe subjected to axisymmetric load was conducted by Féret and Bournazel [3]. The model results in a linear system of algebraic equations which is capable of predicting the riser structural response and was implemented in a computer program named CAFLEX [4]. Using Clebsch-Kirchhoff's non-linear differential governing equations described in Love [5], Witz and Tan [6] presented an analytical model for prediction of strain, interlayer contact pressures and gap formation between the layers, as well as the torsional strain. In their model, the flexile pipe was divided into a set of individual elements (cylindrical and helical). Based on such method, Claydonet et al. [7] conducted a rather rigorous analysis of flexible pipes and tried to cover all aspects of their behavior. Furthermore, non-linear finite element methodology can also be used for axisymmetric analysis of flexible risers [8]. In addition, numerous examples of theoretical description of axisymmetric behavior of flexible pipes have been conducted, seen in Refs. [9–12]. Some experimental tests in flexible pipes under tensile load have also been performed by Ramos [13] and Merino [14]. All previous mechanical studies addressed that the axial force and strain follows a linear relationship due to the basic elastic material assumption. Although some important parameters such as the axial stiffness could be predicted with relative accuracy, the dissipated energy induced by the polymeric material intrinsic viscoelasticity cannot be calculated. Therefore, viscoelastic axisymmetric analysis of flexible risers should be considered to enable an analytical description of the hysteretic behavior. Little attention has been paid on this topic, only Guedes [15] discussed the effect of the polymer matrix viscoelastic behavior in thick multilayered composite pipes. Medina [16] started to study the viscoelastic behavior of flexible pipes. Liu and Vaz [17] proposed an axisymmetric viscoelastic analysis model in time domain. Note that all previous studies about viscoelastic analysis ignored the influence of temperature. Thus, in this paper, the emphasis is placed on the construction of a model in frequency domain taking viscoelasticity and temperature into consideration by which axial force and strain relationships under different temperature and oscillation loading conditions can be achieved.

The viscoelastic solutions come from the mechanical model in elastic domain in accordance with the correspondence principle. Note that the viscoelastic property of polymeric material is represented by a dynamic modulus, which is determined by experimental tests. In addition, the temperature significantly affects the material viscoelastic characteristics and it may also lead to a dimensional change. The latter is not taken into consideration in this paper as its effect is insignificant for the energy dissipation mechanism. Therefore, there are four aspects of the model construction that needs to be addressed. The first question involves finding an available mechanical model of flexible riser under axisymmetric loads in elastic domain. Such model is based on the separate analysis of cylindrical and helical layers and some assembly conditions. The second problem relates to viscoelastic model in frequency domain converted by elastic model through correspondence principle, where the exact modulus of polymeric material is expressed by Prony series. The third aspect deals with viscoelastic properties represented by relaxation function. According to the experimental data, the constants in modulus are obtained by Levenberg-Marquardt curve-fitting method. With the help of shift factor, the expression of relaxation function at any temperature can be observed when the function at a reference temperature is given. Finally the temperature distribution of flexible riser in both radial and axial direction should be proposed. The results of model in frequency domain show an obvious hysteresis loop related to dissipated energy. The area of loop and amount of axial strain are dramatically affected by frequency and temperature. Unfortunately, a strict law cannot be found.

2. Mathematical formulation in elastic domain

The mathematical formulation for predicting the elastic stress and strain state of flexible pipes under axisymmetric loads will be derived by dividing the layers into two classifications, i.e., cylindrical and helical layers, and analyzing each one separately. With the purpose of simplicity and convenience, the materials employed in flexible pipes are considered homogeneous and isotropic and the deformations induced by axisymmetric and evenly distributed forces and moments are assumed small. Moreover, the friction forces between adjacent layers are not taken into account.

2.1. Cylindrical layers

Inner liner and external sheath, for instance, can be classified as thick wall cylindrical layers with length L, internal radiusR_{in} and external radius R_{ex}, as shown in Fig. 1, which also shows the stresses produced on an elemental volume, where σ_{zz}, σ_{rr}, $\sigma_{\theta\theta}$ respectively denote the stresses in the axial, radial and hoop directions. The parameters average radius $R = (R_{in} + R_{ex})/2$ and thickness $t = R_{ex} - R_{in}$ are introduced herein for the sake of convenience.

The cylinder variations in radius and thickness can be expressed as a function of axisymmetric loads (axial force F, internal pressure P_{in} and external pressure P_{ex}) and global axial strain $\Delta L/L$, respectively [17]: