

Chapter 2

Evaluation of Resistance, Sinkage and Trim, Self Propulsion and Wave Pattern Predictions

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Abstract In Chap. 2 results in several areas are discussed. Resistance predictions were requested for all three hulls and there is a large number of submissions. It is found that for grid sizes larger than 3M cells all submissions are within 4 % of the measured data. The mean comparison error (data-simulation) is only -0.1 % and the mean standard deviation is 2.1 % of the data value, excluding self-propelled cases for which the error is larger. There is no discernible effect of the turbulence model; two equation models work as well as the more advanced ones. Sinkage and trim exhibit large comparison errors for the smallest Froude numbers, but this is likely to be due to measurement inaccuracies. For Froude numbers above 0.2 the mean comparison error is around 4 % and the standard deviation 8–10 %. Self-propulsion results are reported with real operating propellers as well as modeled ones. For K_T and K_Q the mean comparison errors are 0.6 and -2.6 % resp. The standard deviations are 7.0 and 6.0 % resp. Comparing actual and modeled propellers it is seen that the actual propeller has a much smaller mean standard deviation. For K_T it is half, and for K_Q it is only 1/3 of that of the modeled propeller. There is no clear advantage when it comes to comparison error, however. In general, the wave contour on the hull and at the wave cut closest to the hull is well predicted. Further away from the hull the results differ considerably between the methods. The best submissions for all three hulls capture all the features of the waves out to the edge of the measured region.

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1 Resistance

1.1 Statistics

One of the most important questions in computational hydrodynamics is how well resistance can be predicted. Resistance is the primary parameter when designing a ship, and virtually all new designs are tank tested to find its resistance characteristics. Together with the propulsive efficiency the resistance determines the required power and this is the most important quality of the ship from an economical and environmental point of view.

The present Workshop received 89 predictions of resistance for three different ship types at several Froude numbers, both in fixed and free conditions, and with and without an operating propeller. Therefore there is a reasonably large statistical basis for answering the question:

- *How accurately can the resistance of a ship be predicted today?*

A related question is how computational accuracy compares with experimental accuracy. How close is CFD to towing tank accuracy? Also, it is of considerable interest to evaluate the increase in computational accuracy compared with previous Workshops in the series.

Apart from that, the data base of computed results may be used to look into an equally important question, namely:

- *How can we learn from the data base to set up the most accurate computations?*

By relating the achieved accuracy to the features of the computations, as described in detail in the answers to the Questionnaire (see the web site extras.springer.com and the summary in Chap. 1), in principle the most promising approach could be found. This is not an easy task, however, since the methods and computations constitute an extremely complex combination of features, and evaluating the influence of each of them would require a much larger set of results than that available here. Therefore the statistical evaluation is restricted to the two main parameters which determine the accuracy of a CFD prediction, namely the grid density and the turbulence model.

In Table 2.1 a statistical analysis of all computed total resistance coefficients is presented. Cases which include such coefficients are 1.2a&b, 2.2a&b, 2.3a&b, 3.1a&b and 3.2. For KVLCC2 and KCS cases, “a” means fixed in sinkage and trim, while “b” means free to sink and trim. For 5415 3.1a&b are with the sinkage and trim fixed to the dynamic values at the corresponding Froude number, while the model is free in 3.2. The fixed computations for Cases 1 and 2 are for only one Froude number, while the free computations are for a range of speeds. 2.3a&b are self-propulsion cases where the resistance is equal to the sum of the propeller trust and the applied towing force.

In column 4 of Table 2.1 the mean comparison error E_{mean} is given in per cent of the measured data value, D . According to the sign convention of the Workshop E_{mean} is defined as $D - S_{mean}$, where S_{mean} is the mean of all simulated values for

