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Effect of internal sloshing on added resistance of ship*

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Abstract: The motion responses of ships carrying liquid cargo are affected not only by external wave excitation, but also by internal sloshing-induced forces and moments. Sloshing flow is coupled with the ship motion. This means the added resistance in waves may change when sloshing occurs inside the tank of the ship. In this study, the motion responses and added resistance of a ship, coupled with the sloshing-induced internal forces and moments are considered by using the linear potential theory. The three-dimensional Rankine panel method, in which the physical quantities are represented by using B-spline basis function, is applied. The sloshing flow of inner tanks is also simulated by using the Rankine panel method and linearized boundary value problem. To study the added resistance, a near-field method, which integrates the second-order pressure on a body surface, is applied. The model ship is a blunt modified Wigley model with two inner tanks. Numerical results obtained without inner tanks are compared with the experimental data, and then the effect of filling ratio of inner tanks on ship motion and added resistance are observed. The components that induce added resistance are examined, and the effects of surge motion on sloshing flow and added resistance are briefly considered. This study shows that the sloshing flow inside the inner tanks may significantly influence not only the motion responses, but also added resistance, especially, when the incident wave frequency approaches the resonance frequency of the sloshing flow.

Key words: Added resistance, sloshing, seakeeping, coupled effect, Rankine panel method

Introduction

The motion of liquid cargo vessels such as liquefied natural gas (LNG) carriers is affected by internal sloshing-induced forces and moments. conversely, the sloshing flow in inner tanks is excited by the vessel motion. In other words, sloshing motions inside tanks interact with vessel motion and these are closely coupled with each other. This coupling is important for two aspects of marine engineering: prediction of sloshing-induced loads on tank surfaces and effects on ship motion dynamics. The former plays an important role in the design for safe cargo containment system of LNG carriers and offshore structures dealing with liquid cargo. Violent sloshing flow in cargo holds can generate impulsive pressure that acts on the internal structure resulting in damage; therefore, LNG cargo containment systems should be designed to endure sloshing-induced impact loads. The latter aspect is related mainly to ship stability and reduction in roll motion. The anti-rolling tank is the representative example of devices for dealing with such engineering problems.

Studies on sloshing-induced impact loads were conducted extensively in the 1970s and 1980s. Recently, the demand for the analysis of sloshing-induced impact load has been increaseding because of the use of numerous types of liquid cargo vessels, such as LNG carriers, large oil tankers, floating production, storage, and off-loading (FPSO), and floating storage and regasification units (FSRU). In the 1960s, a few studies were carried out on effects of coupling between sloshing flow and ship motions, and these mainly focused on anti-rolling tanks. These studies included investigations based on experiments and simplified analysis methods. In recent years, numerical computations for the coupling analyses were introduced by some researchers. Kim[1] obtained computational results for fully coupled ship motion and sloshing flow for an anti-rolling problem. Rognebakke and Faltinsen[2] investigated experimentally and numerically the cou-

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pling effects for two-dimensional hull sections containing tanks filled with different levels of water excited in sway by regular waves. Malenica et al.[3] proposed a thorough methodology for the dynamic coupling between liquid motions in tanks and rigid body motions of ships in the frequency domain. Newman[4] presented the computation results for coupling motions of sloshing and vessel motions by means of a linear analysis. Changes in sway drift force with water density were also examined in the study. Nam et al.[5] conducted a series of experiments for LNG-FPSO with two tanks in regular waves. In addition, they presented the computation results obtained by coupling a nonlinear sloshing solver based on computational fluid dynamics (CFD) and a linear impulse-response-function method for ship motion. Kawabe et al.[6] investigated the sloshing effects on ship motion and wave drift force by using a frequency domain potential-based panel method. Kim et al.[7] presented the numerical results of the coupling effect between sloshing flow and ship motion by using a potential-based computer program WISH (Wave Induced Ship motion program), which was developed in Seoul National University. They developed a prescreening tool for predicting the coupling effect by adopting a linear sloshing analysis method. Systematic experimental studies were conducted by Seakeeping of structures Affected by Liquid motions in Tanks (SALT) JIP organized by MARIN. Other studies on coupling analyses include those conducted by Kim[1], Lee et al.[8], Kim and Shin[9], Cho[10].

Added resistance has been widely studied during the 1970s and 1980s. In recent years, this problem has once again received great attention because of regulations related to the measurement of energy efficiency levels, such as energy efficiency design index (EEDI), which are intended to restrict greenhouse gas emission from ships. Many attempts have been made to predict the added resistance of ships experimentally. Through experiments on the added resistance of a cargo ships, Gerritsma and Beukelman[11] showed that added resistance varies linearly as the square of wave height and the influence of surge motion on added resistance may be negligible. Storm-Tejsen et al.[12] measured the added resistance of a destroyer, a high-speed displacement hull, and five Series 60 parent hulls. The added resistance corresponding to an irregular wave was also calculated by using results of a regular wave test and wave spectrum. The added resistances of a S175 containership were measured by Fujii and Takahashi[13] and Nakamura and Naito[14]. In addition, the added resistances of Wigley hull forms were measured by Journee[15]. Recently, Guo and Steen[16] investigated the added resistance of KVLCC2 model, focusing on short wave range. Sadat-Hosseini et al.[17] predicted the added resistance of KVLCC2 experimentally and through CFD-based numerical simulation. Kuroda et al.[18], Lee et al.[19], and Park et al.[20] examined the effects of bow shape on added resistance. Kuroda et al.[18] conducted an experiment using container ships with various bow shapes, while Lee et al.[19] and Park et al.[20] used KVLCC2 with different bow shapes. Park et al.[21] investigated the uncertainty in the experiment on added resistance of ships.

Two major numerical approaches based on potential theory have been used to analyze the added resistance problem: far-field and near-field methods. The far-field method, which is based on the momentum conservation theory, was introduced by Maruo[22]. It was further elaborated by Newman[23], Gerritsma and Beukelman[11], and Salvesen[24]. Recently, Kashiwagi et al.[25] adopted Maruo's approach to calculate added resistance by applying the enhanced unified theory, and they introduced a practical factor that complements the calculation of added resistance at short wave-lengths. In the near-field method, added resistance is calculated by integrating the second-order pressure on a body surface. Faltinsen et al.[26] used the near-field approach and obtained good validation results. They also introduced a simplified asymptotic method to overcome the limitation of this approach to short waves. Ye and Hsiung[27] applied the Green function of waves to the added resistance problem. These efforts were mostly based on frequency-domain approaches. Although previous studies on the added resistance problem have achieved some major successes, very few studies were based on the Rankine panel method, which has been widely applied today to both linear and nonlinear ship motion problems. Bunnik[28] predicted the added resistance of ships by using the Rankine panel method. Three kinds of linearization methods were adopted for the boundary condition (uniform flow, double-body flow, and non-linear flow) and the effects of linearization methods on ship motion and added resistance were examined. Joncquez[29] analyzed the added resistance problem by using a time-domain Rankine panel method, applying both far- and near-field methods. Kim and Kim[30] and Kim et al.[31] also applied the higher-order Rankine panel method to the added resistance problem by using the far- and near-field methods. The analysis of added resistance in irregular waves was carried out, and the proper criteria of time window and number of wave frequencies were suggested for irregular waves. In recent years, owing to the rapid development of computer power, CFD has been applied to solve seakeeping and added resistance problems too[32-35].

The present study is based on the research of Kim et al.[7] which has validation results for coupling effect of ship and inner tank. The motion responses and added resistance of a ship in regular waves coupled with sloshing-induced internal forces and moments were investigated. To this end, the three-dimensional Rankine panel method in which the physical