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An experimental investigation on nonlinear behaviors of synthetic fiber ropes for deepwater moorings under cyclic loading

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ABSTRACT

The nonlinear mechanical behaviors of synthetic fiber ropes including polyester, aramid and HMPE under cyclic loading are of vital importance to the dynamic response and fatigue life of taut-wire mooring systems. In the present work, important topics including how the stiffness develops and how the main factors influence the evolution of dynamic stiffness as well as the nonlinear tension–elongation relationship are systematically investigated utilizing a specially designed experimental system. The similarity criterion for the dynamic stiffness of fiber ropes is derived from the dimensional analysis and verified by experiments. The empirical expressions of dynamic stiffness, which are currently used, are examined by the measured data. It is observed that the mean load is a main factor that significantly affects the dynamic stiffness; not only the effect of strain amplitude on the stiffness can not be ignored, but also the influence of loading cycles is of vital importance to the dynamic stiffness. Based on the measured data, an empirical expression that takes into account both the mean load, strain amplitude and number of loading cycles is proposed, which is the only one that can evaluate the evolution of dynamic stiffness under long-term cyclic loading.

1. Introduction

Since 1980s, people have made an effort to use synthetic fiber ropes as the main component of mooring lines for station keeping of the floaters like MODU, FPSO, Spar and Semi. Indubitably, synthetic fiber ropes have been proved to be the most suitable substitute for steel wire ropes or chains in deepwater mooring applications. The most widely used fiber rope is of polyester since the first engineering application by Petrobras in 1997 [1]. In deep waters, the mooring lines are quite long and the diameter of the polyester rope is usually several-hundred millimeters for the demand of breaking strength, which bring in a big challenge for the storage ability of the installation vessels. Therefore, researchers have been trying to find other better materials than the polyester [2]. In fact, about 30 years ago, the aramid and HMPE which have higher modulus than the polyester have been applied in the moorings [3]. Some reported failure cases [4–6] and their disadvantages restricted their wide application.

Other than the steel wire ropes or chains, the mechanical properties of synthetic fiber ropes are generally nonlinear and time-dependent and exhibit viscoelasticity and viscoplasticity. Bitting [7] studied the dynamic stiffness and hysteresis of nylon and polyester double braid lines 1.5 and 2 in. in diameter based on a series of laboratory tests. Del Vecchio [8] proposed an empirical expression for determining the rope modulus at constant temperature as a function of the testing parameters including the mean load, load amplitude and loading period, which was the first attempt to define a formula of the dynamic modulus for synthetic fiber ropes. Fernandes et al. [9] performed a comprehensive set of tests of actual full-scale polyester mooring cables with diameter of 0.127 m, and detected a weak dependence of the dynamic stiffness on the frequency. Bosman and Hooker [10] carried out experimental studies of dynamic modulus characteristics of the polyester subrope with breaking strength of 11.25 tons and the full-size rope with breaking strength of 150 tons, which demonstrated that good predictions of the modulus can be made from small-scale tests to full-size tests. Casey and Banfield [11] performed an investigation into the dynamic axial stiffness of polyester ropes in the size range 600–1000 tons, and pointed out that the strain amplitude does exist as a variable for the dynamic stiffness. It was further demonstrated that, for stochastic loading, the effect of strain amplitude was sufficiently small which could be neglected when considering dynamic stiffness for mooring design under low strain amplitude up to 0.3%; at higher strain amplitude around 0.6%, the effect should not be ignored. Based on the public domain data, Wibner et al. [12] utilized the upper and lower bound stiffnesses to describe the dynamic stiffness of the polyester rope, in which only the mean load was taken into account. Davies et al. [13] performed experimental studies of synthetic fiber ropes including polyester, aramid and HMPE ones in a dry condition, and the effects of the mean load, load range and loading frequency on stiffness were investigated. The

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Table 1
Parameters of synthetic fiber ropes.

Parameter	Polyester		Aramid		HMPE	
D (m)	0.006	0.008	0.006	0.008	0.006	0.008
MBL (kN)	6.8	9.8	9.7	34.1	27.8	49.7

stiffness and bending behavior of aramid and HMPE ropes for deep sea handling operations were also investigated in their Subsequent experiments [14]. François and Davies [15] carried out experiments on the polyester subrope samples with 70-ton breaking strength and the full size rope with 800-ton breaking strength, in which a "quasi-static stiffness" was defined to consider the visco-elastic response of ropes to slow variations of mean load under the effect of changing weather conditions; the upper and lower bound stiffnesses that only took into account the effect of mean load were presented.

To sum up, most of the previous studies focused on the value of the stable dynamic stiffness and seldom concerned about some important issues including how the stiffness develops and how the main factors influence the evolution of dynamic stiffness and the nonlinear stress–strain hysteresis loops. Therefore, four points of knowledge can be summarized: firstly, although the synthetic fiber ropes show obvious time-dependent behaviors, which are recognized to be of vital importance to the dynamic response and fatigue life of taut-wire mooring systems, there are seldom systematic experiments focusing on the time-dependent behaviors of the fiber ropes under cyclic loading partially due to the complexity and uncertainty of them; secondly, most researches focused on the stable dynamic stiffness and factors based on the empirical expression proposed by Del Vecchio [8]; however there were different opinions on the effects of the mean load and strain amplitude. To obtain a uniform and generally accepted empirical expression of dynamic stiffness is still the final objective of these researches; thirdly, there were seldom researches that involved the stiffness changing with loading cycles. However under cyclic loading, the stiffness would significantly change with the cycles. This is a particular property due to the time-dependent behaviors of synthetic fiber ropes; fourthly, because a higher storage ability of the installation vessel is demanded by polyester ropes, recently the aramid and HMPE ropes become attractive again. The studies on the mechanical properties of aramid and HMPE ropes are not only necessary but also urgent.