Table 2.1 Resistance statistics, all cases

Hull	Case No.	Fr	$E_{mean} \%D$	$\sigma_{SD} \%D$	$U_D \%D$	No. of entries
KVLCC2	1.2a (fixed)	0.1423	-1.7 (0.0)	1.3 (6.2)	1.0 (0.7)	5 (13)
	1.2b (free)	0.1010	-0.3	-	1.0	1
		0.1194	-1.3	-	1.0	1
		0.1377	-2.3	-	1.0	1
		0.1423	-2.9	-	1.0	1
		0.1369	-2.8	-	1.0	1
		0.1515	-2.8	-	1.0	1
	Mean of KVLCC2		-2.0	-		
KCS	2.2a (fixed)	0.26	-1.3 (-1.1)	1.2 (4.2)	1.0	8(11)
	2.2b (free)	0.1083	+1.6	1.4	1.0	4
		0.1516	-0.1	1.1	1.0	3
		0.1949	-0.9	1.7	1.0	4
		0.2274	-1.0	1.4	1.0	6
		0.2599	-0.3	1.2	1.0	4
		0.2816	-0.4	0.8	1.0	6
	2.3a (fixed, prop.)	0.26	-0.3 ^a (-0.9)	3.1(1.0)	-	14 ^a (4)
	2.3b (free, prop.)	0.26	7.2	3.3	-	3
	Mean of KCS		-0.3	1.3		
5415	(w/o prop.)					
	Mean of KCS		3.7	3.2		
	(prop.)					
	3.1a (fixed σ & τ)	0.28	2.5 (1.6)	3.8 (5.3)	0.6 (2.2)	5 (11)
	3.1b (fixed σ & τ)	0.28	-2.6	4.4	0.6	5
	3.2 (free)	0.138	-2.8	4.4	1.3	5
		0.28	0.1 (-1.9)	2.1 (-)	0.6 (2.2)	6(1)
		0.41	4.3	1.4	0.6	5
	Mean of 5415		0.3	3.2		
Mean of cases with $Fn < 0.2$		$E_{mean, Fn < 0.2} = -1.2 \%D$	$\sigma_{SD mean, Fn < 0.2} = 2.0 \%D$			27
Mean of cases with $Fn > 0.2$		$E_{mean, Fn > 0.2} = -0.3 \%D$	$\sigma_{SD mean, Fn > 0.2} = 2.3 \%D$			62
Mean of all cases		$E_{mean, all cases} = -0.1 \%D$	$\sigma_{SD mean} = 2.1 \%D$			89 (40)

^a Results from MARIC with a hub cap are excluded

the particular case and Froude number. The standard deviation, σ_{SD} , is given in column 5 in per cent of the data value, and in column 6 the estimated data uncertainty is presented. Finally, in the last column the number of entries for the case is seen. Values within brackets are from the 2005 Workshop (Hino 2005).

A very surprising conclusion from the 2005 Workshop was that the mean comparison error E_{mean} was so small for the five different cases that included resistance predictions. These cases correspond to 1.2a, 2.2a, 2.3a, 3.1a and 3.2 in the present notation. For these cases E_{mean} was 0.0, -1.1, -0.4, 1.6 and -1.9 % of the data, respectively. The standard deviation in the predictions was however quite large for 1.2a, 2.2a and 3.1a, namely 6.2, 4.2 and 5.3 %, respectively, of the data. For 2.3a it was quite low, and for 3.2 there was only one entry.

Table 2.1 reveals a substantial reduction in the standard deviation (%D) for the towed KVLCC2 and KCS cases, from 6.2 to 1.3 and from 4.2 to 1.2 respectively in the fixed condition. Also, $|E_{mean}|$ for these conditions is well below 2 %, which indicates

that all predictions for this condition are quite accurate, although still not within the experimental accuracy. There is only one submission for the free KVLCC2 condition and it has a somewhat higher $|E_{mean}|$ in the upper Froude number range, about 3 %. The free KCS condition has however several submissions and very small comparison errors and standard deviations, around 1 % for both. The total comparison error for KVLCC2 (including fixed and free conditions) is -2.0 %, while for the towed KCS cases it is -0.3 %. The mean standard deviation of the latter is 1.3 %.

The self-propelled KCS has standard deviations around 3 % and the comparison error is very small for the fixed case. However, for the free case $|E_{mean}|$ is quite high: 7.2 %. All three submissions under predict the resistance significantly. It should be noted that the fixed KCS in self-propulsion is the only case for which the standard deviation has increased compared to 2005. The mean comparison error and standard deviation for the self-propelled cases is 3.7 and 3.2 %, respectively, considerably larger than for the towed cases.

