Available online at www.sciencedirect.com
SCIENCE DIRECT®
Computers & Fluids 35 (2006) 501–524
computers & fluids
www.elsevier.com/locate/compfluid

Unsteady RANS method for ship motions with application to roll for a surface combatant

Robert V. Wilson *, Pablo M. Carrica, Fred Stern

IIHR—Hydroscience and Engineering, The University of Iowa, 100 C. Maxwell Stanley Hydraulics Laboratory, Iowa City, IA 52242-1585, United States

Received 24 February 2004; received in revised form 24 April 2004; accepted 26 December 2004
Available online 14 July 2005

Abstract

An unsteady Reynolds-averaged Navier–Stokes method is developed to compute motions and the resulting flow and wave fields around surface ships. Although the formulation and RANS code are generalized for six-degree-of-freedom motions, the method is demonstrated here for the viscous phenomenon of roll decay motion for a surface combatant. The method is based on an extension of CFDSHIP-IOWA (a general-purpose code for computational ship hydrodynamics) to predict ship motions with larger amplitude and non-slender geometry, in comparison to traditional linearized methods. The flow solver uses higher-order upwind discretization, PISO method for pressure–velocity coupling, a blended k–ω/k–ε two-equation turbulence model, free surface tracking approach, and structured multi-block grid systems. As an initial step, unsteady simulations of a modern surface combatant with predicted roll decay and prescribed sinusoidal roll motion are performed. Roll decay motion is simulated by releasing the model from an initial roll angular displacement and by computing the resulting roll motion. Verification of the time history of the roll motion is performed using iteration, grid, and time step studies and numerical uncertainties are shown to be less than 1%. Validation is performed by comparison with available experimental data with the predictions validated at 1.7% and 1.5% for the uncorrected and corrected solutions, respectively. For simulations with prescribed motions, the periodic response of the boundary layer to the rolling motion is described and quantified using a Fourier analysis. A spring–mass-damper system is used to compare the current non-linear predictions to traditional linear strip theory results. The method is shown to accurately predict the natural rolling frequency and roll decay rate at multiple ship speeds both without and with bilge keels, which demonstrates the ability to assess seakeeping characteristics for practical geometries.

Keywords: RANS method; Seakeeping; Roll motion; Free surface; Unsteady flow; Viscous

1. Introduction

Recent progress in Reynolds-averaged Navier–Stokes (RANS) CFD code development and application is making simulation based design an imminent reality. Development of such a tool will allow the merging of traditionally separate naval architecture sub-disciplines for resistance and propulsion, maneuvering, and seakeeping, and when combined with CFD-based optimization, will likely revolutionize the ship design process.

Of the three sub-discipline areas, application of RANS methods to resistance and propulsion is the most advanced with nearly two decades of experience. Existing approaches are able to predict ship resistance with reasonable accuracy as shown from results for three steady flow test cases at the recent Gothenburg 2000 Workshop on CFD in Ship Hydrodynamics [1]. Methods have recently been applied to optimize hull forms

* Corresponding author. Tel.: +1 319 384 0648; fax: +1 319 335 5238.
E-mail address: robert-wilson@uiowa.edu (R.V. Wilson).

0045-7930/$ - see front matter
doi:10.1016/j.compfluid.2004.12.005

for a variety of objective functions for ships with steady forward speed in calm seas [2].

In comparison, application of RANS methods to maneuvering and seakeeping is less mature due to obstacles from unsteady flows, ship motions, complex environment (e.g., incident waves, wave breaking, bubbly flow) and increased required computer resources. Also, methods developed for resistance and propulsion may not be easily extended into these areas. Application of RANS methods for steady maneuvers (e.g., off-design yaw, steady turn) can be found in [3–7]. However, application of viscous methods to more complex unsteady maneuvers is rare and most investigations rely on motion simulation programs with empirically derived coefficients.

