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DISCREPANCIES IN HYDRODYNAMIC COEFFICIENTS OF WIGLEY HULL FORMS

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ABSTRACT

In the past a series of four Wigley models have been tested at the Delft University of Technology. The hydrodynamic coefficients and the wave loads and motions in regular head waves have been measured at a range of speeds and compared with theoretical data obtained by several computer codes.
The calculated potential mass and damping for heave fits quite well with the experimental data. But for pitch and for the coupling coefficients, sometimes very large discrepancies have been found, which affects the calculated motions significantly.
What aspects could be the reason for this difference?

INTRODUCTION

In 1992, numerous experimental data on vertical motions, wave loads and added resistance in head waves of four Wigley hull forms, with amidships section coefficients of 0.909 and 0.667 and length to breadth ratios of 10 and 5 were reported. The measuring program of the two Wigley’s with a block coefficient of 0.667 has been extended with surge wave forces and vertical relative motions at station 17 and with measurements of vertical motions at zero forward speed.

These model experiments were carried out at the Shiphydromechanics Laboratory of the Delft University of Technology on request of and co-operation with the Department of Naval Architecture and Marine Engineering of the University of Michigan and the Panel H-5 of the Hydrodynamics Committee of the Society of Naval Architects and Marine Engineers.

Also, comprehensive comparisons were given in [4] of all experimental data with computed data derived with the 6 degrees of freedom computer code SEAWAY [5] of the author, based on both the ordinary and the modified strip theory method. For the hydrodynamic coefficients, comparisons of experimental data with results of three-dimensional calculation methods were given too. Use had been made of two different radiation-diffraction panel computer codes for wave-body interactions, the WAMIT computer code of Newman [8] of the Massachusetts Institute of Technology and the DELFRAC computer code of Pinkster [9] of the Delft University of Technology.

All experimental data on these four Wigley hull forms were presented in tables and graphs [4]. For comparative studies, a zip-file (*ExperimentsWigley-180.zip*) has been made available in the public domain on the Internet. This zip-file contains data files with all experimental data in a sequence and notation as given in the tables. The data file names were based on the table number and the Froude number.

Initiated by Newman and Pinkster already in 1992, the author has carried out additional wave loads and vertical motions experiments in regular following waves with these four models. These experiments are presently analysed for being reported in the near future.
But, an old problem arises again when analysing these new data. In some cases, the predicted hydrodynamic coefficients, as reported in 1992, do not fit quite well with the experimental data.

This paper deals with the reliability of these old experimental data. Can they be trusted or not?
To judge this, the measured hydrodynamic coefficients and wave loads have been used to calculate the motions, which will be compared with the experimental motions.

For the equations of motion and the notations used in this paper, reference is given to [4].

MODELS AND EXPERIMENTS

The four Wigley models (C_m = 0.909 and 0.667, L/B = 5 and 10) have been tested at three forward speeds: Fn = 0.20, 0.30 and 0.40. The shape of these hull forms, each having a model length of 3 m, is given in Figure 1.

To describe the mathematical formulation of the hull forms, a right-handed co-ordinate system is defined by $O(x,h,z)$, with:

O	Origin, amidships in the water plane
x	Longitudinal axis, positive forwards
h	Lateral axis, positive to port side
z	Vertical axis, positive downward

In this co-ordinate system, the non-dimensional hull forms of the 4 Wigley models, with the origin O at half the ship length, amidships and in the still water surface, ($-0.5 \leq x \leq +0.5$, $-0.5 \leq h \leq +0.5$ and $0 \leq z \leq +1$), are defined by:

$$h = \left(1 - z^2\right) \cdot \left(1 - x^2\right) \cdot \left(1 + a_2 \cdot x^2 + a_4 \cdot x^4\right) + a \cdot z^2 \cdot \left(1 - z^8\right) \cdot \left(1 - x^2\right)^4$$

with $a_2 = 0.2$ and $a_4 = 0.0$ for all 4 models, $a = 1.0$ for models I and II with $C_m = 0.909$ and $a = 0.0$ for models III and IV with $C_m = 0.667$.

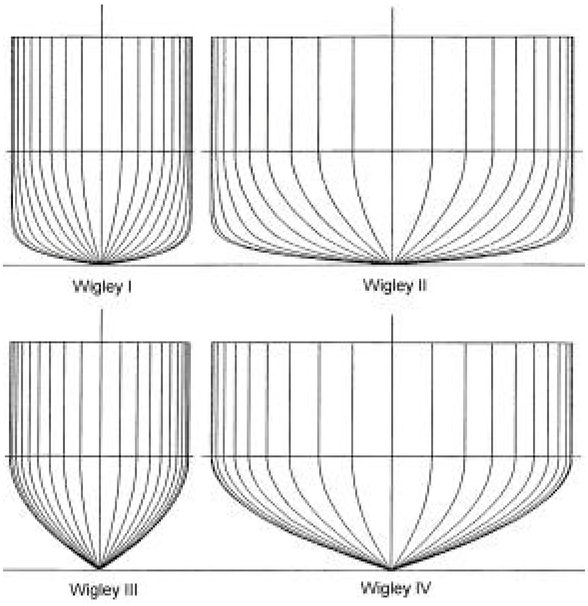

Figure 1 Hull Forms of Four Wigley Models

A multiplication of x, h and z with $L/2$, $B/2$ and d, respectively, provides the dimensional hull forms of the 4 Wigley models, as given in Figure 1 and Table 1.