In the present work, a specially designed experimental system is employed to systematically investigate the nonlinear behaviors of three types of synthetic fiber ropes under cyclic loading, including polyester, aramid and HMPE ones. Important topics including how the stiffness develops and how the main factors influence the evolution of the dynamic stiffness as well as the nonlinear tension–elongation relationship are investigated in detail. The similarity criterion for the dynamic stiffness of fiber ropes is derived from the dimensional analysis and examined by experiments. The empirical expressions of dynamic stiffness, which are currently used, are also examined by the measured data. Based on the measured data, an empirical expression that takes into account both the mean load, strain amplitude and number of loading cycles is proposed, which is the only one that can evaluate the evolution of dynamic stiffness under long-term cyclic loading.

2. Experimental system, synthetic fiber ropes and test cases

The experimental system mainly consists of four parts, i.e., the loading elements, the equipment foundation, the measurement system and the water cycling system, as shown in Fig. 1. The loading elements are constitutive of two divided parts, one is the static loading element, and the other is the dynamic loading element. The maximum capacity of static loading is 6 tons, while the one of dynamic loading is 5 tons. The loading elements can provide two loading ways, i.e., the load-controlled and the displacement-controlled, which are respectively provided by the static and dynamic loading elements. The former is to apply a constant mean load, and the latter is to apply a strain amplitude. The two ways are combined to approximately simulate the response of mooring lines in a taut-wire mooring system, where a specific pre-tension is applied to the mooring line and the floater moves periodically with a relatively unchangeable amplitude. The equipment foundation was designed and jointed by the box irons and rolled angles to be easily taken down. A water cycling system was designed and fabricated utilizing double water tanks to simulate the real water environment. With the help of two water pumps, the water in the outer tank can be injected into the inner one. The tested fiber rope will be always immerged in water as long as the flow of the injected water is larger than the outlet flow. An elongation measurement system was designed combined with the wire transducer, axletree, sliding block and clamp. Two axletrees are parallel installed above the water tanks. On the axletrees, there are two sliding blocks, one of which is used as the base for the wire transducer and the other is used to fix the wire. Two specially designed clamps installed under sliding blocks are used to calibrate the test region, which can be reliably fixed on the gauge marks of the rope even if the load is near the breaking load of the rope. The terminations of the rope are made with the eye splice method instead of the knot method. Therefore the possible slip between contact surfaces at knots when subjected to a large tension can be effectively eliminated.

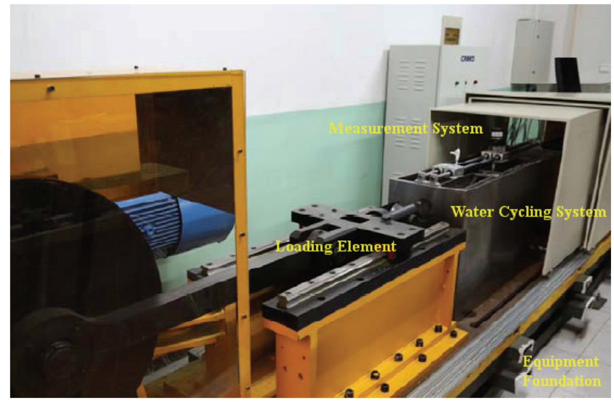

Fig. 1. Experimental system for cyclic loading tests of synthetic fiber ropes.

Three types of materials are employed in the present study, including 3 strand construction polyester ropes, 16 × 2 double braided aramid ropes, and 12 strand construction HMPE ropes. For each type of materials, there are still two sizes, i.e., 0.006 and 0.008 m in diameter, as shown in Fig. 2. The parameters of materials are listed in Table 1, in which *D* denotes the diameter of the rope and MBL means the minimum breaking load of the rope. All the sample ropes were provided by Jiuli Ropes Company Limited. The fiber of HMPE is Dyneema SK75, which was produced by DSM Dyneema. The fiber of aramid is Kevlar49, which was produced by DoPont. The fiber of polyester is polyethylene terephthalate, which was produced by Jiuli Ropes Company Limited. The total length of the specimen including splices is 1.7 m, but the effective length in measurement is 0.8 m. Before cyclic loading tests, the static tension–elongation curve was measured through static loading tests, which repeat five times for each case. Note that enough bedding-in process was performed for all sample ropes before static loading tests. The static tension–elongation curves of polyester ropes are presented in Fig. 3, which indicate that the normalized elongations at rupture of 0.006 and 0.008 m ropes are 14.0% and 14.6%, respectively. The static tension–elongation curves of aramid ropes are presented in Fig. 4, which indicate that the normalized elongations at