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Effect of hull geometry on parametric resonances of spar in irregular waves

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ABSTRACT

The parametric instabilities of spar platforms with different hull shapes are investigated in irregular waves. Parametric instability is a phenomenon that may cause excessive motion in offshore structures. It occurs when a system parameter varies with time, and the change meets certain conditions. For a spar platform, the parameter that causes parametric resonance is usually the metacentric height. In previous studies, the parametric instability of a spar was mainly analyzed in regular waves. However, real sea conditions are irregular. In addition, some accidents and experiments have shown that parametric resonance also occurs in irregular waves. This paper analyzes the parametric instability property of a spar platform being affected by multifrequency waves, which corresponds to realistic sea conditions. The stability is determined using both an analytic method and numerical simulation. The analytic investigation is carried out using Hill's equation. The heave amplitudes of the motion are simulated using the wave spectrum and response amplitude operator (RAO). Different hull shapes cause significant differences when analyzing the parametric instability due to irregular waves because of different RAOs. Stability diagrams containing the boundaries of the stability regions of different hull shapes are given based on the solution of Hill's equation. The numerical simulation can not only determine whether the spar is stable, but can also give the maximum pitch angle. The effects of the design parameters of a spar platform and the wave parameters are analyzed by giving the contours of the maximum pitch angle. The effects of time-varying displacement are also considered in this work. Stability diagrams and the contours of the maximum pitch angle are drawn to help with the prediction of the parametric instability. Some suggestions are also given to avoid the parametric pitch of a spar in design by selecting an appropriate design parameter and hull shape.

1. Introduction

With the exploitation of gas and oil extended to the deep ocean, production systems mounted on platforms are being widely applied. Maintaining the safety of these platforms is of great importance to avoid economic loss and environmental pollution. When a system parameter changes over time, and this change meets certain conditions, the motion of the system will become too large and unstable. This phenomenon is called parametric resonance. Avoiding parametric resonance is an important priority to ensure the safety of ships, platforms, and other offshore structures.

Over the past few decades, several ship accidents have occurred as a result of parametric resonance (Laarhoven, 2009). These accidents have attracted much attention to the parametric rolling of ships. Parametric rolling is caused by a change in the metacentric height, which is mainly affected by the hull shape and wave frequency (Vidic-Perunovic and Juncher Jensen, 2009). For ships encountering waves at different angles, different conditions should be considered. Therefore, parametric roll has been investigated in both following seas and head seas (Neves and Rodríguez, 2007; Spyrou, 2000). However, these studies were carried out under regular wave conditions.

Risers were found to have similar phenomena when the excitation frequency was double the structure's first lateral natural frequency (Chatjigeorgiou and Mavrakos, 2005). The damping effects during the parametric resonance of risers were investigated (Dohnal et al., 2008). Some engineering applications of the parametric instability analysis of risers have also been given (Zhang et al., 2011). Yang and Li (2009) derived an equation of motion for a deep-sea riser, which provided a way to investigate the parametric resonance using the analytic method. Hill's equation, which can be applied under multifrequency conditions, was introduced (Yang et al., 2013) to analyze the parametric instability in irregular waves.

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For a spar platform, the parametric resonance mainly occurs during the pitch/roll motion, as a result of the time-varying metacentric height, which is mainly affected by heave motion. The motion equation is similar to that of ships. However, some differences exist, including the changes in the water plane and displacement volume, which are much smaller for a platform than for a ship because of the small area of the round water plane and deep draft. Moreover, a spar platform is typically stationary. Thus, it cannot avoid parametric resonance by changing its velocity like a ship. As a result, it is much more important to ensure its stability during the design phase.

Several researchers have performed experiments to study the parametric pitch of a spar platform. Rho and Choi investigated the coupling of the heave and pitch motions of a spar platform with a damping plate (Rho et al., 2002), and also studied the effects of mooring (Rho et al., 2003). Lim et al. (2005) observed that pitch motions became unstable at a certain time range in experiments on heave and pitch coupled motion. To investigate the "Mathieu-type instability," Hong et al. (2005) carried out several model tests, in which extreme heave-induced pitch and roll motions were observed when the periods of an encounter wave were similar to the heave resonant period and twice that of the roll/pitch natural periods.

However, an insufficient number of investigations have been performed on the theory for the parametric pitch of a spar platform. Most of the previous theoretical studies only considered regular waves. The parametric pitch was mainly determined via the analytic method using the Mathieu equation divided from the motion equation. Haslum and Faltinsen (1999) analyzed the parametric instability property of spar platforms using a simplified method. Zhang et al. (2002) drew a stability diagram that showed the instability regions with the damping coefficient changes based on calculations using the Mathieu equation. Nonlinear terms were also analyzed in some previous works. Agarwal and Jain (2003) investigated the nonlinear coupled responses of spar platforms under regular waves. Ma and Patel (2001) studied the hydrodynamic interaction of platforms and ocean waves. The effects of damping, mooring, and risers on the parametric stability of a spar platform were investigated in several works (Koo et al., 2004; Li et al., 2011; Spanos et al., 2011; Yang et al., 2012).