Wigley Model No.:	I	II	III	IV
Amidships section coefficient, C_m (-)	0.9090	0.9090	0.6667	0.6667
Length to breadth ratio, L/B (-)	10	5	10	5
Length, L (m)	3.0000	3.0000	3.0000	3.0000
Breadth, B (m)	0.3000	0.6000	0.3000	0.6000
Draught, d (m)	0.1875	0.1875	0.1875	0.1875
Trim, t (m)	0.0000	0.0000	0.0000	0.0000
Volume of displacement, ∇ (m^3)	0.0946	0.1892	0.0780	0.1560
Center of rotation above base, KR (m)	0.1875	0.1875	0.1875	0.1875
Center of gravity above base, KG (m)	0.1700	0.1875	0.1700	0.1875
Radius of inertia for pitch, k_{yy} (m)	0.7500	0.7500	0.7500	0.7500

Table 1 Main Dimensions of 4 Wigley Models

Forced oscillation tests in still water were carried out as well as measurements of wave loads, motions and added resistance in regular head; see Figure 2. The amplitudes of oscillations and waves were varied to investigate the non-linear effects. Additional new tests in following waves have just been completed and the results are analysed presently.

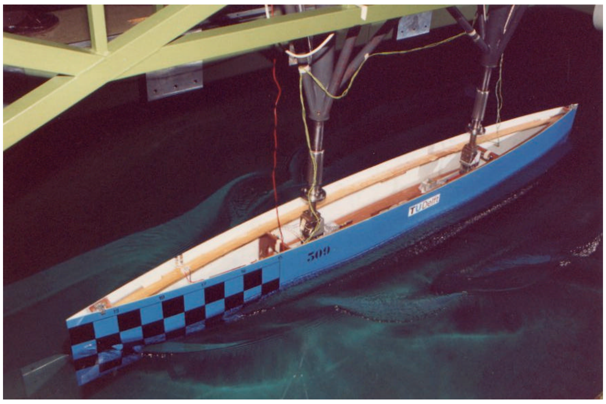

Figure 2 Wigley Model III in Regular Head Waves

The experimental data in head waves were compared with predicted data by several 2-D and 3-D computer programs. For the non-dimensional formats of these data, reference is given to [4].

The purpose of this paper however, is not to show an overall fair agreement between theory and experiment. Moreover, this paper focuses on those (sometimes important) cases where significant differences between theory and experiment were present.

STRIP THEORY

The ship is considered to be a rigid body floating in an ideal fluid: homogeneous, incompressible, free of surface tension, irrotational and without viscosity. It is assumed that the problem of the motions of this floating body in waves is linear or can be linearised. As a result of this, only the external loads on the underwater part of the ship are considered and the effect of the above water part is fully neglected.

The incorporation of seakeeping theories in ship design has been discussed clearly in the past by many authors. As an example: a very clear discussion was presented in 1990 by Faltinsen and Svensen [3] and an overview of seakeeping theories for ships was presented. It was concluded by them that - nevertheless some limitations - strip theories were the most successful and practical tools for the calculation of the wave induced motions of the ship, at least in an early design stage of a ship.

The strip theory solves the three-dimensional problem of the hydromechanical and exciting wave forces and moments on the ship by integrating the two-dimensional potential solutions over the ship's length. Interactions between the cross sections are ignored for the zero-speed case. So each cross section of the ship is considered to be part of an infinitely long cylinder.

The strip theory is a slender body theory, so one should expect less accurate predictions for ships with low length to breadth ratios. However, experiments showed that the strip theory generally appears to be remarkably effective for predicting the motions of ships with length to breadth ratios down to about 3.0, or even sometimes lower.

The strip theory is based on the potential flow theory. This holds that viscous effects are

neglected, which can deliver serious problems when predicting roll motions at resonance frequencies. In practice, for viscous roll damping effects can be accounted fairly by empirical formulas, as for instance given by Ikeda, Himeno and Tanaka in 1978.
Because of the way that the forced motion problems are solved in the strip theory, substantial disagreements can be found between the calculated results and the experimental data of the wave loads at low frequencies of encounter in following waves. As a practical solution, these "near zero frequency of encounter problems" can be solved by forcing the wave loads to go to zero artificially, as for instance given by the author in [7].

For high-speed vessels and for large ship motions, as appear in extreme sea states, the strip theory can deliver less accurate results. Then the so-called “end-terms” can be important too.
The strip theory accounts for the interaction with the forward speed in a very simple (but effective) way, as published in 1970 by Salvesen, Tuck and Faltinsen [10].
The effect of the steady wave system around the ship is neglected and the free surface conditions are simplified, so that the unsteady waves generated by the ship are propagating in directions perpendicular to the center plane of the ship. In reality, the wave systems around the ship are far more complex. For high-speed vessels, unsteady divergent wave systems become important. This effect is neglected in the strip theory.
The strip theory is based on linearity. This means that the ship motions are supposed to be small, relative to the cross sectional dimensions of the ship. Only hydrodynamic effects of the hull below the still water level are accounted for. So when parts of the ship go out of or into the water or when green water is shipped, inaccuracies can be expected. Also, the strip theory does not distinguish between alternative above water hull forms.

