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# Motion responses of a moored barge in shallow water

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Motion characteristics of a floating structure in shallow water are of great concern in ocean engineering. Shallow water effects will significantly affect the hydrodynamic performance of a floating structure. In this study, both numerical and experimental studies have been conducted to investigate the hydrodynamic performance of a barge in shallow water. Numerical simulations are conducted in both frequency and time domains based on 3D potential theory. Second-order wave forces have been incorporated in the numerical model through the calculation of fully quadratic transfer function. The numerical results are validated through a series of physical model tests, including free decay test and irregular wave tests. Responses of the floating structure in different water depths and sea states are studied to clarify the safe conditions for a float-over installation in shallow water. Based on the numerical and experimental results, some conclusions have been drawn. Furthermore, a critical depth for shallow water effects is clarified.



## 1. Introduction

Traditionally, fixed offshore platforms have been widely applied in shallow waters for the exploitation of oil and gas resources. However, nowadays more floating structures have been proposed to be applied in shallow waters. For example, the Floating Production Storage and Offloading system (FPSO) is widely adopted in shallow waters due to its low cost and large capacity of oil storage avoiding the usage of subsea pipelines in a fixed platform program (Xiao and Yang, 2006). More recently, a new concept Floating Storage and Regasification Unit (FSRU) is also proposed as a promising alternative for onshore Liquefied Natural Gas (LNG) terminals due to the environmental and safety issues (Lee et al., 2010). Shallow water area that is not far away from the coast line is the preferred site for FSRU considering the technical efforts and financial risks (Kim et al., 2012). It is reported that seven FPSOs and one floating LNG terminal have been in service in the Gulf of Bohai in China, where the average water depth is only 18 m (Li et al., 2014). Additionally, a lot of large Offshore Support Vessels (OSVs) also operate in this shallow water region such as the derrick vessel for heavy lift operation and the float-over barges for topside installation.

Although the floating structures show advantages in this area, the shallow water depths introduce more technical challenges such as the strong nonlinearities in the propagating waves and the complex wave-structures interactions. In particular, the significant wave height in the Gulf of Bohai can reach up to 6 m in extreme storms with the period of 10.5 s (Xiao et al., 2014). The large wave height and the relatively shallow water depth enhance the nonlinearities and result in more challenges.

There have been research efforts in the estimation of the motion response of a moored structure in shallow waters. Molin and Fauveau (1984) carried out an analysis on the set-down wave in deep and shallow water depths. It is observed that the loads induced by the set-down in shallow water contribute to the slow-drift motion of moored structures. Recently, Yang et al. (2002) used an experimental method to investigate the motions of a single-point moored (SPM) FPSO in different shallow water depths. Li et al. (2003) further conducted numerical studies to analyze the shallow water effects. It is observed that the wave frequency motions decrease with the reduction of water depth, while the low-frequency motions increase at the same time. Naciri et al. (2004) studied the low-frequency motions of LNG carriers moored in shallow water. It is concluded that the shallow water effects play an important role in wave drift forces. When the water depth decreases, the wave drift forces increase. Wim and Ivo (2008) used a new method consisting of a Boussinesq-type wave model with a linear-domain diffraction model to calculate the wave forces on a moored ship in irregular wave in shallow water. It is concluded that both time-domain and frequency-domain methods are capable of dealing with the non-linear incident waves. The frequency-domain method is more efficient, while the time-domain method is practical with good accuracy. Pinkster (2009) studied an LNG carrier moored in shallow water. It is shown that bound waves appear to affect the low-frequency forces more than

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the first-order waves, which is typically a shallow water effect. Yan et al. (2010) investigated the fully nonlinear interaction between a moored FPSO and the shallow water waves, together with the effects of water depth on those issues. The results show that the wave induced force decreases but the nonlinear components and the surge motions become more significant as the water depth decreases. The low-frequency motion response plays a critical role in the design of mooring systems due to the significant resonant responses which might be induced by the second-order wave forces.

To estimate the second-order wave excitation forces, Newman (1974) proposed an approximation to get the Quadratic Transfer Function (QTF) matrix, by using the mean drift force to interpolate the off-diagonal values. Naciri and Poldervaart (2004) studied the low-frequency motions and design aspects of LNG carriers moored in shallow water. The Newman approximation and full QTF approach are expected to yield comparable responses in the sea state with a relatively short peak period. However, studies (Chen, 1994; Tahar and Kim, 2003; Pessoa and Fonseca, 2013) have indicated that Newman approximation underestimates the low-frequency response of a floating vessel in shallow water. Newman (2004) confirmed that the zero-order approximation is poor as the water depth is less than 100 m. Furthermore, Grant and Holboke (2004) concluded that the Newman assumption has limited applicability in cases with shallow water and long wave periods, and full QTF is recommended in shallow water. Xiao (2007) conducted a study regarding the shallow water effects on a soft yoke moored FPSO. Results based on Newman approximation show good agreement with experimental data in general water depth. However, the agreement will become less satisfactory as the water depth decreases. Guillaume et al. (2012) reviewed the approximation methods for the calculation of the second-order wave loads and suggested that the full QTF should be calculated in shallow water to obtain a good prediction.

