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Fatigue assessment for the floating collar of a fish cage using the deterministic method in waves

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ABSTRACT

Fish farms have moved into the open sea in recent years and the failure risk of fish cages has increased in the harsher environmental conditions. Fatigue failure is an important limit state for the floating system of the fish cage under the long-term action of waves. A fatigue analysis of the high-density polyethylene (HDPE) floating system in waves is presented in this study based on the deterministic method and finite element analysis combined with a hydrodynamic model. As the basis of the fatigue assessment, a stress analysis of the floating pipes is first performed based on the joint use of the finite element model and the hydrodynamic model. The fatigue lifetime is then calculated using the Palmgren–Miner cumulative damage theory together with the deterministic method in which the stochastic sea state is decomposed into a reasonably high number of individual wave scatter diagrams. The results show that the recommended replacement period of the HDPE floating pipes is 20 years and that the fatigue lifetime of the floating pipes is more sensitive to the wave period than to the wave height. In addition, the effects of mooring line arrangements, wave incident angle and typhoons are also investigated. Comparisons of the fatigue lifetimes of the floating pipes for different mooring line arrangements indicate that the fatigue lifetime increases dramatically with increasing number of mooring lines. For a symmetrically arranged four-point mooring fish cage, the most unfavourable wave loading angle is 45°. Typhoons lead to a significant decrease in the fatigue lifetime of the floating pipes despite the short durations of the typhoons.

1. Introduction

Because of the increased demand for seafood and the decline of fresh water resources, the development of the marine cage net aquaculture in the open sea is becoming a worldwide trend in the aquaculture industry (FAO, 2010; Olsen et al., 2008; Oppedal et al., 2011; Shainee et al., 2013). Unfortunately, the detrimental environmental conditions in the unprotected open sea may lead to the collapse and fatigue failure of floating fish farms. Thus, it is necessary to ensure the security and sustainability of marine cages.

In past decades, numerous studies have been conducted to analyse the hydrodynamic characteristics of net cage systems. Tsukrov et al. (2003) evaluated the performance of a tension leg fish cage and predicted the overall dynamics of the system in the open ocean environment, using a consistent finite element model to simulate the net panels and nonlinear elastic components of mooring systems. Fredriksson et al. (2003) analysed the reactions of the net cages in waves by physical and numerical methods and compared the results with field observations. To investigate the dynamic properties of a flexible net sheet exposed to waves and currents, Lader and Fredheim (2006) conducted a series of experiments and developed a numerical model in which the super element concept was used to simulate the net sheet. Moe et al. (2010) investigated the deformation of a net cage in currents of different velocities utilizing the commercial explicit finite element software program ABAQU Kim et al. (2011) developed an automatic submersible fish cage system by air control and examined the automatic submergence characteristics of the fish cage using a set of physical model tests. Kristiansen and Faltinsen (2012, 2015) proposed a screen type force model for calculating the viscous hydrodynamic load on nets and simulating the net as a series of trusses, and they investigated the mooring load on the net cage by experimental and numerical study. Shainee et al. (2014) examined the submergence characteristics of the single-point mooring (SPM) cage concept in random waves with following currents using numerical simulations and experimental model tests. Decew et al. (2013) used an acoustic method to monitor the deformation of a small-scale fish cage deployed in currents. Li et al. (2013) applied the commercial explicit finite element software ABAQUS to analyse the dynamic responses of the fish cage system consisting of a floater and nets in

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waves using the "distributed beam method". Zhao et al. (2014) and Bai et al. (2015) analysed the deformations of the floating collar of the fish cage in waves using the curved beam method.

Structural fatigue failure of the fish cage has been defined as the common limit state in the Norwegian standard (Standard Norway, 2009) and has been identified as a likely frequent cause for the collapse of floating fish farms (Thomassen, 2008). Thomassen and Leira (2009) used linear 3D beam elements to simulate a fish cage made of steel cylinders configured as a square and assessed the fatigue lifetime in waves. Huang and Pan (2010) evaluated the failure risk of mooring line of an SPM cage system based on extended-period environmental loadings. Xu et al. (2014) calculated the fatigue damage of mooring lines in the frequency domain by applying Weibull plots and a histogram and compared the results with those the rainflow counting method. Because of its economic benefits and corrosion resistance, HDPE floating pipes have been extensively applied in constructing the floating system of fish cages. However, the application of HDPE pipe increases the risk of failure, owing to the relatively low strength of the composite. Therefore, the performance of the floating structure under various environmental conditions is in dire need of investigation. The material and fatigue characteristics of HDPE have been studied by previous researchers. Fredriksson et al. (2007) conducted a series of experimental tests to investigate the modulus of elasticity for weathered HDPE and proposed finite-element modelling techniques to determine the structural capabilities of the HDPE net pen. Khelif et al. (2008) carried out a probabilistic characterization of HDPE and discussed the choice of the best distribution to fit the fatigue lifetime. Yang et al. (2010) analysed the flexural fatigue behaviour of wood flour/high-density polyethylene composites. Berrehili et al. (2010) investigated the multiaxial fatigue behaviour of HDPE at room temperature and constant frequency. Gonzalez et al. (2011) conducted an experimental analysis to determine the fatigue strength of HDPE pipe in longitudinal and circumferential directions and established *S*–*N* curves for two values of test frequencies (2 and 5 Hz). Dan et al. (2015) studied the mechanical properties of stay cable HDPE sheathing fatigue in dynamic bridge environments. To our knowledge, there have been few studies focusing on fatigue lifetime estimation of the HDPE floating collar of the fish cage.