Because of the added resistance of a ship due to the waves is proportional to the relative motions squared, its inaccuracy will be gained strongly by inaccuracies in the predicted motions.

Nevertheless these limitations, seakeeping prediction methods based upon the strip theory provide a sufficiently good basis for optimization studies at an early design stage of the ship. At a more detailed design stage, it can be considered to carry out additional model experiments to investigate for instance added resistance or extreme event phenomena, such as shipping green water and slamming.

FORCED OSCILLATION TESTS

When carrying out forced heave oscillation tests, the equations of motion are presented by:

$$z = z_a \cos(wt)$$

$$(M_{33}^{*} + A_{33})\ddot{z} + B_{33}\dot{z} + C_{33}z = X_{o3a} \cos(wt + e_{X_{o3}z})$$

$$A_{53}\ddot{z} + B_{53}\dot{z} + C_{53}z = X_{o5a} \cos(wt + e_{X_{o5}z})$$

The hydrodynamic coefficients follow from the in phase and the out of phase parts of the measured exciting forces and moments during the heave oscillations:

$$A_{33} = -\frac{X_{o3a} \cos(e_{X_{o3}z})}{z_a w^2} + \frac{C_{33}}{w^2} - M_{33}^{*}$$

$$B_{33} = +\frac{X_{o3a} \sin(e_{X_{o3}z})}{z_a w}$$

$$C_{33} = +2rg \int_L y_w \, dx_b$$

$$A_{53} = -\frac{X_{o5a} \cos(e_{X_{o5}z})}{z_a w^2} + \frac{C_{53}}{w^2}$$

$$B_{53} = +\frac{X_{o5a} \sin(e_{X_{o5}z})}{z_a w}$$

$$C_{53} = -2rg \int_L y_w x_b \, dx_b$$

The solid mass M_{33}^{*} of the model has been measured separately. For these experiments it is not required that M_{33}^{*} is equal to $\rho\nabla$. Furthermore, it is obvious that $C_{53}=0$ for these Wigley models.

When carrying out forced pitch oscillation tests, the equations of motion are presented by:

$$\theta = \theta_a \cos(\omega t)$$

$$A_{35}\ddot{\theta} + B_{35}\dot{\theta} + C_{35}\theta = X_{o3a} \cos(\omega t + \varepsilon_{X_{o3}\theta})$$

$$(M_{55}^{*} + A_{55})\ddot{\theta} + B_{55}\dot{\theta} + C_{55}\theta = X_{o5a} \cos(\omega t + \varepsilon_{X_{o5}\theta})$$

The hydrodynamic coefficients follow from the in and out of phase terms of the measured exciting forces and moments:

$$A_{35} = -\frac{X_{o3a} \cos(\varepsilon_{X_{o3}\theta})}{\theta_a \omega^2} + \frac{C_{35}}{\omega^2}$$

$$B_{35} = +\frac{X_{o3a} \sin(\varepsilon_{X_{o3}\theta})}{\theta_a \omega}$$

$$C_{35} = -2\rho g \int_L y_w x_b \, dx_b$$

$$A_{55} = -\frac{X_{o5a} \cos(\varepsilon_{X_{o5}\theta})}{\theta_a \omega^2} + \frac{C_{55}}{\omega^2} - M_{55}^{*}$$

$$B_{55} = +\frac{X_{o5a} \sin(\varepsilon_{X_{o5}\theta})}{\theta_a \omega}$$

$$C_{55} = +2\rho g \int_L y_w x_b^2 \, dx_b$$

The solid mass moment of inertia M_{55}^{*} of the model has been measured separately ashore with special measuring equipment. For these experiments it is not required that M_{55}^{*} is equal to $k_{yy}^{2} \cdot \rho\nabla$. It is obvious that $C_{35}=0$ for these Wigley models.

HYDRODYNAMIC COEFFICIENTS

The measured and computed hydrodynamic coefficients are given in Figure 3 through Figure 6.