5415 with sinkage and trim fixed to the dynamic values have comparison errors below 3 % and standard deviations around 4 %. In view of the fact that the only difference between 3.1a and b is the Reynolds number (apart from a very small difference in sinkage and trim), the difference is large, but the statistical basis is too small for a comparison. For the free 5415 in 3.2 both the mean error and the standard deviation seem to depend strongly on the Froude number. The best results is obtained at $Fr = 0.28$, where the water just clears the transom. For this condition the mean error is practically zero and the standard deviation among the 6 submissions is about 2 %. The mean comparison error for 5415 is quite small, 0.3 %, while the mean standard deviation is larger than for the other towed cases: 3.2 %.

Table 2.1 shows the statistics for all cases, and indicates the accuracy obtainable for each case. Even more interesting is however the information found on the last line: the mean error and the mean standard deviation (weighted by number of entries) for all cases. The mean error for all computed cases is practically zero; only -0.1 %, while the mean standard deviation is 2.1 %; a surprisingly small value. In the 2005 workshop the mean error of all 40 submissions was in fact equally small: 0.1 %, while the mean standard deviation was 4.7 %. While the distribution between “simple” and “difficult” cases is not the same in the two workshops, it seems safe to conclude that the scatter has been reduced considerably. In fact, even the largest standard deviation in the present computations (cases 3.1b and 3.2) is smaller than the mean standard deviation in 2005.

In the table a split has also been made between high and low Froude numbers. As will be seen below, the accuracy in these two regions differs considerably when it comes to sinkage and trim, but for resistance this difference is not significant.

We will now turn to the second question above: how to learn from the computed results. The first question is: *how dependent are the results on the grid size?* Note that this is a comparison of completely unsystematically varied grids and methods, as opposed to the systematically varied grids for each method to be described in the next section. In Fig. 2.1 the error of all computed results is plotted versus grid size. There is also a coding of the points where filled symbols represent fixed cases and open ones cases free to sink and trim. Each hull has a symbol, except KCS which has one symbol for towing and one for self-propulsion. Note that the largest grid

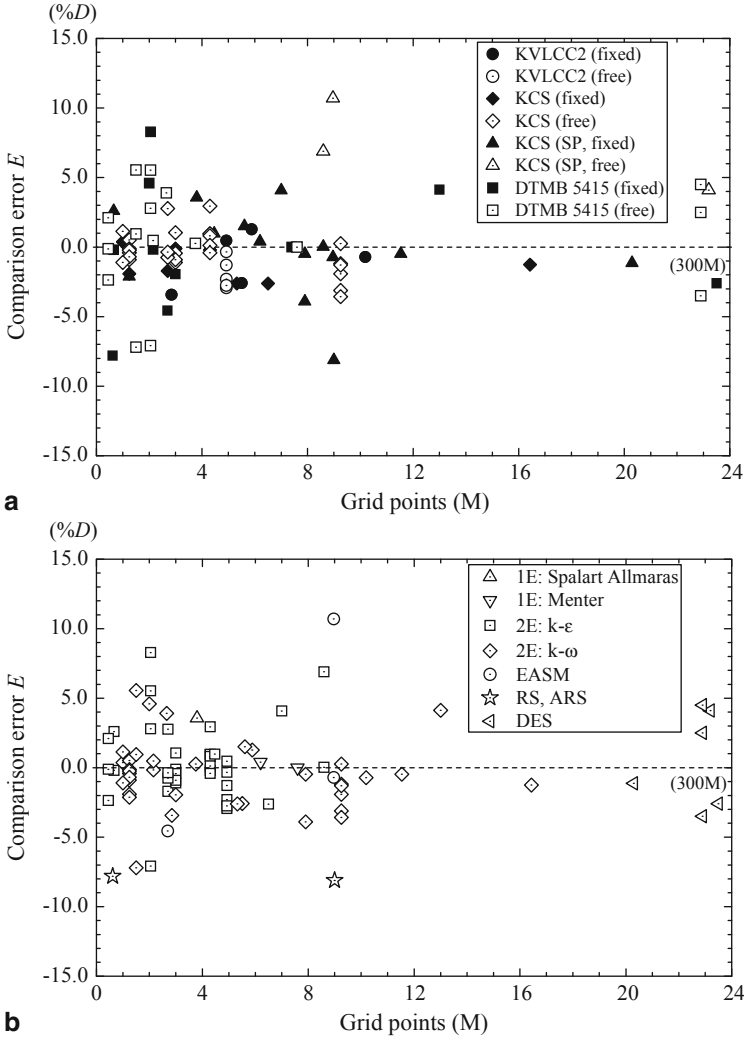


Fig. 2.1 **a** Comparison error for all resistance submissions versus grid size. **b** Comparison error for all resistance submissions versus grid size

is much larger than the others (300 M cells) and has been moved into the plot and marked 300 M.

