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*Publication date:*  
2013

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*Citation (APA):*  
Bingham, H. B., & Amini Afshar, M. (2013). A note on added resistance for slow ships.

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# A note on added resistance for slow ships \*

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## Introduction

Rising fuel costs and increased environmental regulation of emissions, combined with a current over-capacity in the global shipping fleet, have provided a strong incentive for a dramatic reduction in the operating speed of cargo ships. In particular, many ships are routinely sailing at 10 knots and under these days, which translates to an engine load of as little as 10 to 20% of the design operating load. This trend towards slow and ultra-slow steaming is expected to continue, and thus lead to new ship designs with smaller engines and possibly auxiliary wind-propulsion systems. One consequence of slower design speeds and a reduction in installed engine power is an increased concern about the ship's ability to maintain maneuverability and escape a lee shore under heavy weather conditions. While the calm water resistance of a ship tends to increase at a rate proportional to ship speed raised to a high power (typically somewhere from 4 to 6), the added resistance due to waves generally increases only linearly with increasing ship speed. Thus the lower the design speed the more important an accurate prediction of the added-resistance becomes.

This abstract reviews the existing methods for predicting the added resistance of a sailing ship, and highlights the large uncertainties involved in both calculating and measuring this sensitive quantity. This serves to motivate a recently begun PhD project with the goal of an improved added resistance tool based on the high-order finite difference approach described by [9, 10], and references therein.

## Methods for Computing Added Resistance

We adopt a Cartesian coordinate system  $x_i = [x_1, x_2, x_3]$  with origin on the still water level and the  $x_3$  axis vertically upwards. When a ship sails along the  $x_1$  axis at a given speed  $U$  through calm water it experiences a constant force

$$F_1 = -R \quad (1)$$

where  $R$  is the calm water resistance. If the ship now sails through a seaway, it will experience an unsteady force in the  $x_1$ -direction  $F_1(t)$ . The mean value of this unsteady force over some time-period  $T$  is

$$\overline{F_1} = \frac{1}{T} \int_0^T F_1(t) dt = -(R + R_w + R_a) \quad (2)$$

where  $R_w$  is the added resistance due to waves and  $R_a$  is the added resistance due to wind which is typically at least an order of magnitude smaller than  $R_w$ .

There are basically three methods for predicting  $F_1$ :

### 1. Near-Field Pressure integration:

$$F_1 = \int_{S_b} p n_1 dS \quad (3)$$

where  $p$  is the fluid pressure and  $n_1$  is the  $x_1$ -component of the unit normal vector to the body surface  $S_b$ .

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\*The authors wish to thank the EU 7th Framework Programme (grant # 266030, ULYSSES) for funding, and the Danish Center for Scientific Computing for supercomputing resources.

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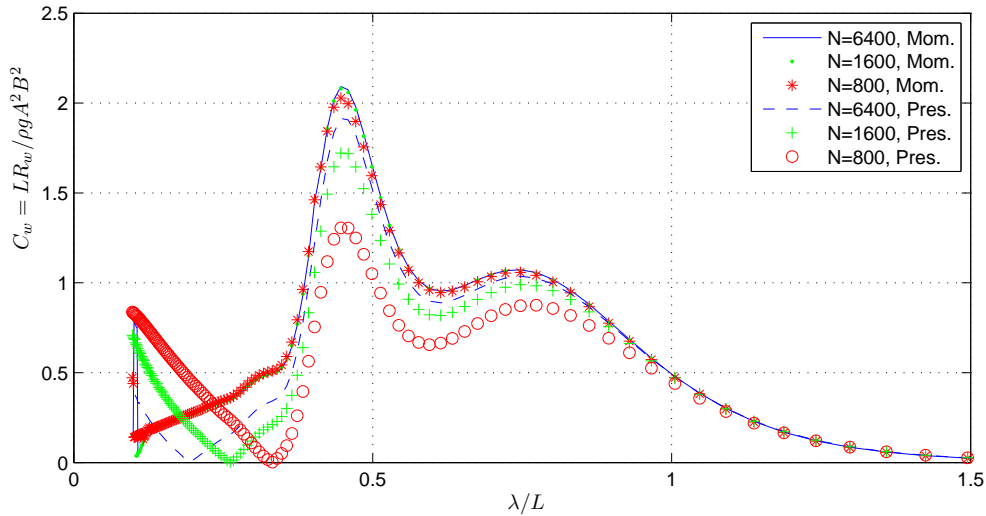


Figure 1: Convergence for calculations of the added resistance of a Wigley hull at zero forward speed using WAMIT and both near-field pressure integration and far-field momentum conservation.

