Numerical Study on Difference-Frequency-Induced Parametric Roll Occurrence

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This study considers the parametric roll phenomena of large container and cruise ships. In particular, a new mechanism of the occurrence of parametric roll is introduced in this paper. This new mechanism is due to the difference-frequency effects in the presence of bichromatic waves. To prove the present finding, theoretical, numerical and experimental methods are applied. In the numerical approach, nonlinear roll motion is simulated by using 2 different time-domain methods: the impulse-response-function method and the 3D Rankine panel method; in particular, a weakly nonlinear method including nonlinear Froude-Krylov and restoring forces is applied. These 2 methods provide favorable results for parametric roll occurrence. The unstable parametric roll is theoretically examined by introducing the quasi-periodic Mathieu equation. Unstable criteria are well predicted from stability analysis in the theoretical approach. The occurrence is also observed in the experiment carried out in an ocean basin.

INTRODUCTION

The roll motion of ships has been of great interest because it is one of the most crucial factors affecting structural loads, dynamic motion stability and passenger comfort. Since modern ships have become faster and larger over the last decade, the nonlinearity of roll motion becomes an essential element of large-ship design.

Much research has proved the possibility of the occurrence of a very large roll angle in head or following waves when the wave encounter frequency is twice that of the roll’s natural frequency. This nonlinear phenomenon, the so-called parametric roll, is of great concern for large modern ships. The mathematical definition of parametric indicates self-excitation or parametric excitation, which can be used in the Mathieu equation.

The analysis of parametric roll requires considering the actual wetted ship surface in motion analysis, since the temporal variation of restoring force is a crucial factor of the occurrence of parametric roll motion. To this end, earlier studies included the 2nd-order nonlinear restoring component in the equation of motion. The harmonic variation of metacentric height, $GM$, leads the classical equation of motion to the Mathieu equation. Pauling and Rosenberg (1959) and Nayfeh (1988) solved the Mathieu equation and indicated the possibility of a large roll angle in head and/or following waves. Dunwoody (1989) used the spectral form of the $GM$ variation to consider the wetted ship surface more accurately. In the case of 2D analysis, Tanizawa and Naito (1998) introduced an excellent study by using not only a nonlinear numerical method but also an experimental approach.

In the computational approach, many of the time domain simulation codes are possible for parametric roll prediction. The 3D panel method, which has recently been widely used in ship motion analysis, makes it possible to consider the effect of nonlinear restoring force in a more accurate manner. In this case, the nonlinear motion analysis should be carried out in the time domain. France et al. (2003) and Shin et al. (2004) applied Rankine panel methods in parametric roll analysis, showing favorable results. However, the 3D panel method is still somewhat expensive in terms of computation time.

The impulse-response-function (IRF) approach formulated by Cummins (1962) can be a candidate to compromise the accuracy and efficiency of numerical computation. This approach solves the equation of ship motion by using precomputed hydrodynamic coefficients. Similar to the 3D panel method, the IRF approach can also consider the nonlinear restoring force on an instantaneous wetted surface (Ballard et al., 2003). Using this advantage, Spanos and Papadikolou (2007) have applied the IRF approach in the parametric roll analysis of a fishing vessel.

In the present method, both the Rankine panel method and the IRF scheme are considered for the simulation of nonlinear ship motion in waves. In the case of the Rankine panel method, a high-order B-spline function is applied to approximate physical parameters such as velocity potential and wave elevation. For the computation of the retardation function, which is necessary for the IRF approach, a set of hydrodynamic coefficients is obtained by using a frequency-domain computational program based on a 3D Green function method.

The nonlinear approach considered in this study is the weakly nonlinear method, which solves the linear free-surface boundary condition but includes the nonlinear Froude-Krylov and restoring forces for the equation of motion. Therefore, this method combines the linear and nonlinear components of excitation force, and the nonlinear component is mostly from ship geometry. This scheme is popular in recent seakeeping analysis for ships and offshore structures; it is sometimes called the Blended Method.

In the numerical simulation of nonlinear roll, large roll motion is observed in 2 wave components. To analyze the large roll angle theoretically, the restoring component is assumed to have 2 component harmonic variations. This theoretical approach leads to the quasi-periodic Mathieu equation. Some theoretical and numerical approaches are developed by Zounes and Rand (1998) to achieve the solution and the stability with the same amplitude of fluctuation in 2 components. Further improvements are developed in a different amplitude of fluctuation (Rand et al., 2003), and in a damped and nonlinear restoring model (Guennoun et al., 2001, and Abouhazim et al., 2005). From the observation of the stability diagram, an unexpected instability region is found where it does not correspond to that of the single-component Mathieu equation. By the numerical simulation of nonlinear roll, a possible source