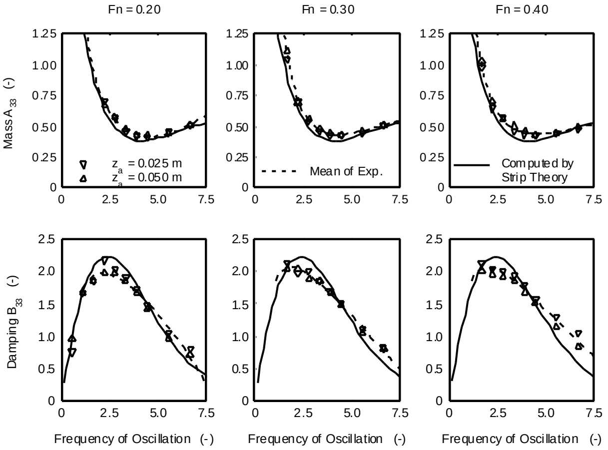

Figure 3 Heave Coefficients Wigley III

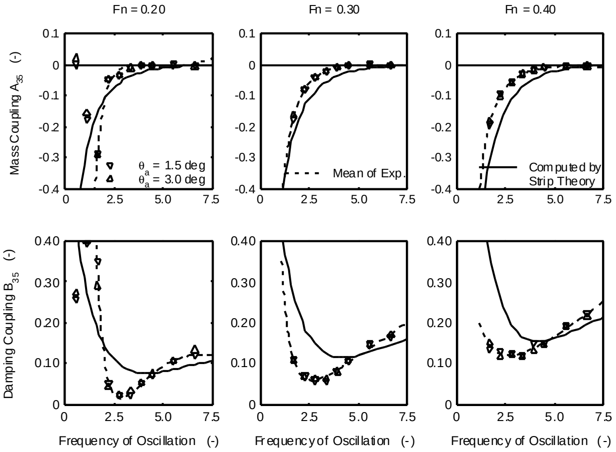

Figure 4 Heave Coupling Coefficients Wigley III

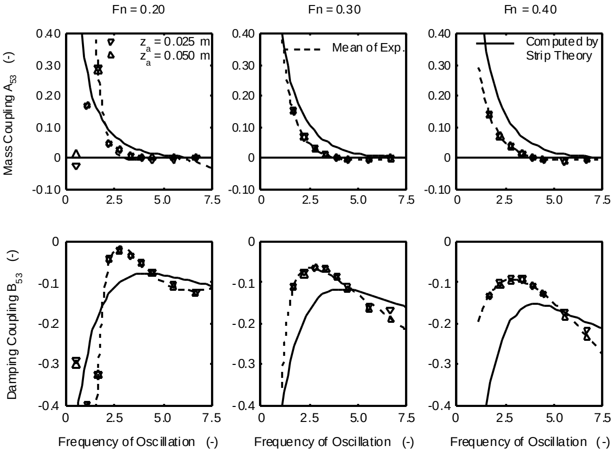

Figure 5 Pitch Coupling Coefficients Wigley III

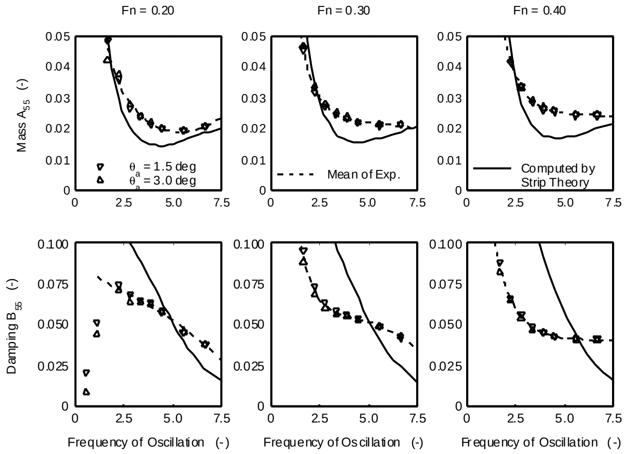

Figure 6 Pitch Coefficients Wigley III

The forced heave and pitch oscillations have been carried out with two amplitudes each: $z_a = 0.025\,\mathrm{m}$ and $z_a = 0.050\,\mathrm{m}$ for heave oscillations and $q_a = 1.5^0$ and $q_a = 3.0^0$ for pitch oscillations. In all cases a very linear behaviour of the measured coefficients has been found.

Then, per velocity, these measured data have been used to obtain polynomials of the mean experimental values.

Finally, the hydrodynamic coefficients have been computed by two separate 2-D potential theories: the theory of Ursell (1949) with 10-parameter close-fit conformal mapping of the cross sections to the unit circle and the direct pulsating source method of Frank (1967). Both methods are described in detail in [7]. For the very "smooth" cross sections of these Wigley models, both methods gave very much the same computed coefficients.
This verification of the potential source code holds that 2-D computing errors are very unlikely. The computed data are the true results of the used theories.

The heave coefficients A_{33} and B_{33} are predicted rather accurately.
But, considerable differences between theory and experiments were found for the pitch coefficients A_{55} and B_{55}.

Problems were encountered too in the prediction of the heave and pitch coupling coefficients A_{35}, B_{35}, A_{53} and B_{53}. The computed mass coupling coefficients were sometimes about double the experimental values. A significant different "behaviour" of experimental and computed curves has been found for the damping coupling coefficients.

The question arises now: "What is wrong: theory, experiment or even both?".
To answer this question, the computed as well as the measured hydrodynamic coefficients and the measured wave loads have been used in the next sections to compute the heave and pitch motions in regular head waves.
These computed motions will be compared with measured motions. Because the hydrodynamic coefficients, the wave loads and the resulting motions will be determined separately and independently, probably some conclusions could be drawn.

EXPERIMENTAL WAVE LOADS

The measured heave wave forces and pitch wave moments in regular head waves are given in Figure 7 and Figure 8.