## 2. Momentum Conservation:

$$F_1 = \int_{S_c} (p n_1 + \rho u_1 n_i u_i) dS \quad (4)$$

where  $u_i$  is the fluid velocity vector and  $S_c$  is a control surface away from the body. Here the summation convention applies to repeated indices.

3. **Energy Conservation:** The work done by the ship on the undisturbed waves (per wave period) equals the average energy flux removed from the wave propagation direction and sent in other directions.

$$F_1 [c + U \cos(\beta)] = \text{Ave. energy flux sent sideways.} \quad (5)$$

where  $c$  is the wave phase speed and  $\beta$  the wave heading angle measured from the  $x_1$ -axis.

Many particular forms for these relations have been derived over the years depending on the approximations and assumptions made, and on the numerical methods applied. Common to all forms however, is the assumption that higher-order potentials do not contribute to the mean force which can therefore be computed from the first-order solution alone. Most existing solutions are based either on the strip theory of Salvesen, Tuck & Faltinsen [12] or on 3D Boundary Element Methods (BEMs).

At zero forward speed, the added resistance (or drift force) can be robustly computed using 3D panel methods and either near-field pressure integration or far-field momentum conservation. However, much finer resolutions are required to show convergence for drift forces than are necessary for strictly linear quantities, at least when using near-field pressure integration methods. An example is shown in Figure 1 which shows the convergence of the drift force on a Wigley hull computed using the 3D BEM code WAMIT [8] and both near-field pressure integration and far-field momentum conservation. Here quantities have been non-dimensionalized using the fluid density  $\rho$ , the gravitational acceleration constant  $g$ , the ship length  $L$  and beam  $B$ , and the incident wave length  $\lambda$  and amplitude  $A$ . These results have been computed using the low-order (constant-strength flat panel) version of the code and  $N$  indicates the total number of panels on the hull. From this plot it is clear that the two methods are converging towards the same result

