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Fatigue reliability analysis of mooring system for fish cage

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ABSTRACT

Fish cages in the open sea are exposed to cycle loads due to irregular wave climate during their service life, and thus the fatigue reliability assessment of mooring system should be conducted to ensure the safe operation. The aim of this study is to evaluate the fatigue failure probability of mooring system for fish cage. Numerical simulation of net cage in random waves is performed and the time dependent approach is applied to conduct the fatigue reliability analysis of shackle chains based on S-N curve method. The sensitivity analysis of fatigue reliability of mooring line to the uncertainty of random variables in the fatigue limit state is conducted. In addition, the system reliability for mooring system is analyzed and the effect of the initial pretension and safety factor on system reliability is investigated. The results indicate that a case without the initial pretension on anchor lines is helpful to decrease the failure probability of mooring system and the safety factor of mooring lines in the current regulation is conservative for the system reliability against fatigue damage.

1. Introduction

Aquaculture is today the fastest growing sector of the world food industry, increasing in volume by more than 10% per year, and currently accounting for more than 35% of all fish consumed, and now it is becoming the world's largest protein source. In the past decades, the aquacultural farms have been located in sheltered waters inside the fjords, where the farms are protected from extreme weather. However, the expansion of near-shore aquaculture is becoming more difficult due to coastal multi-use issues and environmental impact concerns [1]. Thus, the fish farm is recently forced to move into the offshore area, which means that the more exposed area will be utilized and the more severe environmental load will be applied. Therefore, the future designs of fish farm must be significantly more robust than the present designs, which frequently experience the escape of fish. From an engineering perspective, the main focus will be to design a system which has an overall acceptable reliability. Time-dependent reliability analysis of mooring lines for single-cage and multi-cage system was conducted for the ultimate limit state considering the corrosion effect and the uncertainties of the significant wave height and period, and the corrosion depth of chains [2]. Although the extreme environmental event may govern the design on some occasions, the complicated mooring system of fish farms exposed to wave loads is vulnerable to cumulative fatigue damage due to the cyclic nature of the wave loading, and the fatigue failure may occur earlier than the emergence of the extreme environmental event. Thus, for both existing and future fish farms, the integrity of the mooring system should be investigated in order to withstand the environmental cyclic loads.

Numerous numerical studies have been conducted on the hydrodynamic analysis of fish cage structures, including net panels, floating collars, net cages and mooring systems. Lader and Fredheim [3] established a numerical model using super element to investigate the dynamics properties of a flexible net sheet under the wave loads. Balash et al. [4] analyzed the steady loads on the plane net through numerical simulation, in which the net is considered as an inter-connected system of lumped masses and springs. Patursson et al. [5] modeled the net as a sheet of porous media to improve the computational efficiency and obtained the flow characteristics through and around net panel. Bouhoubeiny et al. [6] performed Time-Resolved Particle Image Velocimetry measurements to study the hydrodynamic flow interaction with fishing net structure and demonstrated the influence of fluttering net structure. Zhou et al. [7] investigated the hydrodynamic characteristics of knotless nylon netting with the variation of solidity ratio in normal, parallel and angle of incline to free stream. Kristiansen [8] analyzed fully nonlinear wave body interaction problems by numerical