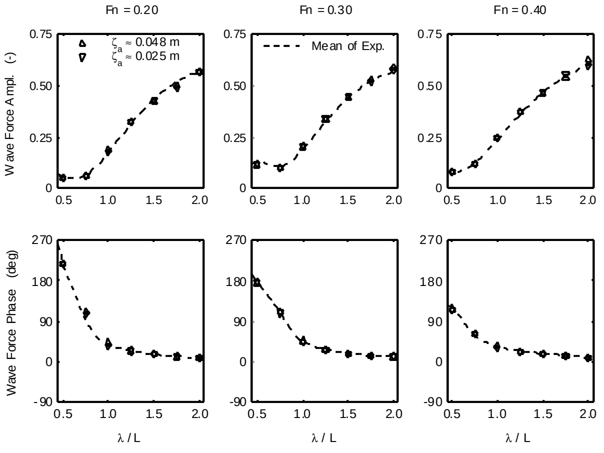

Figure 7 Measured Wave Forces Wigley III

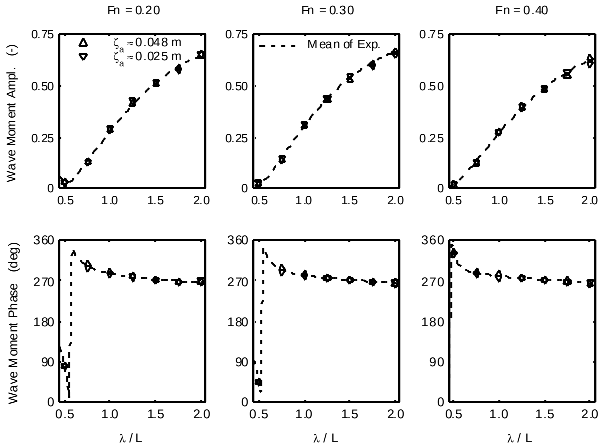

Figure 8 Measured Wave Moments Wigley III

The experiments have been carried out for two mean regular wave amplidues: $z_a \approx 0.025$ m and $z_a \approx 0.048$ m. The experiments show a very linear behaviour of the wave loads.

The in-phase and the out-of-phase components of these experimental data have been used to obtain per velocity polynomials for the mean experimental values, from which the amplitudes and phase lags could be obtained again.

Because this paper is focussed on the determination of the hydrodynamic coefficients, these wave load polynomials (so not the theoretical wave loads) have been used in the computations of the heave and pitch motions in the following section.

HEAVE AND PITCH MOTIONS

The measured and computed heave and pitch motions in regular head waves are given in Figure 9 and Figure 10.

The experiments have been carried out for two mean regular wave amplidues: $z_a \approx 0.011$ m and $z_a \approx 0.019$ m. The experiments show a very linear behaviour of the motions.

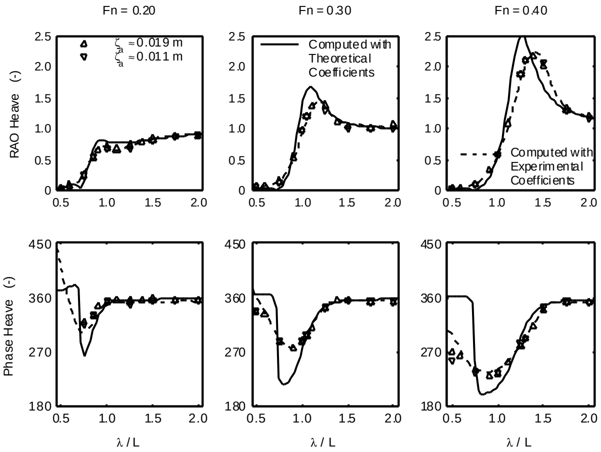

Figure 9 Heave Motions Wigley III

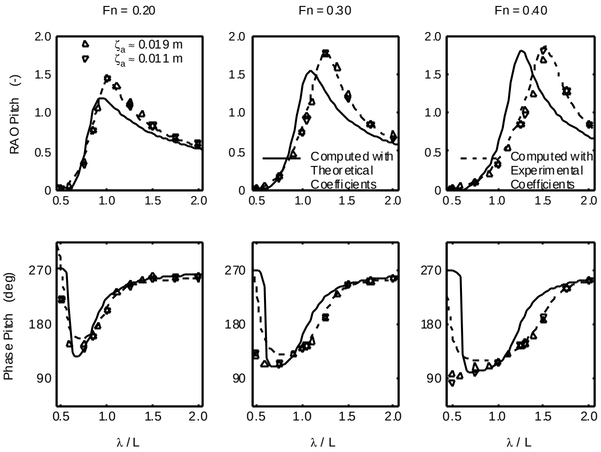

Figure 10 Pitch Motions Wigley III

Firstly, the heave and pitch motions have been calculated by using the computed potential hydrodynamic coefficients and the polynomials of the measured wave loads; see the straight line in the previous figures. Large differences with the measured motions have been found.

Secondly, the heave and pitch motions have been calculated by using the polynomials of the mean experimental values of both the hydrodynamic coefficients and the wave loads; see the dotted line in the previous figures. These “computed” motions fit the experimentally determined motions almost perfectly.

