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Model test and simulation of a ship with wavefoils

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ABSTRACT

The paper describes model tests of a tanker with two fixed bow-mounted foils (wavefoils), for resistance and motion reduction in waves. Measured ship resistance, wavefoil thrust and ship motions were compared with time-domain simulations. The wavefoil forces were calculated using a slightly modified Leishman–Beddoes dynamic stall model, with a two-way coupling to the ship motions. In typical sea states in head seas, employing the wavefoils reduced ship resistance by 9–17%, according to scaled model test resistance. Heave and pitch were reduced by −11% to 32% and 11% to 25%, respectively. The foils affect the flow around the hull. This should be considered when selecting the wavefoil location in the design process.

1. Introduction

To achieve stabilization of the global temperature at two degrees above pre-industrial levels, global anthropogenic greenhouse gas emissions must be reduced by 40–70% by 2050, compared to 2010 [1]. If all sectors accept the same percentage reductions and global maritime trade doubles from 2010 to 2050, which is in accordance with conservative predictions [2], greenhouse gas emissions from shipping per tonne nautical mile must be reduced by 70–85% by 2050, compared to 2010. Faced with this substantial challenge, harnessing the non-polluting and free resource of wind and waves for ship propulsion seems unavoidable.

Using waves to propel a boat was, to the authors' knowledge, first proposed in 1858 [3] and first successfully done in practice in the 1890s [4]. The simplest and most common method of wave propulsion is outfitting the ship with foils, so-called wavefoils, that convert the vertical motion in waves into propulsive thrust. In addition to producing thrust, the foils generally dampen the ship motions, causing reduced added resistance in waves. Jakobsen [5] introduced a foil with spring-loaded pitch to avoid stall. Active pitch control has also been proposed [6,7] and tested in practice [8,9]. In the present work, however, the foil pitch was fixed at zero to validate the simulation model for the simplest wavefoil possible. A more detailed summary of previous work on partly and fully wave-powered boats, both experimental and theoretical, is given by Bøckmann [9].

In theory, the motions and resistance in waves of a ship with foils as appendages can be found by using a Navier–Stokes solver, but this is still computationally very expensive. A faster approach is to model the ship with foils in a panel code. Panel codes neglect viscous effects, which is not applicable when flow separation is likely to occur on the foils. A simple and common approach is to obtain the hydrodynamic force coefficients for the bare hull using a computer program based on 3D panels with a distribution of potential flow singularities [10] or strip theory [11], add the separately calculated foil forces, and solve the equations of motions (see e.g. [6,7]).

The equations of motions can be solved both in the time domain and in the frequency domain. When adding foil forces to the equations of motion and solving these equations in the frequency domain, one must assume that the foil forces oscillate with the frequency of encounter and are linearly proportional to the wave amplitude. This implies that one must neglect drag and stall and assume that the foil lift acts vertically relative to the ship in its calm-water position, which rules out studying cases where the foil has a large angle of attack. In time-domain simulations there is no inherent limit to the angle of attack since the foil forces can vary arbitrarily with time.

Solving the equations of motions in the time domain requires the calculation of retardation functions which account for memory-effects – i.e., the ship motions at a given time depend on the ship motion at previous time steps. Calculating these retardation functions from frequency-domain coefficients is not numerically straight forward although the expression is simple (see Eq. (13)). The ship seakeeping and manoeuvring simulator VeSim [12],

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developed by MARINTEK and previously used by the first author to study a ship with wavefoils [9], is an example of a computer program where the equations of motion are solved in the time domain. Before the ship motions are found by stepping the solution forward in time in VeSim, retardation functions are calculated from frequency-domain hydrodynamic coefficients obtained from the strip-theory program VERES [13].

In the present paper, VeSim was used to simulate a ship with wavefoils, and simulation results are compared with model test results. A slightly modified version of the Leishman–Beddoes dynamic stall model [14] was used to calculate the foil forces with a two-way coupling between the ship motions and foil forces.

2. Ship and wavefoils

Experiments were conducted with a 1:16.57 scale model of an 8000 DWT tanker known as R&D 8000, designed by Rolls-Royce Marine. This ship was model-tested at the MARINTEK towing tank in Trondheim, Norway, in 2010 with three different foreships and three different aftships. In the experiments and simulations described in this paper, the foreship (MARINTEK model M2946A) had a bulbous bow, vertical stem with very little flare (see Fig. 1), and the aftship (MARINTEK model 2944A) had a twin skeg design with Rolls-Royce Promas rudders and a dummy propeller boss (see Fig. 5). The main particulars of the ship and wavefoils in full and model scales are given in Tables 1 and 2, respectively.