Typical seakeeping solution techniques are based on assumptions of small amplitude motions and potential flow so that the general 6DOF non-linear equations of motions are reduced to two separate sets of linear equations (i.e., vertical plane motions become uncoupled from horizontal plane motions) and are solved in the frequency domain. Within those assumptions, predictions show good agreement for vertical plane motions. For horizontal plane motions, seakeeping codes based on potential flow methods model viscous effects by incorporating empirically derived roll damping data. For example, [8] used a linear frequency-dependent hydrodynamics model augmented by empirically derived linear and non-linear roll damping data from [9] and non-linear roll and heave/pitch restoring forces. Predictions with these methods are limited to the range of geometry, frequency, and operating parameters from the empirical data and suffer from scale effects. Simulations in the time-domain have been performed to predict larger non-linear roll motions, but most suffer from use of potential flow methods with empirical damping data, e.g., [10]. Thus, there is a critical need for development of numerical methods for viscous flows and prediction of larger amplitude motions for surface ships with appendages.

In an effort to develop a physics-based approach to seakeeping problems, RANS methods have recently been applied to the prediction of ship motions, although most studies have focused on 2D oscillating bodies. These methods have the potential to produce superior results since effects due to viscosity, creation of vorticity in the boundary layer, vortex shedding, and turbulence are naturally included. RANS methods have been used to study the flow around 2D oscillating cylinders, e.g., [11–13]. Accurate prediction of forces and moments on a 3D submerged cylinder fitted with bilge keels and with prescribed roll motion was demonstrated in [14]. Prediction of pitch and heave motions for ships in regular head waves was demonstrated for the Wigley hull and Series 60 cargo ships using density function free surface modeling [15]; a container ship using overlapping structured grids and density function free surface modeling [16]; and a container ship using level-set free surface modeling [7]. Simulations of free roll decay motion of a barge in calm sea and incident waves were performed using a Chimera RANS method in [17].

Development of unsteady RANS methods within the ship hydrodynamics group at IIHR—Hydroscience and Engineering Lab (IIHR) enables extensions from previous work for resistance and propulsion to applications for seakeeping and maneuvering. A step-by-step approach was followed towards this goal by initially performing unsteady RANS simulations for the forward speed diffraction (ship advancing in waves but constrained from motions) and radiation (prescribed ship motions in calm water) problems. In the former case, simulations were performed for the Wigley hull for a wide range of conditions [18] and for the surface combatant, David Taylor Model Basin (DTMB) model 5512 (5512), for medium speed/long wave and high speed/short wave conditions [19] including comparisons with IIHR towing tank data [20,21]. In the latter case, simulations were performed for a double body 5512 model with prescribed vertical (pitch and heave) and horizontal (roll) plane motions as part of a DoD challenge project on 6DOF motions and maneuvering for surface ships [22]. Pitch and heave motions for the Wigley hull in incident waves were predicted and the RANS results were compared to those from strip theory [23].

As an initial step towards prediction of general ship motions, simulations are performed for a barehull and bilge keel appended surface combatant model (subsequently referred to as 5512) for predicted and prescribed roll motions. Simulations with free roll decay are used to predict roll damping and resonant frequencies for the surface combatant and to verify and validate the simulations. Simulations with prescribed motions are used to quantify the unsteady response of the flow and free surface fields to roll motion using a Fourier analysis. Simulations are performed using the RANS CFD code, CFDSHIP-IOWA, which was shown to be one of the better codes at the recent Gothenburg 2000 Workshop on CFD in Ship Hydrodynamics for the surface combatant test case [24].

The contributions of the present work are in (i) extending the previous work to unsteady RANS simulations of general 6DOF ship motions and maneuvering (with focus on applications for predicted and prescribed roll motions), (ii) performing verification and validation to quantify numerical and modeling errors, (iii) explaining the unsteady response of the boundary layer, axial vortices, and free surface to roll motion, (iv) predicting roll decay motion and analyzing seakeeping properties of the ship model using a spring–mass-damper model, and (v) guiding experimental measurements currently underway at the IIHR and filling-in the sparse experimental dataset.