Analyzing Fig. 2.1a it is seen that about 90 % of all computations are made with grids smaller than 10 M cells. The scatter within this range seems to be significantly larger than for the larger grids. However, this is mainly caused by the large scatter of the self-propulsion submissions (triangle symbols), so if these are excluded, and only towed resistance is considered, there is no error decrease above 3 M grid points. All points seem to be within approximately $\pm 4\%$. Not even the very large grid at

300 M cells shows any significant improvement; it is slightly below 3 %. However, below 3 M cells the maximum errors increase to about 8 %.

The second lesson to learn from the computed results is: *how dependent are the results of the turbulence model?* In Fig. 2.1b the same points as in Fig. 2.1a are plotted, but with a different symbol coding. Each symbol represents a turbulence model. Up-triangle symbol means 1-equation Spalart-Allmaras models, down-triangle symbol means 1-equation Menter models, square symbol means 2-equation $k-\varepsilon$ models, diamond symbol represents 2-equation $k-\omega$ models, circle symbol represents Explicit Algebraic Stress Models (EASM), star symbol Reynolds stress models and left-triangle Detached Eddy Simulation models (DES). There is a large number of entries for the 2-equation models so for them the statistical basis is rather good. For the others there are rather few entries, but a reasonable conclusion is that a more advanced model is not a guarantee for a good result, even with a large number of grid points.

Table 2.2 gives the statistics for the different models. Note again that there are very few entries for some of them. The relatively poor result for the more advanced methods is apparent, while the simpler 2-equation models seem to do a good job. EASM and RS, ARS suffer from one bad point for a very coarse grid and two bad points computed for the self-propulsion cases, which may be more difficult than the towed cases, while the three very good results for the Menter model were obtained with the same code and user.

1.2 Grid Dependence and Uncertainty

In this Section a brief analysis of the uncertainty of the computed resistance will be presented. A more comprehensive discussion is found in Chap. 5.

According to standard procedures (see e.g. ITTC 2008) the comparison error $E = D - S$ is to be compared with the validation uncertainty U_{val} , defined as $U_{val}^2 = U_{SN}^2 + U_D^2$, where the numerical uncertainty $U_{SN}^2 = U_G^2 + U_I^2$ and U_D is the data uncertainty specified in Table 2.1. U_G and U_I are the grid and iterative uncertainties, resp. In the ITTC vocabulary, if $|E| \leq U_{val}$, validation has been achieved at the U_{val} level, meaning that the error is within the “noise level”. If on the other hand $|E| \gg U_{val}$, validation has not been achieved and the sign and magnitude of E could be used to improve the CFD modeling.

Thus, to compute the numerical uncertainty U_{SN} we need the grid uncertainty U_G and the iterative uncertainty U_I . Information about both quantities was requested by the organizers. To obtain U_G , participants were asked to provide solutions for at least three grids and the estimated U_I was to be compared with the difference between the solutions on the two finest grids, ε_{12} . For $|U_I/\varepsilon_{12}| \ll 1$ the effect of the iterative error may be neglected. Unfortunately these instructions were not well followed and more than half of the submissions were with only one grid. This is a pity, since for the first time a large scale test could have been made of the proposals made in the literature for estimating the grid uncertainty U_G through systematic grid variations.

