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Modeling nonlinear time-dependent behaviors of synthetic fiber ropes under cyclic loading

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Attributed to the time-dependent property, synthetic fiber ropes employed as mooring lines in the taut leg mooring system may present special mechanical behaviors such as the dynamic stiffness, creep-recovery and stress relaxation, which directly affect the dynamic response and fatigue performance of the mooring system. In the present work, a new stress–strain constitutive model, which can fully take into account the loading history and the time-dependent property of synthetic fiber ropes under cyclic loading, is proposed based on the Schapery's theory and Owen's rheological theory. The present model is capable of quantifying the change-in-length property of fiber ropes under cyclic loading reported by Flory et al. (2007), and can be incorporated into the commercial software for mooring analysis. Detailed methods for identifying the model parameters are also proposed. In order to examine the accuracy of the present model, the dynamic stiffness and hysteresis loop of aramid and polyester ropes under cyclic loading are simulated by the present model, and are used to compare with the measured data and empirical expression. The good agreement proves that the present model can well simulate nonlinear time-dependent behaviors of synthetic fiber ropes under cyclic loading.

1. Introduction

Since the first taut leg mooring system (TLM) adopting polyester ropes was installed by Petrobras in 1997, the TLM using synthetic mooring lines has become a very attractive alternative to conventional steel catenary systems for the station keeping of all kinds of floating structures in deep waters (Nielsen and Bindingbø, 2000). However, due to mechanical properties of synthetic fiber ropes, the dynamic response of mooring systems utilizing these materials under cyclic loading is extremely complicated. In order to evaluate and predict the real response of the TLM, the most important point is to precisely grasp the load-elongation relationship of mooring ropes. It is well known that, no matter how severe the environmental loading condition is, the elastic modulus of steel chains or wire ropes can be regarded as a constant. But it is totally different for synthetic fiber ropes. The stress–strain relationship is obviously nonlinear and time dependent (François et al., 2010). Due to the nonlinear viscoelasticity and viscoplasticity of mooring ropes, the significant hysteresis arises under cyclic loading. Based on experimental observations, the stress–strain hysteresis loops are gradually superimposed with each other, and become nearly stable after a certain number of loading cycles. The stiffness changing with the loading cycles is different to the steel mooring chains or wire ropes. Besides, the creep-recovery and stress relaxation characteristics of synthetic fiber ropes are also the evidences to show that they are typical time-dependent materials.

Many researchers have carried out numerical and experimental studies on the mechanical properties of synthetic fiber ropes. Del Vecchio (1992) proposed the first empirical expression of dynamic stiffness considering main loading factors. Subsequently, a series of experiments were performed to study the dynamic stiffness and its influential factors (Fernandes et al., 1999; Davies et al., 2002; Casey and Banfield, 2005; Davies et al., 2011). Note that all of these studies focused on the stable dynamic stiffness of fiber ropes under cyclic loading and tried to gain an empirical expression. However, the empirical expression of stable dynamic stiffness cannot take into account the loading history and the time-dependent properties of fiber ropes. Bitting (1985) developed a three-parameter model to describe the stress–strain relationship of fiber ropes, but the method for identifying the corresponding coefficients as well as the quantitative calculation were not presented. Flory et al. (2004, 2007) proposed a physical model which is constitutive of spring and damping elements to describe the change-in-length properties of fiber ropes under different loading

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Nomenclature

a, b, c	coefficients in the function used to fit the discrete values of g_0
$\alpha, \beta, \gamma, \delta, \kappa$	coefficients used in Eq. (48)
L_m	mean load
t_e	effective time of the viscoplastic strain
ε_a	strain amplitude used in Eq. (48)
$\varepsilon(t)$	total strain at time t
$\varepsilon_{ve}(t)$	viscoelastic strain at time t
$\varepsilon_{vp}(t)$	viscoplastic strain at time t
$\varepsilon_{e,m}$	elastic strain
$\varepsilon_{ve,m}$	mean viscoelastic strain
$\varepsilon_{vp,m}$	mean viscoplastic strain
$\Delta\varepsilon_A$	strain amplitude
$\sigma(t)$	stress at time t
$\Delta\sigma(t)$	oscillatory stress
$\Delta\sigma_A$	stress amplitude
φ	phase difference between stress and strain
ω	load frequency
σ_m	mean stress
R	coefficient in Eq. (39)
σ_c	constantly applied stress
σ_Y	yield stress
σ_Y^0	initial yield stress
g_0	parameter of the instantaneous compliance
g_1	parameter of the transient compliance
g_2	parameter of the load rate effect
a_σ	parameter of the reduced time
D_0	instantaneous compliance
ψ	reduced time
$\Delta D(\psi)$	transient compliance
$\hat{D}^*$	linear transient compliance
$\hat{D}'$	real part of the linear transient compliance
$\hat{D}''$	imaginary part of the linear transient compliance
D_{NL}^*	nonlinear complex compliance
D_{NL}'	real part of the nonlinear complex compliance
D''_{NL}	imaginary part of the nonlinear complex compliance
E_p	elastic modulus of the spring
η_p	viscosity constant
H	hardening parameter
N	number of items
D_n	the nth coefficient of the Prony series
λ_n	the nth reciprocal of retardation time
$q_n(t-\Delta t)$	hereditary integral at the previous time $t-\Delta t$
$q_n(t)$	hereditary integral at the time t
$\Psi(t)$	part of the first item of Eq. (11)
$\Phi(t)$	part of the second item of Eq. (11)
K_r	dynamic stiffness