However, experiments on spar platforms in irregular waves have shown that parametric resonances also occur under irregular conditions (Pettersen and Machado-Damhaug, 2007). These experiments, and various ship accidents, have shown that parametric resonance occurs, not only in regular waves, but also in irregular waves, which correspond to real sea conditions. These facts show the urgent need to investigate the parametric pitch of a spar platform in irregular waves. In addition, the heave response of a spar platform in irregular waves differs from that in regular waves, and it is greatly affected by the hull shape. The damping and natural periods of a classic spar platform are low, which will result in a large heave motion. This is dangerous because it can lead to parametric resonance. Compared with increasing the draft, mass, and added mass of an existing platform, it is more economical to properly design the hull shape. Thus, investigations on the effects of different hull shapes are important.

The main methods applied in this work are the analytic method and numerical simulation. Numerical simulation has been used extensively to analyze parametric roll in ships, but it has seldom been applied to studies of spar platforms. This is primarily because it takes a long time as a result of the large amount of calculation required. The analytic method is mainly based on the analytic solutions of equations. Although equations can be used to determine the boundaries of stability regions through the analytic method, it takes much longer to create a stability diagram compared to the time needed to carry out numerical simulations. Another advantage of numerical simulation compared to the analytic method is that it can take more parameters into consideration, such as the nonlinear damping and restoring moment, which are ignored when using Mathieu–Hill's equation. However, the analytic method can give a continuous boundary for a stability region with dimensionless parameters, whereas numerical simulations use discrete design points. Therefore, a stability diagram based on the analytic method has broader applicability.

Compared to analyses under regular waves, the main difference in irregular waves is that the heave motion, namely, the change in metacentric height, cannot be simply expressed as a harmonic signal. Thus, the most widely used Mathieu equation cannot work for a multifrequency condition. This paper applies the linear wave theory and Hill's equation in order to solve this problem. In addition, the hull shape also affects the heave function. The effects of the hull shape can be shown as the response amplitude operator (RAO), which results in different peak frequencies and amplitudes for the heave motion in multifrequency waves; in single-frequency waves, it only affects the amplitude. The effects of different spar hull shapes cannot be considered using a simple parameter. Therefore, the effects are studied by drawing stability diagrams based on Hill's equation in this paper.

The parametric instability property of a spar platform is analyzed in multifrequency waves, which correspond to real sea conditions. Laarhoven (2009) drew the contours of the roll angle under the condition of regular waves. In a similar manner, the design parameters of a spar platform and the wave parameters are studied by drawing stability figures based on numerical simulation results. Nonlinear damping and the restoring moment are also considered in this simulation, although it is found that these nonlinear parameters have little effect on whether the instability resonance occurs, but mainly control the maximum pitch angle.

In addition, the displacement, added mass, and damping of a spar platform were considered to be constant in previous studies. However, in reality, these coefficients all change during the motions of a spar platform. Thus, numerical simulations are also conducted by taking the change in displacement into consideration to see how it affects the parametric instability property, whereas the other coefficients are still constants to avoid making the calculation too complex. It is hoped that their effects can be investigated in further studies.

This paper presents two methods for avoiding or predicting parametric resonance based on analytic investigations and numerical simulations. The analytic investigations are conducted through rewriting the motion equation into Hill's equation and investigating the solution of the equation. This method can be applied for qualitative analyses of factors that cannot be simply described by several parameters. The effects of different hull shapes are then given based on the analytic investigation. The numerical simulations are carried out by directly solving the motion equation through numerical method. It can give the time history of pitch, which can be applied in analyzing the effects of some parameters. Thus, through numerical simulations, the design parameters of the hulls are investigated using the contours of the maximum pitch angle. The nonlinear damping, nonlinear restoring moment, and time-varying displacement are also considered and investigated in this paper. Some suggestions are given to prevent parametric resonance at the design stage by properly choosing the design parameters and hull shape based on stability diagrams.

2. Theory and method

2.1. Simulation of heave in irregular waves

The wave spectrum method is the most widely used method to simulate irregular waves based on the linear wave theory. It can also be applied to the simulations of structural responses if they are assumed to be linear.

In this work, JONSWAP is chosen to simulate the irregular waves. The equation is as follows:

$$S(\omega)=\frac{5{H_s}^2{\omega_p}^2}{16\omega^5}\cdot(1-0.287\lg\gamma)\cdot\exp\left(-\frac{5{\omega_p}^4}{4\omega^4}\right)\cdot\gamma^{\exp\left[-\frac{(\omega-\omega_p)}{2\sigma^2{\omega_p}^2}\right]} \tag{1}$$