Assessment of motions and loads of catamarans

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ABSTRACT: Different methods to compute wave induced motion of catamarans are compared, with the special objective to evaluate how hydrodynamic hull interaction is modelled. Three numerical implementations, representing the no-interaction scheme, two-dimensional interaction and a three-dimensional interaction scheme, are applied in a total of 7 different hull forms of catamarans found in the literature. The first case is accomplished by post-processing of a strip theory method implemented in an in-house code developed at CENTEC in IST with additional end-terms inclusion. The two-dimensional interaction scheme results are obtained by a similar in-house code based on strip theory method, where the hydrodynamic coefficients are computed using symmetric demi-hulls. This code includes an empirical method, cross-flow for inclusion of viscous effects. For comparison it is included results using a commercial three-dimensional Rankine panel method, Wasim from DNV-GL. Motion results comparison between experimental and computed ones is done using transfer functions and Root Mean Square Error (RMSE). The uncertainty in numerical errors is evaluated using a frequency independent model error. Considering the relevant variables of the problem a linear correlations study is accomplished using the RMSE. A frequency dependent model error is studied using the best correlations found. Results indicate relevance of interaction schemes and strong dependence on Froude number, however better results are obtained using the three-dimensional interaction scheme.

Keywords: catamaran; interaction; strip theory; Rankine panel method; model errors

1 INTRODUCTION

The understanding of ship motions is today considered to have been developed to the stage of engineering accuracy. Even with relatively simple methods from the 70's, such as strip theory, that has been proven and widely used in computations of ship motions due to waves in a seaway, especially for single hulls. Other aspect of this advanced subject, ship motions, is the amount of methods existing to perform such computations, from thin theory, strip theories, three dimensional methods linear and non-linear based on potential theory, until recently CFD (computer fluid dynamics) that allow inclusion of viscosity. Compilations on such methods can be found in books and notes like, (Bertram 2012) and (O. M. Faltinsen 2005). Nowadays it is the concern of general scientific community the comparison and evaluation of different methods. Comparing the results and the quality of the outcomes, sometimes regarding specific methods or conditions like linearity of solutions, or even general achievements in such computations are of most use for readers that are interested in the final ability to perform design optimisations regarding seakeeping criteria, (Bunnik, et al. 2010), (Watanabe e Guedes Soares 1999), (Dhavalikar 2011), (Nestegard, et al. 2008) and (Temarel, et al. 2016)

Early application of strip theory methods, like (Salvesen, Tuck e Faltinsen 1970) in prediction of catamaran's motions led to less satisfactory results, it was found that direct application of such theory would not assure the operability of the vessel, (A. P. Van't Veer 1998). Consideration on the hydrodynamic hull interaction where not accounted properly, and therefore studies on the subject followed in attempts to include this effect on simple strip theories. A sequence of works, (Ohkusu 1970) and (Ohkusu e Takaki 1971) studied a way to include interaction between multi-hull floating structures with forward speed, starting by the definition of the hydrodynamic problem for cylinders and later testing the results using a generic hull form. Based on strip method the hull sections where approximated using Lewis forms and the radiation problem solved using Tasai method. This two-dimensional approach resulted in over prediction of heave and pitch motions, which increased with the forward speed. The possible solutions for the major problem of failure to predict the catamaran motions started with (Lee, Jones e Curphey 1973). They mention three-dimensional influences regarding the hull spacing and possible strong effect of viscous effects due to the fast forward speed of SWATH (Small Waterplane Area Twin Hull).

Similar two-dimensional implementations for catamaran motions predictions, (Veer e Siregar 1995), (Fang, Chan e Incecik 1996) and (Centeno et. al. 2000) having the later an improvement regarding the viscous effects. Inclusion of the cross-flow method to account for viscous effect was applied to

SWATH type of vessels with relatively good results, (Lee e Curphey 1977). The same approach was used in other type of methods, three-dimensional methods included better modeling of hull interaction althow took significantly more time for computations. (Chan 1993) work on SWATH ships, included cross-flow method applied on 3D panel method results and gave better results when predicting the heave and pitch resoannce frequencies.