To gain insight into the structural performance and fatigue lifetime of the HDPE floating collar of the fish cage, a fatigue analysis is presented in the study. First, by applying the lumped-mass method, hydrodynamic modelling of the fish cage is performed, and the loads on the floating pipes are determined by the hydrodynamic model. The stress histories of the dangerous position as a base of the fatigue analysis are then evaluated by the finite element method using the shell element. Finally, based on the *S*–*N* curve and the Palmgren–Miner rule, the fatigue lifetime of the HDPE floating pipes of fish cages is derived by the deterministic method.

This paper is organized as follows. In Section 2, hydrodynamic modelling and finite element analysis are introduced in detail. Section 3 presents the fatigue analysis method. In Section 4, a case study of the fatigue lifetime of the floating HDPE pipes of a full-scale fish cage is presented. Section 5 studies the sensitivity of the fatigue lifetime to wave height, wave period, wave propagation direction, mooring line arrangement and typhoon. Finally, in Section 6, conclusions are drawn.

2. Numerical method

For the estimation of fatigue damage, time-series of stress history associated with the structural member of interest are needed. In this section, the stress analysis of the HDPE floating pipes in waves is introduced. The external forces on the floating pips are calculated by hydrodynamic modelling, including the wave forces, gravity, buoyancy, net tensions and inertial force. The finite element model of the floating pipes is constructed using the shell element to calculate the stress histories of the floating pipes.

2.1. Hydrodynamic model of the fish cage

The dynamic responses of the fish cage and forces on the floating pipes in waves are analysed using the hydrodynamic model. The hydrodynamic model of the fish cage based on the lump-mass method was developed at Dalian University of Technology, China (Li et al., 2006; Zhao et al., 2007a,b; Bi et al., 2014) and implemented in the software package DUT-FlexSim. The hydrodynamic model is briefly outlined in this section.

The floating pipes of the fish cage are mainly subjected to wave forces, gravity, buoyancy, net force and mooring line tension. When calculating wave force, the floating pipes are divided into many mini-segments. Fig. 1(b) gives a sketch of a mini-segment of the float pipes with a local coordinate system defined in each mini-segment. Regarding the coordinate system, n and w are in the normal and tangential directions of the mini-segment, respectively. v is then normal to the mini-plane. Because the diameter of the cross section of a flotation ring is much smaller than the wavelength, the Morison formula is employed to calculate the wave forces acting on the pipes. For example, the ratio between the wavelength and the pipe diameter is 99:1 for wave period T = 4 s. As Brebbia and Walker (1979) suggested, the n component of wave-induced forces on a mini-segment are calculated using the modified Morison equation as follows:

$$F_n = \frac{1}{2} C_{Dn} \rho A_n |\vec{u}_n - \vec{U}_n| (\vec{u}_n - \vec{U}_n) + \rho V_0 \vec{a}_n + C_{mn} \rho V_0 (\vec{a}_n - \vec{\dot{U}}_n) \quad (1)$$

where $\vec{u}_n$ and $\vec{U}_n$ are the normal velocity vectors of water particles and the mini-segment, respectively; $\vec{a}_n$ and $\vec{\dot{U}}_n$ are the normal acceleration vectors of water particles and the mini-segment, respectively; ρ the water density; V_0 is the underwater volume of the mini-segment; A_n is the projected area normal to the wave-propagation direction of component n; C_{Dn} and C_{mn} are the normal drag and added mass coefficients. The same expression is applied to other wave-induced forces (F_w, F_v). According to our previous research (Li et al., 2007), the hydrodynamic coefficients of the floating collar are taken as constants: the drag coefficients are chosen as $C_{Dw} = 0.4$, $C_{Dn} = C_{Dv} = 0.6$; the inertial coefficients are chosen as $C_{mn} = C_{mv} = 0.2$, $C_{mw} = 0$.

To obtain the motions of the floating collar, coordinate systems are defined: the global coordinate system *x*-*y*-*z* and the body coordinate system *a*-*b*-*c* as shown in Fig. 1(c). Initially, axes x, y and z are parallel to axes a, b and c, respectively. According to Newton's second law, six equations of motion are shown as follows:

$$\ddot{x}_G = \frac{1}{m_G} \sum_{j=1}^{Nsum} F_{xj}, \qquad \ddot{y}_G = \frac{1}{m_G} \sum_{j=1}^{Nsum} F_{yj}, \qquad \ddot{z}_G = \frac{1}{m_G} \sum_{j=1}^{Nsum} F_{zj}$$
$$I_a \frac{\partial \omega_a}{\partial t} + (I_c - I_b)\omega_c \omega_b = M_a, \quad I_b \frac{\partial \omega_b}{\partial t} + (I_a - I_c)\omega_a \omega_c = M_b, \quad I_c \frac{\partial \omega_c}{\partial t} + (I_b - I_a)\omega_a \omega_b = M_c \quad (2)$$

where F_{xj}, F_{yj}, and F_{zj} are the components of the force vector. F_j ($j = 1, N_{sum}$) is along the global coordinate axes *x*-*y*-*z*, N_{sum} is the number of external forces, and m_G is the mass of the rigid body: $\ddot{x}_G$, $\ddot{y}_G$, and $\ddot{z}_G$ are accelerations of the pipes' rigid centroid. Subscripts a, b, and c represent the body-coordinate axes a, b, and c; M_a, M_b and M_c ($j = 1$, N_{sum}) are the components of the moment vector M_j ($j = 1$, N_{sum}) along the principal axes; I_a, I_b, and I_c are the components of the moments of inertia I along the three moving coordinate axes;