Ocean Engineering 144 (2017) 1–13

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Study on added resistance of a ship under parametric roll motion

Jae-Hoon Lee, Yonghwan Kim *

Department of Naval Architecture and Ocean Engineering, Seoul National University, Republic of Korea

A R T I C L E I N F O

Keywords:
Parametric roll
Nonlinear roll
Added resistance
Rankine panel method
Ship stability

A B S T R A C T

Parametric roll of ship is a rare event occurring in specific conditions, but it can cause the dynamic roll instability. Since this phenomenon is dependent on ship speed and wave frequency, the development of roll motion and the resultant added resistance which can cause speed change should be considered simultaneously when parametric roll occurs. This paper considers a numerical study on the added resistance of a modern containership under parametric roll. A time-domain Rankine panel method adopting a weakly nonlinear formulation is adopted to obtain ship motions and added resistances in waves. Seakeeping computations in regular head-sea conditions are performed with and without parametric roll, and the increment of added resistance is investigated with regard to the components classified in the direct pressure integration method. Furthermore, according to the decoupling phenomena between the components of the vertical motions and the roll motion, a correlation between the parametric roll and the added resistance is derived. Lastly, a simple prediction method for the added resistance in irregular parametric roll motion is suggested based on the correlation, and its accuracy and efficiency are discussed by comparing the prediction with the results of the direct numerical computation.

1. Introduction

Prevention of the parametric roll phenomena, which is one of the dynamic stability problems of ships, has been a matter of concern, because the resonant roll motion is excited rapidly during several encounter periods of waves. Although there have been attempts to examine a direct control on the roll motion, such as the application of the bilge keel and the active fin stabilizer (Levadou and van't Veer, 2011), and the U-tank (Holden, 2011), the operational guidance for a ship crew's decision-support system can serve as a prior countermeasure in order to avoid vulnerable environmental and operational conditions to the phenomena (Song et al., 2013). The conditions are directly related to the encounter wave frequency; therefore, the forward speed and the heading angle of ships should be controlled for its prevention.

When the excitation of parametric roll starts under the vulnerable conditions, the speed of ship is changed simultaneously due to the added resistance occurred in the phenomena. Therefore, in order to tackle vulnerabilities relevant to the parametric roll, the speed variations should be accounted in numerical simulations. To this end, the accurate prediction of the added resistance induced by the large-amplitude roll motion is also required. In other words, with regard to the parametric roll phenomena, the added resistance of a ship is considered in terms of the dynamic stability in waves, not the efficiency during ship operations.

Historically, the added resistance due to waves has been widely investigated because the actual performance of ships in seaways is determined by the resistance. Several previous researchers conducted experiments for the added resistances on the typical ship models such as the series 60 models (Gerritsma and Beukelman, 1972), the S175 containership (Fujii and Takahashi, 1975), and the Wigley models (Journee, 1992). In the cases of analytical and numerical approaches, two major methods have been introduced to analyze the added resistance problem. First, a far-field method, which was originally derived by Maruo (1960) and further refined by Newman (1967), is based on a momentum conservation theory. This method is simple and efficient that does not involve solving a boundary value problem for the pressure acting on a body. In the method, however, there are difficulties in handling a proper control surface. Alternatively, a near-field method, which represents direct integration of the second-order pressure on the body surface has also applied to the calculation of added resistance. One of the advantages of the near-field method is the decomposition of added resistance, which enables the physical observation by a component analysis and an extension to considerations for nonlinearities in the phenomenon. Faltinsen et al. (1980) validated the computation results obtained by the near-field method, and formulated a simplified asymptotic approach to enhance the results for short waves. Grue and Biberg (1993) also adopted the method along with the frequency-domain wave Green function to

* Corresponding author.
E-mail address: yhwankim@snu.ac.kr (Y. Kim).

https://doi.org/10.1016/j.oceaneng.2017.08.015
Received 31 May 2017; Received in revised form 27 July 2017; Accepted 11 August 2017
Available online 18 August 2017

evaluate the resistance induced by waves on a floating body advancing with a small speed. It should be noted that most of the researches in the early stages were based on the linear potential theories; hence, the effects of nonlinear free surface flows and hull geometries were not included.

Recently, nonlinear approaches using computational fluid dynamics (CFD) simulation have been applied owing to the development of computing power. A simulation method called the WISDAM-X was used by Orihara and Miyata (2003) and Orihara et al. (2008) to examine the added resistance for different bow shapes above the mean-water level. In this method, the Reynolds-averaged Navier-Stokes equation (RANSE) was solved using a finite volume method (FVM) in an overlapping grid system. Furthermore, Yang (2015) developed a Cartesian-grid-based method for solving the Euler equation, and investigated the effects of the nonlinear bow waves on the added resistances for different wave amplitudes. In the operation of a large modern ship, the major issues are not only the efficiency of reducing greenhouse gas emissions, but also the performance of ships in rough seas. Therefore, the trend of adopting the nonlinear simulation is expected to continue. However, there have been limitations in the application of the CFD methods, because of high computational costs and a strong dependency on the grid system.

In the case of parametric roll phenomena, the time-domain simulations for nonlinear ship motions have been conducted. The most important parameter in the numerical simulation is an accurate prediction of the time-varying nonlinear restoring forces in waves. For an efficient computation, a weakly nonlinear approach, which considers the partial nonlinearities of hull geometry, was used in many previous research efforts. For example, France et al. (2003) and Shin et al. (2004) applied the Rankine panel method (RPM) to evaluate not only the susceptibility criteria but also the amplitude of roll motion for large containerships. Spanos and Papanikolaou (2007) analyzed the parametric roll of a fishing vessel in regular waves using the impulse response function (IRF) method. Kim and Kim (2011b) developed a multi-level analysis, which include level-by-level applications of an analytical formula based on the metacentric height (GM) variation, the IRF method, and the Rankine panel method to compare the properties of each method.