Three-dimensional modelling of the problem regarding catamarans have been developing and even with linear potential flow condition they include hydrodynamic interaction between hulls and more recently the inclusion interaction with the static wave created by the ship's forward speed. (Hudson, Price e Temerel 1995), (Varyani, Gatiganti e Gerigk 2000), (Fang e Chan 2004) with panel and source distribution and (A. P. Van't Veer 1998) with Rankine singularities panel method solved the problem and comparisons where still done with strip theory methods. The three-dimensional solutions are nowadays in practice more often, largely due to the computational evolution, (Kring 1994), (Söding, et al. 2009).

Applications of Reynolds averaged Navier-Stokes (RANS) methods in seakeeping and manoeuvering problems represent a new approach in numerical methods which implies the effects of viscosity and turbulence in the flow equations. The work of (Castiglione, et al. 2011) presents CFD results for a high-speed multi-hull with rigorous verification and validation. Results using Unsteady Reynolds-Average Navier-Stokes (U-RANS) are compared with experimental data and strip theory, for heave and pitch motions. The amount of computations present in the work are small due to the method applied. The comparison of results is done with a two-dimensional fast strip theory (Faltinsen e Zhao 1991), that includes the interference effects, (Hermundstad, Aarsnes e Moan, 1999), and the experimental results of the hull in study. In both cases fully three-dimensional and U-RANS methods, the computational effort is very high, or the methods are difficult to implement, even for the case of mono-hulls that do not have the problem with the interference effects.

2 SOFTWARE OVERVIEW

To consider the interaction effect for motions computations of catamarans, three levels of numerical implementations are used, considering the base case of no-interaction to the two-dimensional interactions scheme and finally a three-dimensional. The case of no-interaction and the two-dimensional interaction are implemented in strip theory codes, the first using *Fonseca* results and the second with *CatCenteno*. The three-dimensional results are obtained from *Wasim*.

Availability was given to the author of this work and their characteristics related to the objective of increasing the understanding on interaction effects. The main characteristics of each software is presented in Table 1.

Table 1-Software used.

Acronym	**Fonseca**	**Cat Centeno**	**Wasim**
Reference	(Fonseca e Guedes Soares 1998)	(Centeno, Fonseca e Soares 2000)	(Kring 1994)
Method	Strip Theory	Strip Theory	Rankine Panel Method
Domain	Frequency	Frequency	Time & Fourier
End terms	No	Yes	Kutta condition
Multi-hull	No	Two-dimensional	Three-dimensional

A frequency domain strip theory code, *Fonseca*, which is the linear version of the time-domain software presented in the article, (Fonseca e Guedes Soares 1998), is used to perform computations for the base case. The transformation to catamaran case is done by computing the demi-hull motions as a single hull case and then post-processing the results to represent the catamaran motions, implying no-interaction between the demi-hulls. To obtain the catamaran motions without considering interaction the demi-hulls are modelled symmetric and with constant spacing between centre lines, $S = 2y_T$. The cross deck is considered rigid and without mass. Roll motion is considered a function of each demi-hull heave motion and the local roll motion felt by each demi-hull. Excitation forces are in different phases on each demi-hull and in some frequencies, heading and hull spacing the difference in phase can be 180 degrees, resulting in very low or even no-exciting forces at all. Such type of implementations can be found in texts like (Journee e Adegeest 2003) or (O. M. Faltinsen 2005). The software, *Fonseca*, was provided by the department CENTEC University of Lisbon. Its calculations are based on the strip theory from (Salvesen, Tuck e Faltinsen 1970) from which followed the inclusion of end-terms was added by post processing, the bi-dimensional hydrodynamic coefficients are computed using Frank's close fit, (Frank 1967).