The wavefoils were mounted to the ship with a fixed roll angle of 10° (see Fig. 2) and a fixed pitch angle of 0°. The horizontal distance from the fore perpendicular to the trailing edges of the foils was 16.926 m in full scale.

Fig. 1. Side view of the bow with port wavefoil shown.

Table 1
Main particulars of the Rolls-Royce R&D 8000 tanker in full and model (1:16.57) scales.

Main particulars	Full scale	Model scale
Waterline length (L_{WL})	117.297 m	7.079 m
Length between perpendiculars (L_{PP})	113.200 m	6.832 m
Breadth at waterline	19.000 m	1.147 m
Draft	7.200 m	0.435 m
Wetted surface area	3387.816 m^2	12.339 m^2
Displaced volume	11,616.770 m^3	2.553 m^3

Table 2
Main particulars of the wavefoils in full and model (1:16.57) scales.

Main particulars	Full scale	Model scale
Profile	NACA 0015	NACA 0015
Span (tip to root)	10.8 m	0.652 m
Inner chord	3.2 m	0.193 m
Outer chord	2.2 m	0.133 m
Foil area	29.2 m^2	0.106 m^2
Planform	Tapered	Tapered

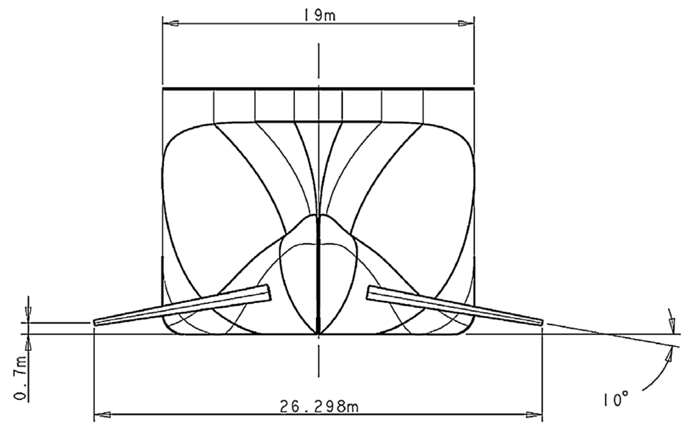

Fig. 2. Front view of the ship. Illustration courtesy of Rolls-Royce plc.

3. Model test

3.1. Test set-up

The present combination of fore- and aftship was tested in the seakeeping carriage of the MARINTEK towing tank in March 2015. The ship model was towed from wires attached to an aluminium beam mounted perpendicular to the ship, allowing the ship to move freely in heave and pitch (see Fig. 3). A spring system allowed the ship to move relatively freely in surge. The towing force was measured at both port and starboard side of the towing boom and summed to yield the total towing force. The ship motions were measured by an optical motion capture system from Qualisys.

The wavefoils went through foil-shaped openings in the hull, just larger than the foils, and were then mounted to a vertical circular beam. This circular beam went through a circular pipe, creating a circular partially filled moonpool in the hull. Atop the beam carrying the wavefoils were mounted three vertical force transducers (one in front of the other two), and a horizontal force transducer

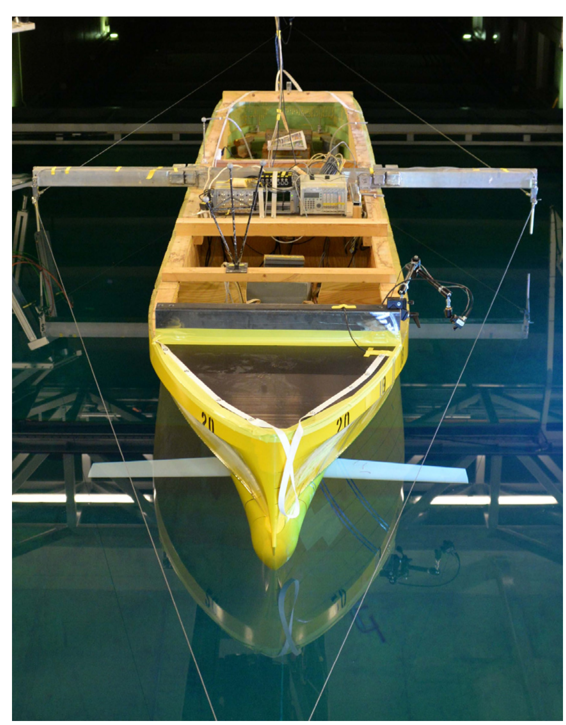

Fig. 3. Model test set-up.