In this study, a direct second-order pressure integral method is adopted to calculate the full QTF of a moored barge at Gulf of Bohai with water depth of 9.41 m. Coupled analysis has been conducted in time domain to estimate the motion response of the barge and loads on the mooring lines. Numerical simulations are completed by the commercial software SESAM. Model tests are conducted in the wave basin at Shanghai Jiao Tong University to validate the numerical results. The numerical results agree well with the experimental data. Based on the numerical and experimental study, some conclusions have been drawn regarding the hydrodynamic performance of the referenced floating barge in shallow waters.

## 2. Numerical modeling

### 2.1. Potential theory

With the assumption of irrotational motion and incompressible fluid, the fluid motion can therefore be described by a velocity potential $\phi$, which satisfies the Laplace equations:

$$\nabla^2\phi(x,y,z,t)=0, \tag{1}$$

where $x,y,z$ are the spatial coordinates with $xy$-plane coincides with the calm water and $z$-axis points upwards, $t$ represents time. The total velocity potential can be divided into three parts: incident potential $\phi_I$, radiation potential $\phi_R$ and diffraction potential $\phi_D$, namely (Zhao et al., 2014):

$$\phi=\phi_I+\phi_R+\phi_D. \tag{2}$$

The incident potential $\phi_I$ for a regular wave at finite water depth is, according to Airy's wave theory, expressed by Reinholdtsen and Falkenberg (2001)

$$\phi_I=\frac{gA}{\omega}\frac{\cosh k(z+H)}{\cosh kH}\cos\left(\omega t-kx\cos\beta-ky\sin\beta+\varphi_\zeta\right), \tag{3}$$

where $A$ represents the wave amplitude, $g$ the acceleration of gravity, $\omega$ the wave frequency, $\beta$ the direction of wave propagation and $\varphi_\zeta$ the wave component phase angle. The wave number $k$ satisfies the dispersion relation:

$$\frac{\omega^2}{g}=k\tanh kH. \tag{4}$$

The fluid velocity components can be computed from Eq. (4). It suggests that trajectories of fluid particle will become elliptical in shallow water, which would induce the shallow water effects.

Each part in Eq. (2) can be solved under their corresponding boundary conditions, which is shown as follows:

$$\begin{cases} \frac{\partial^2\phi}{\partial t^2}+g\frac{\partial\phi}{\partial z}=0, \quad at\ z=0 \\ \frac{\partial\phi_R}{\partial n}=\vec{U}\times\vec{n}, \quad \frac{\partial(\phi_I+\phi_D)}{\partial n}=0, \quad \text{at body surface} \\ \frac{\partial\phi}{\partial n}=0, \quad \text{at } z=-H \\ \lim_{R\to\infty}\sqrt{R}\left(\frac{\partial\phi}{\partial R}-ik\phi\right)=0 \end{cases}, \tag{5}$$

where $\vec{n}$ stands for the normal vector of the corresponding surface, $\vec{U}$ the velocity vector of body surface and $H$ the finite water depth.

Once the velocity potential is known, it is easy to calculate the hydrodynamic forces of the barge, including the wave exciting force, wave radiation force and restoring force by the pressure integration on the wet surface. At the same time, hydrodynamic coefficients such as the added mass and the potential damping can be obtained from the radiation potential (Bingham, 2000; Hong et al., 2005).

### 2.2. Motion equation of a floating body

Motion equation of the barge can be expressed in time domain as follows (DNV, 2011; Zhang et al., 2013; Zhao et al., 2011):

$$[m+a(\infty)]\left\{\ddot{\xi}\right\}+D_1\left\{\dot{\xi}\right\}+D_2f\left(\dot{\xi}\right)+K(\xi)\{\xi\}+\int_0^t h(t-\tau)\left\{\dot{\xi}\right\}d\tau$$
$$=F^{wave}+F^{wind}+F^{current}+F^{ext}, \tag{6}$$

where $m$ is the mass matrix for the barge hull, $a(\infty)$ the added mass matrix at the infinite frequency, $\{\xi\}$ the matrix of vessel's six DOF motion, $K$ the hydrostatic restoring stiffness matrix, and $D_1$ and $D_2$ the linear and quadratic damping matrix, respectively. The forces excited by waves, wind and current are represented by $F^{wave}$, $F^{wind}$, and $F^{current}$ respectively. The last item $F^{ext}$ denotes the other possible force such as the specified forces, mooring force and so on. The retardation function $h(\tau)$ represents the memory effect in the free surface. It can be obtained from the added mass matrix $a$ and potential damping matrix $c$:

$$h(\tau)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}[c(\omega)+i\omega a(\omega)]e^{i\omega t}d\omega, \tag{7}$$

where $\omega$ is the frequency. It should be noted that the viscous damping and the wave drift damping should also be included in the term $\int_0^t h(t-\tau)\left\{\dot{\xi}\right\}d\tau$ in the form of critical damping, because these variants are related to the motion velocity of the vessel (Zhao et al., 2014).

Using the fact that $c(\omega)=c(-\omega)$ and $a(\omega)=a(-\omega)$, it gives

$$h(\tau)=\frac{1}{\pi}\int_0^\infty[c(\omega)\cos\omega\tau-\omega a(\omega)\sin\omega\tau]d\omega=\frac{2}{\pi}\int_0^\infty c(\omega)\cos\omega\tau d\omega$$