CatCenteno code is a step in the interaction scheme, including computations of motions using a two-dimensional interaction scheme. (Centeno, Fonseca e Guedes Soares 2000), have developed a software that is based on strip theory method. The work aimed for motions computations on catamaran vessels. On top of the interaction feature the author included cross-flow method in order to account for viscous effects. The two-dimensional hydrodynamic coefficients are obtained using Frank's close fit, however the definition of demi-hulls geometry, placed at y_T from the catamaran centre line, generates a solution of the radiated problem that accounts for a two-dimensional interaction between transversal strips of demi-hulls. Considering this two-dimensional interaction scheme, with the radiated waves travelling traversal to the hulls centre lines, it is possible to predict in a simple way the interaction relevance and limit. Following formulation from (Veer e Siregar 1995) for the condition in which the radiated wave from one hull interacts with the other hull is as in Equation

$$\tau = \frac{U}{V_p} = \frac{U}{\lambda_e/_{T_e}} = \frac{Uk_e}{\omega_e} = \frac{U\omega_e}{g} \qquad (1)$$

When τ is greater then the relation between length and inner hull distance L/H , the wave generated at the bow of one demi-hull does not interact with the other demi-hull, since it will pass behind the most aft section of it. From this equation it is possible to determine either the encounter frequency at which interaction reach the limit, Equation 2, or for a given forward speed and encounter frequency the length of demi-hull that is affected by the radiated waves from the other demi-hull, Equation 3 .

$$\omega_e > \frac{L}{H} \cdot \frac{g}{U} \qquad (2)$$

$$Int. = \frac{x_{st}}{L} = 1 - \tau\frac{H}{L} \qquad (3)$$

In the effort of including a fully three-dimensional interaction study for catamarans, a state-of-the-art method is used. *Wasim* software is already used in classification societies as an everyday motions computations tool in a very wide range of cases, (Nestegard, et al. 2008). This software is originated from a cooperation between DNV and MIT starting in beginning of the 90's, its basic implementation had two stages of evolution, SWAN1 and SWAN2. From its beginning the software was applied to practical applications in the new-building activities. Nowadays it is included in a package provided by DNV-GL called HydroD - SESAM. Within this, analysis can be done for either stationary floating structures or with forward speed. For the case of this work only the Wasim package was used, (Veritas 2011). Based on potential flow theory the program uses a three-dimensional Rankine panel method creating a fully three-dimensional solution.

Table 2-Programs limitations in hull shape definition.

Acronym	**Fonseca**	**CatCenteno**	**Wasim**
Input type	Sec. points	Sec. points	Sec. points + FEM
Number of sections	40	40	200
Points number per section	20	20	200
Longitudinal coordinates	Yes	No	Yes
Stems definition	Bow & Stern points	Bow point	Stem curves

From *Table 2*, where the limitations of shape definitions are showed, there are two differences that had an important influence in modelling of hulls geometries. Both of the strip theory codes require that the bow is modelled by a single point, intersection between the bow stem and mean water line. This limits the type of hull forms possible to include in the calculations, especially if the bow is of a not conventional form, as bulbous or wave piercing. *Fonseca* code requires the longitudinal location of the sections, and both the bow and stern must be defined with a singular point. Because longitudinal position of sections can be defined, the previous problem, when modelling the bow shape, can be improved. For the case of *CatCenteno* the sectional description of the models starts with a single point at the bow. From this point the code will split the ship's length in constant spaced sections. The number of sections must be the number of shaped sections plus one for the bow point. Which does not allow a very precise hull form definition. Differently, *Wasim* allows the user to create a curve that defines the stems shapes and therefore it allows any types of bows. In this software the sections are introduced in sequences that generates patches representing the hull surface. Because of this, the types of hull forms possible to create are incredibly big, from SWATH to Trimarans and others.

3 CASE STUDIES

Experimental works have been used for validation of theories and computations on the subject, the number of these regarding the problem with catamaran is less than the amount for the single hull type of vessels, (Guedes Soares, Fonseca, et al. 1999). In this work the collection of experimental works is found in the literature in the form of published reports or articles with the objective to expand the pool of data available over the theme.

3.1 Catamaran models

NPL round bilge series: (Wellicome, et al. 1995) The motions experiments describes the seakeeping properties of catamarans for three geometrical similar hull forms. The tests were performed in the Southampton Institute test tank (SITT). Three hull forms are used, 4b, 5b and 6b. Tests were for head waves with Froude numbers ranging from 0.2 until 0.8. Each hull shape was tested with two configurations of spacing, $S/L = 0.2\ and\ 0.4$.