conditions, but it was limited to qualitative analysis. Falkenberg et al. (2011) proposed to introduce the empirical model which consists of the spring and dashpot into the frequency analysis of the synthetic fiber rope mooring systems. Flory and Ahjem (2013a, 2013b and 2013c) proposed six change-in-length properties (6 CILP) empirical method together with the test method to identify the parameters to describe how the length of a fiber rope changes under various tension conditions and histories. The 6 CILP method can account for permanent length change due to construction stretch and long term polymer stretch as well as the dynamic strain and temporary creep and recovery effects. François and Davies (2008) figured out that the time-dependent properties brought more complexity in the deformation characteristics of synthetic fiber ropes. Only using the static tension–elongation curve was not sufficient, and a true “time domain” rheological model still required further effort. In fact, the viscoelasticity and viscoplasticity also exist in other materials such as the High-Density Polyethylene (HDPE) (Lai and Bakker, 1995; Haj-Ali and Muliana, 2004; Kim and Muliana, 2009), the epoxy resin (Xia et al., 2005), and the asphalt (Ye et al., 2010). The research achievements of the constitutive model for these materials could give reference to the present work.

However, for the synthetic fiber mooring lines, there are still no tension–elongation constitutive models which can take into account the loading history and the time-dependent properties. Actually, in certain sea states, the dynamic response of the mooring system including both the platform and the mooring lines is the key problem concerned by designers and researchers, which is directly influenced by the stress–strain relationship of fiber lines. Further study of the time-domain cyclic constitutive relationship is significant to the engineering application of the TLM in deep waters. The present work is to establish a stress–strain constitutive model that can fully consider the loading history and the time-dependent properties of synthetic fiber ropes. The total strain is assumed to be divided into two parts, i.e., the viscoelastic and viscoplastic strains, which are quantified based on Schapery's theory and Owen's rheological theory. Being an important work, the parameter identification methods are proposed in detail based on dynamic mechanical tests. Note that a similar procedure was adopted to model nonlinear creep and recovery behaviors of synthetic fiber ropes for deepwater moorings (Huang et al., 2013). Although Chailleux and Davies (2003, 2005) firstly proposed to utilize Schapery's theory to simulate the creep-recovery response of aramid and polyester fiber yarns, they just considered the creep-recovery loading condition and did not extend to cyclic loading conditions. Within the authors' knowledge, it is the first time to utilize this theory to deal with mechanical properties of synthetic fiber ropes under cyclic loading. In order to examine the present model, the dynamic stiffness and hysteresis loop of aramid and polyester ropes under cyclic loading are simulated and compared with measured data and empirical expressions.

2. The constitutive theories and parameter identification

2.1. Schapery's single integral constitutive model for viscoelastic behaviors

Schapery's theory and Owen's rheological theory are employed to quantify the viscoelasticity and viscoplasticity of synthetic fiber ropes. Viscoelasticity is the property of materials that exhibits both viscous and elastic characteristics when undergoing deformation. Viscous characteristic means the strain is relevant to time and elastic means the strain can be recoverable. Viscoplasticity is the property of materials that exhibits permanent deformations subjected to applied load and continues to undergo a creep flow as a function of time. The total strain $\varepsilon(t)$ is divided into two parts, i.e., the viscoelastic strain $\varepsilon_{ve}(t)$ and the viscoplastic strain $\varepsilon_{vp}(t)$.

The viscoelastic strain is relevant to the loading history and can be described by Schapery's single integral constitutive equation, which is a macroscopic model based on thermodynamic assumptions. It enables the nonlinear properties of the creep compliance to be described, which reflects the relation between