There are essentially two such procedures in use: the ITTC procedure (ITTC 2008) based on the work at the Iowa University (for the most recent development

Table 2.2 Mean comparison errors for the turbulence models

Turbulence model	E_{mean}	$ E _{mean}$	No. of entries
1-E Spalart Allmaras	3.6	3.6	1
1-E Menter	0.1	0.1	3
2-E $k-\varepsilon$	0.3	2.1	37
2-E $k-\omega$	-0.5	1.8	37
EASM	1.8	5.9	3
RS, ARS	-8.0	-8.0	2
DES	0.6	3.1	6

along this line, see Xing and Stern 2010) and the procedure stemming from the three Workshops on CFD Uncertainty held in Lisbon during the last decade (for the most recent development of this procedure, see Eça et al. 2010). Both procedures are based on systematic grid variations for a number of simple test cases. There is however very little information in the literature of how well the procedures can be applied to cases of industrial interest. As pointed out in Eça et al. (2010) such cases are prone to include perturbations of the solutions for various reasons, such as not exactly scaled grids (aspect ratio, skewness, etc), limiters of different kinds in turbulence models and numerical schemes, and post processing errors. Even more important is perhaps also the fact that iterative convergence may be so slow in real applications, particularly for fine grids, that the iterations are stopped prematurely with an iterative error too large to be neglected. Any perturbation of this kind will affect the difference between the successively refined solutions, which is the basis for all methods for uncertainty estimation based on grid sequencing.

Although many grid variations are missing we have a substantial number of submissions with such variations. There is in fact a large difference between the cases. For KVLCC2 *all* resistance submissions include grid variations, while for 5415 this is so for less than 25 % of the submissions. For KCS the number is around 40 %. The reported results will be used below to shed some light on the most important question:

- *How useful is grid sequencing for numerical uncertainty estimates in cases of industrial relevance?*

It will be hard to give a strict answer to this question, but some indications may be found, as will be seen below. A relevant question is however what happened to the submissions which did not report grid variations. Was that due to failure to apply proposed procedures or were variations not tried?

To start with, the reported iterative convergence U_I may be analyzed. As stated, this must be small enough not to affect the solution differences significantly, and as a practical limit U_I may be set to 10 % of the difference between the two finest grid solutions, ε_{12} . It should be stated that this limit is not substantiated by systematic investigations, and it is not a very strict requirement. Nevertheless 25 % of the reported grid convergence studies do not satisfy this criterion and in some cases U_I is of the same order as ε_{12} . This is a source of scatter in the reported results. It should be pointed out that even the determination of U_I is not unambiguous. In most cases it is determined as the amplitude of the resistance fluctuation over one or more wave lengths at the end of the iterations.

Methods for estimating the discretization error U_G from systematic grid variations are based on the fact that the error of the numerical solution can be expressed as a series expansion in the typical step size of the grid, h . The order of accuracy of the method, p , is determined by the first term in the series, proportional to h^p . As h is reduced the importance of this term increases and for sufficiently small h the influence of all other terms may be neglected. h is then said to be in the “asymptotic range”. Since the error is proportional to h^p it may be computed if the constant of proportionality (α) is known, and the solution S_0 at zero step size may be obtained from the formula $S_0 = S_1 - \alpha h^p$, where S_1 is a known solution. To determine α , another solution S_2 is required. This technique is known as Richardson extrapolation. If p is not known a priori a third solution S_3 is required. From the three known solutions S_1 , S_2 and S_3 the three unknowns S_0 , α and p are computed.

Richardson extrapolation in its original form is of limited practical value since h is seldom in the asymptotic range, at least not for cases of interest in hydrodynamics. However, the equation for S_0 is still used. The power p will then be influenced by the neglected higher order terms in the error expansion and will thus be different from the theoretical order of magnitude p_{th} of the method. The difference between p and p_{th} , or the ratio p/p_{th} is then used as a measure of the “distance” to the asymptotic range.

In Richardson extrapolation methods the error in the solution S_1 , i.e. $S_1 - S_0$ is denoted δ_{RE} . This quantity is taken as a metric for the numerical uncertainty. In the original approach by Roache (1998) δ_{RE} was multiplied by a safety factor FS to estimate the numerical (grid) uncertainty U_G . The factor was either 1.25 or 3, depending on conditions. In the most recent developments of the Iowa method (Xing and Stern 2010) FS is computed from p/p_{th} using two empirical formulas; one for values above unity and one for smaller values. The original Iowa method, endorsed by the ITTC (ITTC 2008) is slightly more complicated but the basic idea is the same. Eça and Hoekstra (see Eça et al. 2010) use different formulas for U_G in different ranges of p . For most conditions these formulas are based on δ_{RE} . The exact formulas for both methods are given in Chap. 5.