The hydrodynamic coefficients, wave loads and motions have been measured separately and independently. When assuming the validity of the (linear) superposition principle, the agreements between these "computations" strongly indicate that all experimentally determined values should be reliable.

Comparable results as found here for the Wigley III model have been found for the Wigley IV model too.
A detailed analysis for the Wigley I and Wigley II models will be carried out in the near future, but a mesh analysis showed already almost the same results for these other two models.

ANOTHER WIGLEY MODEL

In the early nineties, Adegeest [1] has carried out numerous forced oscillation tests, as well as wave load and motion experiments in head waves, with (segmented) Wigley models with and without bow flare with C_m = 0.909 and L/B = 7 to study the non-linear hull girder loads in ships. His experimental and theoretical results for a modified Wigley model, with a speed corresponding to Fn = 0.20, are presented in Figure 11 and Figure 12. This modified Wigley model has wall-sided cross-sections around the water line which reduces nonlinear effects in the geometry when pitching and heaving, since the water plane area and moment only marginally change during these oscillations.

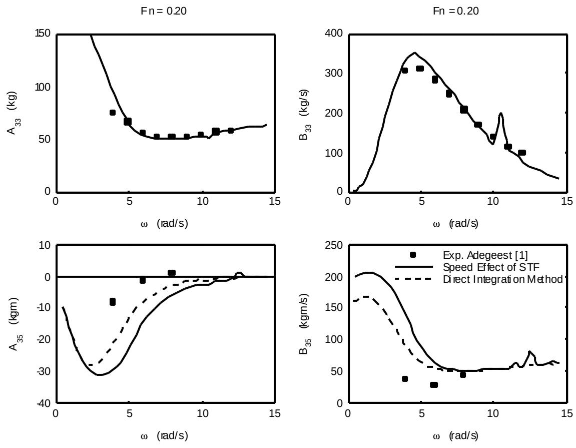

Figure 11 Heave Coefficients of Adegeest [1]

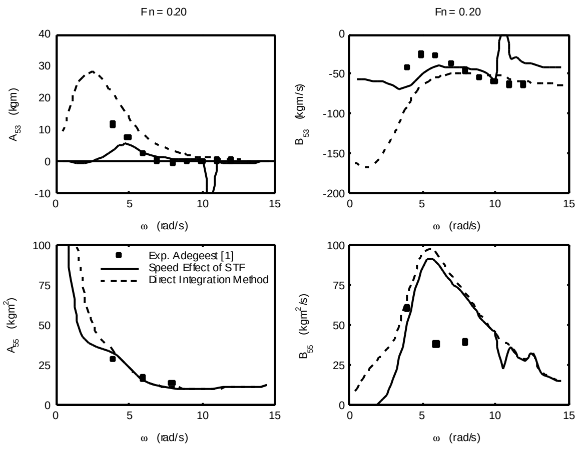

Figure 12 Pitch Coefficients of Adegeest [1]

Firstly, Adegeest has computed the hydrodynamic coefficients by using a zero-speed 3-D solution of the radiation problem - by using the DELFRAC computer code of Pinkster [9] - in combination with the 2-D forward speed correction of Salvesen, Tuck and Fatinsen [10], often refered to as STF method, which was used here by the author too. More or less similar trends for the differences between theory and experiment as have been found by the author for Wigle III, have been found by Adegeest too.
Furthermore, Adegeest has used a direct integration of the potentials and their longitudinal derivatives over the mean wetted hull surface, which resulted in speed-dependent potential mass and damping coefficients. However, the agreement of the computed heave coupling coefficients with the theoretical data became even worse, the fit of the pitch coupling coefficients became better and the other computed coefficients did not change significantly.

In 1998, van 't Veer [11] developed the computer code SEASCAPE, which uses a first-order Rankine panel method. Interactions between the steady ship resistance problem and the unsteady ship motion problem were neglected, by which he could solve these two flow problems separately. A double-body potential served as the base-flow in both flow problems.

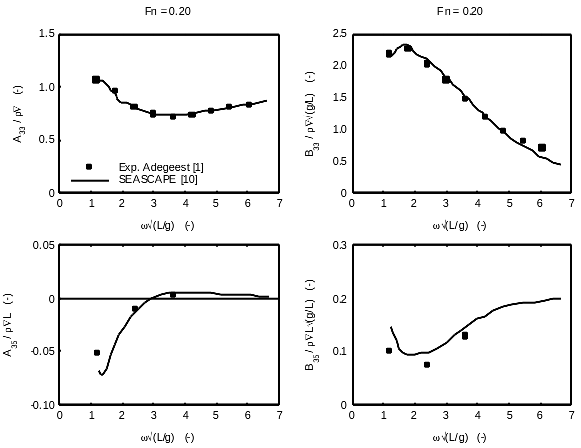

Figure 13 Heave Coefficients of Van 't Veer [11]