For realistic simulations of parametric roll motions, the speed variation due to resistance caused by severe roll motion should be considered along with occurrences and magnitudes of the phenomena. Therefore, there have been attempts to develop the surge-roll coupled model to account for the interaction between the development of parametric roll and the speed variation (Vidic-Perunovic and Jensen, 2009). Also, Breu and Fossen (2010) applied the speed and heading control to the coupled model for mitigation of the phenomena. However, in most of the previous studies, a relatively simple method was applied to estimate the added resistance, considering only for the surge added mass and Froude-Krylov and restoring forces. On the other hand, to predict the added resistance induced by parametric roll more accurately, Lu et al. (2015) adopted a roll motion obtained by model experiments to a revised formula from the linear far-field method of Maruo (1960). However, according to a linear perspective, the method did not consider the nonlinear effects of the large-amplitude roll motion. Therefore, an efficient nonlinear approach is required to account for the effects on the added resistance.

In the present study, the time-domain 3-D Rankine panel method developed by Kim et al. (2011) is applied to predict ship motions and added resistance of a containership under the parametric roll phenomena. The near-field method derived by Joncquez (2009) and Kim and Kim (2011a), which is the direct pressure integration method for the evaluation of added resistance, is modified based on a weakly nonlinear approach. In other words, the higher-order restoring and Froude-Krylov forces at the actual wetted surface are included to consider the nonlinear effects induced by parametric roll motion. Through the decomposition analysis according to components of the near-field method, the increased resistance due to the parametric roll in a regular wave is investigated. Also, the correlation between the parametric roll motion and the added resistance is derived based on the decoupling phenomena between the components of vertical motions (heave and pitch motions) and roll motion, and the limitations of the relationship are also confirmed by considering the weakly nonlinear coupling in large-amplitude ship motions. Ultimately, a simple prediction method for the added resistance in irregular parametric roll is suggested based on the correlation, and its accuracy and efficiency are discussed in comparison with the result of the direct time-domain simulations.

2. Mathematical background

2.1. Boundary value problem: Rankine panel method

Ship motions can be defined in a mean-body fixed coordinate considering a ship's advancement with a forward speed, U in waves as shown in Fig. 1. Here, A, ω, and β are the wave amplitude, frequency, and heading angle, respectively. In addition, the problem domains, S_B and S_F, denote the body surface and the free surface, respectively. When a ship is assumed to be a rigid body, it has six degrees of freedom (DOF) with the translation, $\vec{\xi}_T = (\xi_1, \xi_2, \xi_3)$, and the rotation, $\vec{\xi}_R = (\xi_4, \xi_5, \xi_6)$; the linear displacement induced by waves can be written as follows:

$$\vec{\delta}(\vec{x}, t) = \vec{\xi}_T(t) + \vec{\xi}_R(t) \times \vec{x}. \quad (1)$$

The linear potential theory is applied to the ship motions analysis. Under the assumption of an incompressible and inviscid fluid with irrotational motion, the velocity potential, ϕ satisfies the following boundary value problem:

$$\nabla^2\phi = 0 \quad \text{in fluid domain} \quad (2)$$

$$\frac{\partial\phi}{\partial n} = \vec{U}\cdot\vec{n} + \frac{\partial\vec{\delta}}{\partial t}\cdot\vec{n} \quad \text{on } S_B \quad (3)$$

$$\left[\frac{d}{dt} + \nabla\phi\cdot\nabla\right][z - \zeta(x, y, t)] = 0 \quad \text{on } z = \zeta(x, y, t) \quad (4)$$

$$\frac{d\phi}{dt} = -g\zeta - \frac{1}{2}\nabla\phi\cdot\nabla\phi \quad \text{on } z = \zeta(x, y, t) \quad (5)$$

where $d/dt = \partial/\partial t - \vec{U}\cdot\nabla$ and $\vec{U} = (U, 0, 0)$. In addition, ζ and g indicate the wave elevation and the gravitational acceleration, respectively. In this study, the total velocity potential and the wave elevation are decomposed as follows:

$$\phi(\vec{x}, t) = \Phi(\vec{x}) + \phi_I(\vec{x}, t) + \phi_d(\vec{x}, t) \quad (6)$$

$$\zeta(\vec{x}, t) = \zeta_I(\vec{x}, t) + \zeta_d(\vec{x}, t) \quad (7)$$

where Φ is the basis potential which has the order of $O(1)$. ϕ_I and ζ_I are the velocity potential and elevation of incident wave, respectively. Similarly, ϕ_d and ζ_d are those of disturbed wave, respectively. The orders of incident and disturbed components are $O(\varepsilon)$. By substitutions of Eqs. (6) and (7) into Eqs. (3)–(5), the linearized boundary conditions can be derived according to the double-body (DB) linearization, such that:

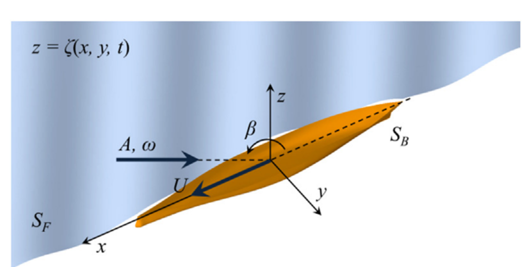

Fig. 1. Coordinate system and notations in Rankine panel method.