In Fig. 2.2 all grid variation studies submitted to the Workshop (for resistance) are presented, case by case. The comparison error E is plotted against grid density represented by the non-dimensional step size h_i/h_1 , where h_i is the step size of grid i and h_1 refers to the finest grid. In the legend the submitting organization is given, followed by the type of grid used. The notations for the grids are S, MS, OS, U and MU, which stand for single block structured, multi-block structured, overlapping structured, single block unstructured and multi-block unstructured, respectively. Within the round brackets the step ratio, r_G between successive computations is given first, followed by the ratio of the observed and theoretical order of accuracy. There are altogether 40 grid variations in Fig. 2.2. Surprisingly enough 33 of these are for structured grids. In general, the grid convergence is quite good for these grids. Visual inspection yields that almost all converge monotonically, i.e. $0 < R < 1$, where $R = (S_1 - S_2)/(S_2 - S_3)$ and S_n represents the solution on the n :th grid. Only one seems to be divergent ($R > 1$) and one oscillatory ($-1 > R > 0$). The convergence characteristics are confirmed by the given p , but this has not been computed for all cases.

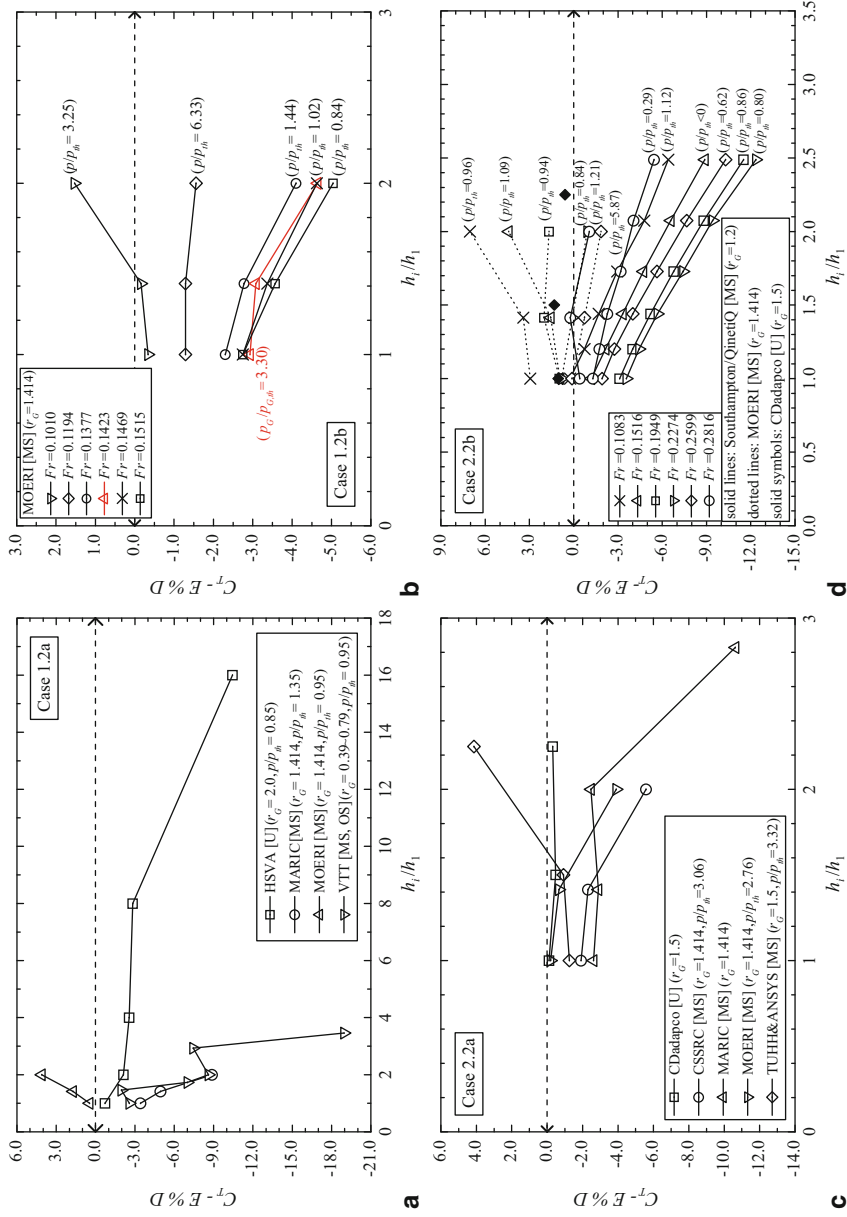


Fig. 2.2 **a** Grid dependence of C_T comparison error E in Case 1.2a. **b** Grid dependence of C_T comparison error E in Case 1.2b. **c** Grid dependence of C_T comparison error E in Case 1.2c. **d** Grid dependence of C_T comparison error E in Case 2.2a. **e** Grid dependence of C_T comparison error E in Case 2.2b. **f** Grid dependence of C_T comparison error E in Case 2.3a. **g** Grid dependence of C_T comparison error E in Case 2.3b. **h** Grid dependence of C_T comparison error E in Case 3.2.

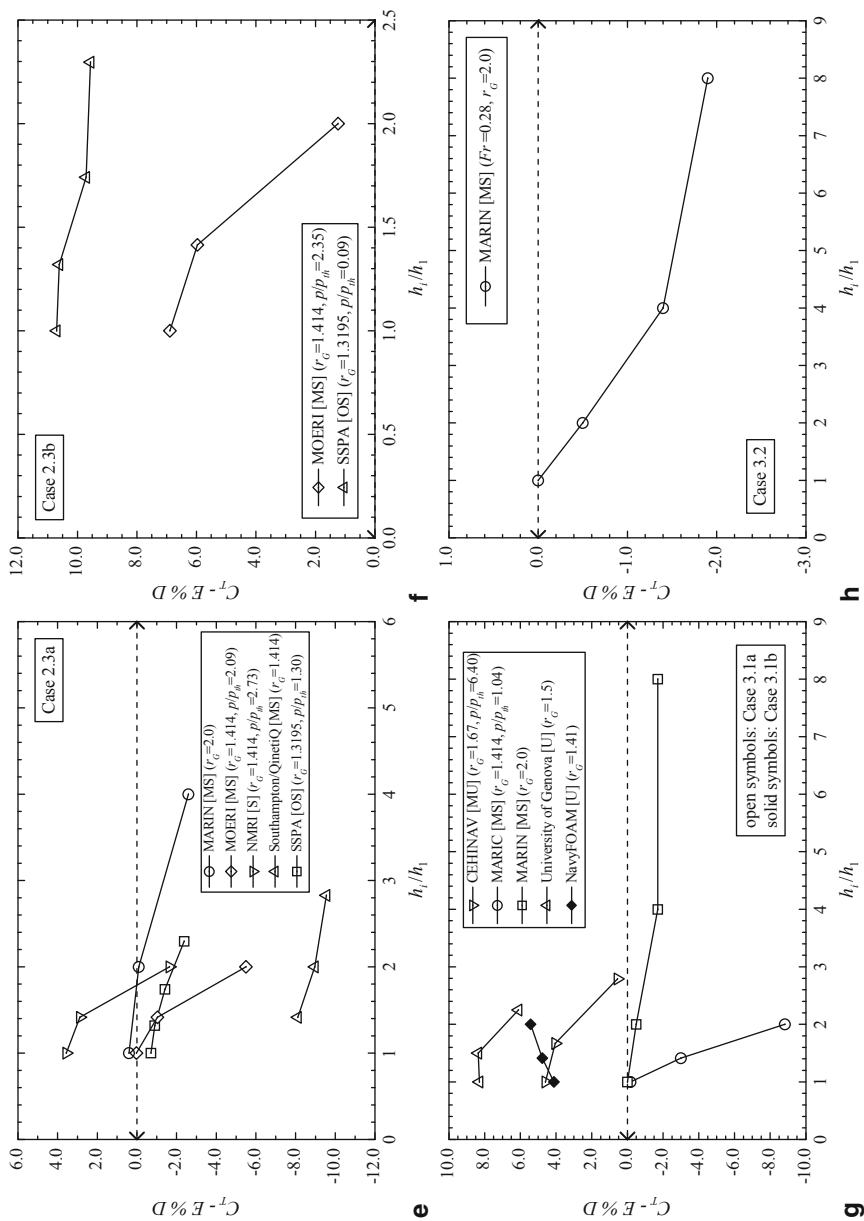


Fig. 2.2 (continued)

Numerical Ship Hydrodynamics

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