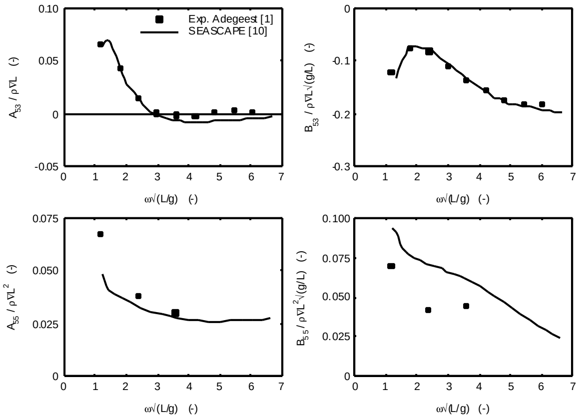

Figure 14 Pitch Coefficients of Van 't Veer [11]

A lot of attention was paid to the accuracy of the linearised hull boundary terms, the so-called *m*-terms; the already calculated double-body velocities on each panel were used to solve a Dirichlet boundary value problem, as stipulated by Chen and Malenica [2].

Among others, this calculation method was validated with Adegeest's experimental data of the modified Wigley model; see Figure 13 and Figure 14.

Van 't Veer's computed data agrees much better with Adegeest's experimental data. The heave mass and damping coefficients and the heave and pitch coupling coefficients show an almost perfect fit. However, the pitch mass moment of inertia and damping coefficients still differ.

CONCLUSIONS

Some conclusions can be drawn from all of this for the hydrodynamic coefficients:

- Both, the 2-D theory of Ursell (1949) with 10-parameter close-fit conformal mapping of the cross sections to the unit circle and the 2-D direct pulsating source method of Frank (1967) povide similar potential coefficients. These coefficients however deviate sometimes significantly from the experimental data of the 4 Wigley models.

- The calculated motions, obtained from the measured hydrodynamic coefficients and the measured wave loads (two independent sets of experiments), fit the experimental motions (a third independent set of experiments) almost perfectly. This indicates strongly that the experimentally determined coefficients of the 4 Wigley models are reliable.

- A direct integration of the potentials and their longitudinal derivatives over the mean wetted hull surface, which results in speed-dependent potential mass and damping coefficients, does not result in all cases in a significant improvement.

- The use of a first-order Rankine panel method to solve the flow problems results in an almost perfect fit for the heave mass and damping coefficients and the heave and pitch coupling coefficients. But the pitch mass moment of inertia and damping coefficients still differ.

It was not expected that these problems have been found here for the "nice and smooth" slender Wigley hull forms, while for normal more "ship-like" hull forms much better agreements have been found; see [6]. More research is required to solve this coefficients problem.

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APPENDIX: SURVEY OF ORIGINAL EXPERIMENTAL AND THEORETICAL DATA OF WIGLEY MODEL III AT Fn = 0.20 [4]

Some relevant figures from reference [4] are given in this Appendix.

Figure 15 through Figure 18 show the experimental and computed data - as they have been published in reference [4] – for Wigley III in head waves at a model speed corresponding to $Fn = 0.20$.

With respect to the used computer programs and computation methods, the legend in these figures is as follows:

L1 *SEAWAY*: Ordinary strip theory method of DUT, with 2-parameter Lewis conformal mapping.
L2 *SEAWAY*: Modified strip theory method of DUT, with 2-parameter Lewis conformal mapping.

C1 *SEAWAY*: Ordinary strip theory method of DUT, with 10-parameter close-fit conformal mapping.

C2 *SEAWAY*: Modified strip theory method of DUT, with 10-parameter close-fit conformal mapping.

F1 *SEAWAY*: Ordinary strip theory method of DUT, with pulsating source method of Frank.

F2 *SEAWAY*: Modified strip theory method of DUT, with pulsating source method of Frank.

W1 *WAMIT*: Three-dimensional diffraction method of MIT, with a speed correction according to the ordinary strip theory method.

W2 *WAMIT*: Three-dimensional diffraction method of MIT, with a speed correction according to the modified strip theory method.

D1 *DELFRAC*: Three-dimensional diffraction method of DUT, with a speed correction according to the ordinary strip theory method.

D2 *DELFRAC*: Three-dimensional diffraction method of DUT, with a speed correction according to the modified strip theory method.

It was concluded from reference [4] that the heave coefficients A_{33} and B_{33} were predicted rather accurately.
However, considerable differences between theory and experiments were found for the pitch coefficients A_{55} and B_{55}.