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Nomenclature

T	Tension force
Δl	Elongation of mooring lines
l	Initial length of mooring lines
$S(f)$	Input wave spectrum
H_s	Significant wave height
T_s	Significant wave period
T_p	Spectral peak period
f	Wave frequency
f_p	Spectral wave frequency
γ	Peak enhancement factor
σ	Peak shape factor
$u(x, z, t)$	Horizontal velocity of water particles at time t
$w(x, z, t)$	Vertical velocity of water particles at time t
a_i	Wave amplitude of ith component wave
h	Water depth
f_i	Wave frequency of ith component wave
k_i	Wave number of ith component wave
ε_i	Random phase of ith component wave
x	Horizontal coordinate of water particles
z	Vertical coordinate of water particles
p	Occurrence probability of each sea state
C_{Dj}	Drag coefficient in the direction of the j component, $j=\tau,\eta,\xi$
C_{mj}	Added mass coefficient in the direction of the j component, $j=\tau,\eta,\xi$
F_j	External forces on the net twine for the j component, $j=\tau,\eta,\xi$
u_j	Fluid particle velocity vector at the element center for the j component, $j=\tau,\eta,\xi$
A_j	Projected area for the j component, $j=\tau,\eta,\xi$
V_0	Water displaced volume of an element
$\dot{R}_j$	Central velocity vector of element for the j component, $j=\tau,\eta,\xi$
$\dot{u}_j$	Fluid particle acceleration vector at the element center for the j component, $j=\tau,\eta,\xi$
$\ddot{R}_j$	Central acceleration vector of element for the j component, $j=\tau,\eta,\xi$
ρ	Density of water
μ	Viscosity of water
C_η	Normal drag coefficient for mesh bar
C_η	Tangential drag coefficient for mesh bar
$V_{R\eta}$	Normal component of the fluid velocity relative to the bar
S	Stress range (double amplitude) in MPa
N	Number of cycles for the stress range S to failure
K	Intercept parameter of S-N curve
m	Slope parameter of S-N curve
D	Accumulative fatigue damage
T_L	Design lifetime
$N(S_j)$	Number of cycles to failure at stress range S_j
$N(T_L)$	Number of stress cycles in total time T_L
A	Scale parameter in Weibull distribution
B	Shape parameter in Weibull distribution
$\nu_0{}^+$	Load cycle per unit time
Δ	Allowable fatigue damage
$\mathrm{N}(e, sd)$	Normal distribution with the expected value e and standard deviation sd
$\mathrm{LN}(e, sd)$	Log-normal distribution with the expected value e and standard deviation sd
$\mathbf{H}$	Hessian matrix
$C_{A,B}$	Covariance matrix
ρ_{AB}	Correlation coefficient of scale and shape parameters
σ_A	Standard deviation of scale parameter
σ_B	Standard deviation of shape parameter
$\Gamma(\cdot)$	Gamma function
$\boldsymbol{X}$	Random variables
$z(\boldsymbol{X})$	Limit state function for variable vector $\boldsymbol{X}$
$P\{z(\boldsymbol{X})\le 0\}$	Probability of $z(\mathrm{X})\le 0$
$f(\boldsymbol{X})$	Joint probability density function of $\boldsymbol{X}$
p_f	Failure probability of structures
R	Reliability of structures
$\boldsymbol{Y}$	Independent variables
β	Reliability index
$\boldsymbol{X}^*=(\mathrm{x}_1,x_2)$	Design point in $\boldsymbol{X}$ space
$\boldsymbol{Y}^*=(y_1,y_2)$	Design point in $\boldsymbol{Y}$ space
$\Phi^{-1}(\cdot)$	Inverse function of the standard normal probability distribution
μ_{Xi}	Expected value of random variable X_i
σ_{Xi}	Standard deviation of random variable X_i
ε_{Xi}	Important factor of random variable X_i
SF_i	Sensitivity factor for random variable X_i
$P(C_i)$	Failure probability of the ith component
P_{lower}	Lower bound for system failure probability
P_{upper}	Upper bound for system failure probability
$P(C_{ij})$	Joint failure probability of the ith and the jth components
β_i, β_j	Reliability indices for the ith and jth components
$\Phi(\cdot)$	Cumulative probability distribution function for 1-D standard normal distribution
ρ_{ij}	Correlation coefficient between the ith and the jth components
F	Safety factor
γ_f	Partial safety factor for fatigue load
K_c	Characteristic value of K
$\nu_{0c}{}^+$	Characteristic value of $\nu_0{}^+$
B_c	Characteristic value of B
A_c	Characteristic value of A
Δ_c	Characteristic value of Δ

wave tank to calculate wave loads on a floating horizontal collar. Fu and Moan [9] predicted the dynamic response of 5 by 2 floating collars by the application of an extended 3D hydroelasticity theory in regular waves. Huang et al. [10] developed a finite element model to investigate the elastic deformations and mooring line tensions of floating collar in waves. Lee et al. [11] developed a mass-spring model to analyze the performance of fish cage system in current and waves. Moe et al. [12] performed strength analysis to obtain the loads distribution in the net cage due to current, weights and gravity. Xu et al. [13] investigated the hydrodynamic behavior of multi-cage and mooring system by lumped-mass model under the action of waves combined with current. Li et al. [14] analyzed the nonlinear hydro-elastic response by finite element model of a deep-water gravity cage in irregular waves. Grue [15] predicted the mooring line loads for two systems of gravity net cages under the action of wave and currents through numerical simulation. Kim et al. [16] analyzed the flow field characteristics within the abalone containment structure with computational fluid dynamic software and investigated the hydrodynamic response of the moored containment structure with a Morison equation type finite element model. Ito et al. [17] investigated the hydrodynamic behaviors of a cubic shaped elastic net structure and estimated the mooring forces and mooring displacements. Yao et al. [18] proposed a hybrid volume approach to add the resistance force of the net cage into the flow field for coupling the fluid and net. Winthereig-Rasmussen et al.