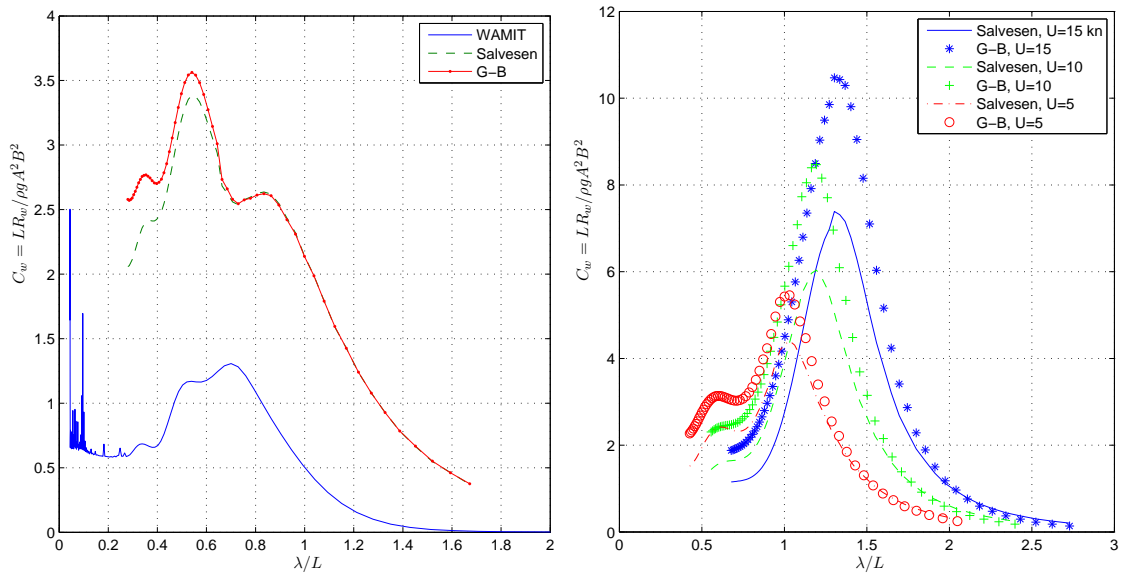


Figure 2: Added resistance calculations for a tanker hull at various forward speeds using strip theory methods.

for all relative wave lengths, but the momentum conservation method does so much faster than the pressure integration method.

At non-zero forward speed the situation is less satisfying. Two methods are widely applied to strip theory calculations: Salvesen’s method based on near-field pressure integration [11]; and the energy conservation method first suggested by Gerritsma & Beukelmann [4]. Figure 2 shows an example of some converged strip theory calculations for a modern tanker hull at  $U = 0, 5, 10$  and 15 knots calculated using these two methods. WAMIT results for  $U = 0$  are also shown for reference. Clearly both methods fail completely when  $U = 0$ , which is not surprising since the main assumptions of strip theory are violated in this case. At non-zero forward speed, there is good agreement between the methods for where the peak response lies but the predicted magnitude of the force differs dramatically for all but the longest waves and can be almost a factor of two near the peak.

3D BEM methods are also available for computing added resistance at forward speed; based either on the time-domain free-surface Green function *e.g.* [6, 1] or on the Rankine Green function *e.g.* [7, 5]. These calculations show a reasonable agreement with experiments in the sense that uncertainties in the measurements can easily be a factor of two or more; but convergence of the calculations has so far not been demonstrated. Presumably the quadratic scaling of the solution effort with increasing resolution associated with BEM methods prevents a true demonstration of convergence for this sensitive quantity.

## A High-Order Finite Difference Method for Added Resistance

Building on ongoing work discussed in [9, 10, 3, 2] we are developing a high-order finite difference solver for the linear forward speed problem, using both Neumann-Kelvin and double-body linearizations, which will also give predictions of added resistance. Due to the combination of high-order numerical accuracy and a linear scaling of the solution effort with increasing resolution, we hope to be able to show convergence for both pressure integration and momentum conservation methods. At this point we have validated the double-body flow solution and are currently implementing the radiation and diffraction solutions. Figure 3 shows the convergence of the double-body  $m$ -terms on a translating hemisphere along with a snapshot of the double-body surface elevation. The slopes of these convergence curves are approximately 4, consistent with the

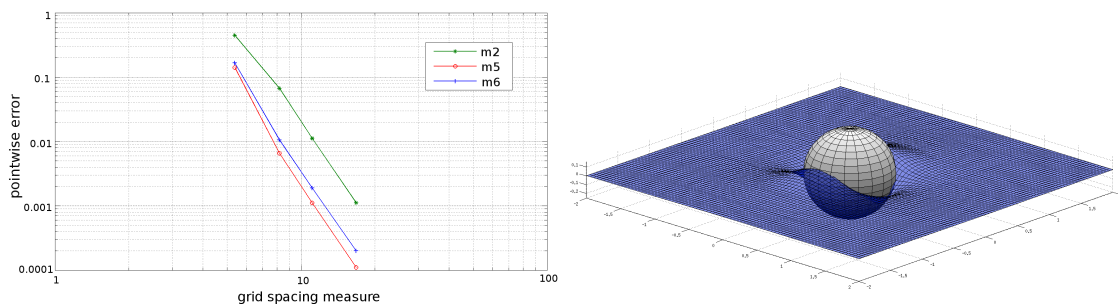


Figure 3: Convergence of the double-body  $m$ -terms on a sphere and a snapshot of the double-body free-surface elevation.

fourth-order finite-difference schemes used in this test case. Further results will be presented at the workshop.

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