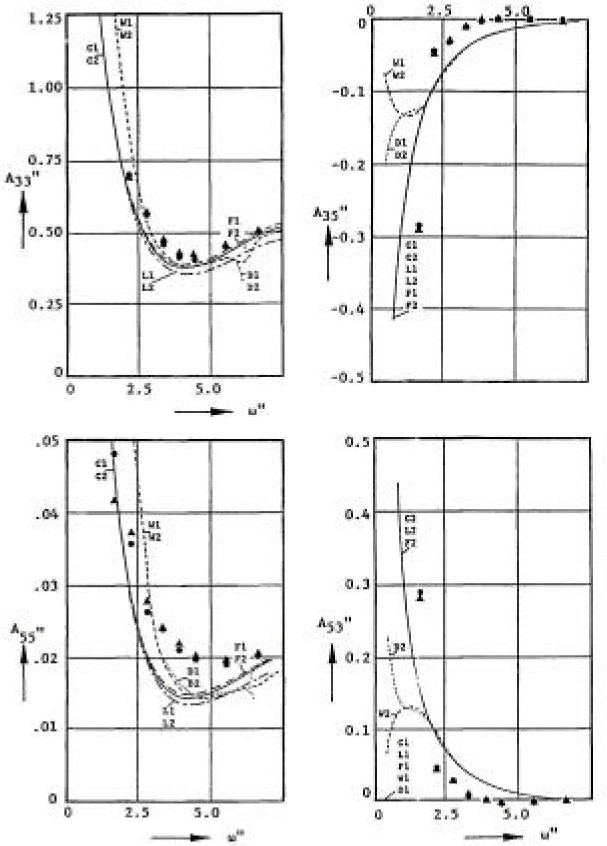

Figure 15 Mass Coefficients (III, Fn=0.2)

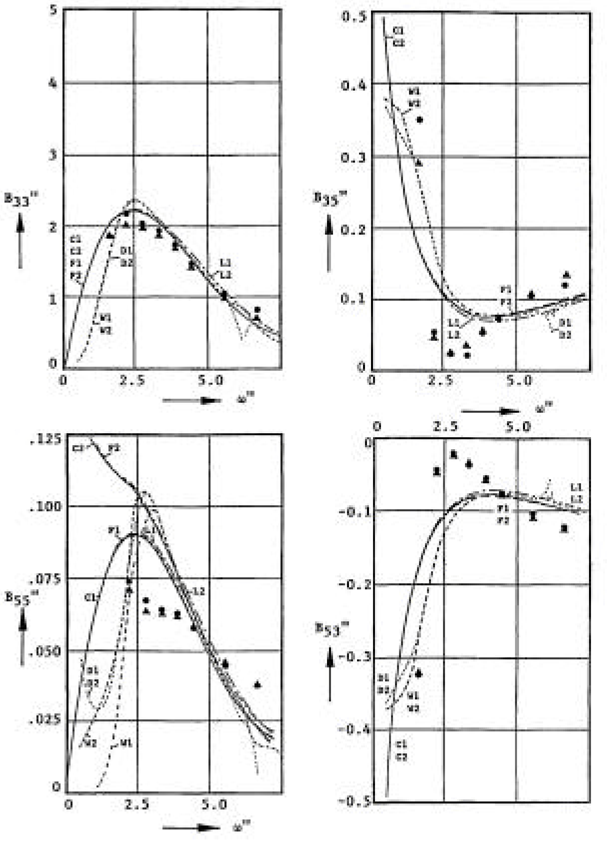

Figure 16 Damping Coefficients (III, Fn=0.2)

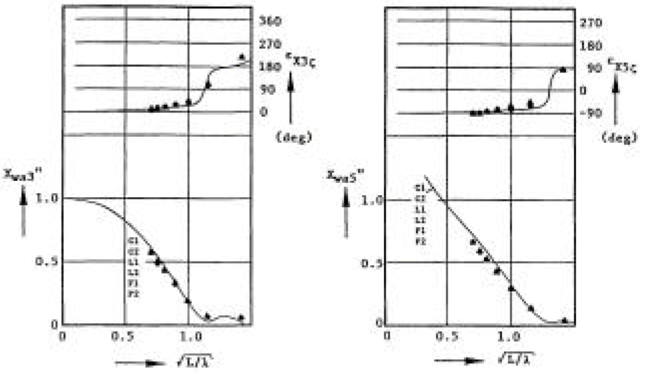

Figure 17 Wave Loads (III, Fn=0.2)

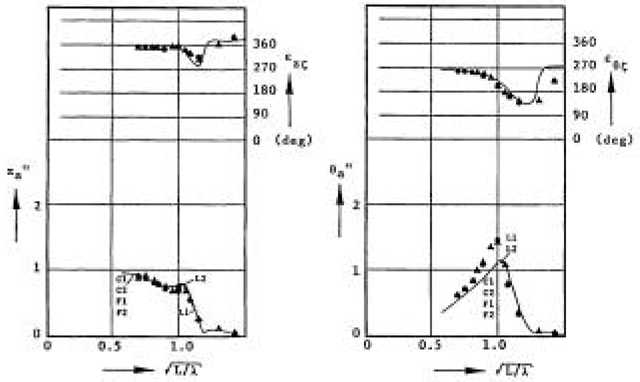

Figure 18 Heave and Pitch Motions (III, Fn=0.2)

Problems were encountered too in the computation of the heave and pitch coupling coefficients A_{35}, B_{35}, A_{53} and B_{53}. The computed mass coupling coefficients were double the experimental values. A significant different "behaviour" of experimental and computed curves has been found for the damping coupling coefficients.

The first order exciting wave forces and moments have been predicted fairly well.

Large to very large differences – especially at higher model speeds - have been found for the resulting heave and pitch motions in regular head waves. The resonance frequencies shift to lower frequency regions, mainly caused by too high calculated potential mass and potential mass moment of inertia values in those regions. Differences in the heave and pitch coupling coefficients appeared to have a significant influence too.