MARINTEK: (Hermundstad 1995) Motions and global loads of the model are tested in the Ocean Environment Laboratory of MARINTEK. Experimental results include four regular wave conditions, with combinations of two Froude numbers, $Fn = 0.49$ and $Fn = 0.66$ and three directions, $\beta = 90°, 150°, 180°$.

DELFT 372: (R. Van't Veer 1998)(a) and (R. Van't Veer 1998)(b). Two different tests are performed in distinct towing tank facilities, the initial one was performed in Delft Ship Hydrodynamic Laboratory (DSHl) considering only head waves, and the second one in Seakeeping basin at MARIN (Maritime Research Institute in Wageningen, The Netherlands), with three different headings. Froude numbers tested for this model ranged from 0.3 until 0.8.

El Pardo: (Guedes Soares, Fonseca, et al. 1999) The tests were executed in the Laboratory of ship Dynamics of El Pardo Model Basin (CEHIPAR) in Madrid. The work produced by the authors focused on the heave, pitch and roll motions of a model catamaran produced for the experiments. The range of Froude numbers is between 0 and 0.6 for head waves, being the variation of headings, $\beta = 150°, 165°$ studied for the design speed which meets Froude number equal to 0.4.

VOSPER: (Centeno, Varyani e Soares, 2001) The experiments were performed at the Hydrodynamic Laboratory at the University of Glasgow (HLUG) with the purpose of study heave and pitch for two different spacings between the catamaran demi-hulls. The experimental program consisted in the study of heave and pitch motions with incident wave angle of 180 degrees and a range of Froude number between 0 and 0.75.

Table 3-Catamarans main dimensions.

Catamaran	**Scale**	**L**	**T**	**B$_{dh}$**	**S/L**
NPL4b	1:25	40	2.22	4.44	0.2&0.4
NPL5b	1:25	40	2.22	3.64	0.2&0.4
NPL6b	1:19	40	1.53	3.05	0.2&0.4
MARINTEK	1:10	37.78	2.01	2.67	0.199
DELFT372	1:10	30	1.50	2.40	0.233
El Pardo	1:10	40	1.35	2.70	0.200
VOSPER	1:20	41	1.70	3.16	0.2&0.3

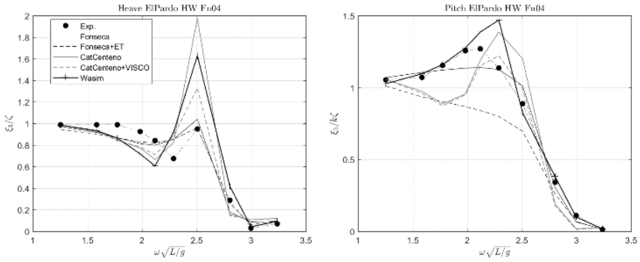
4 RAO RESULTS

Computational results are showed in form of RAO's (Response Amplitude Operators), they are displayed in non-dimensional form. Due to the objective of study catamaran motions, with a large amount of computations, phase angles are not included. Non-dimensional axis for displacement movements such as heave, are obtained by dividing the amplitude of motion by the wave amplitude in the vertical direction; ξ_3/ζ. Rotational motions such as pitch and roll are further divided by the wave number $k = \omega^2/g$; $\xi_{5,4}/k\zeta$. Frequencies are non-dimensional following ITTC recommendation; $\omega\sqrt{L/g}$.

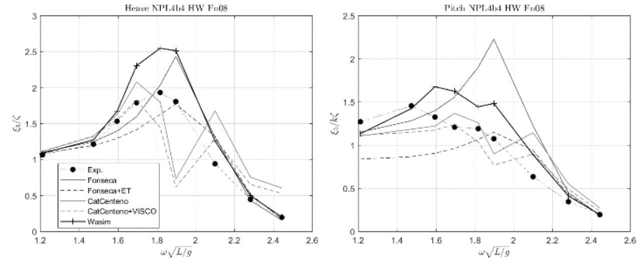
In total the 7 hull forms resulted in 11 models, when accounting for the hulls spacing differences. And with combinations of headings and Froude numbers the amount of tested conditions is 48. For all the cases the three methods where used to compute motions. In addition, both strip based methods have implemented extra considerations, post processing of *Fonseca* allowed inclusion of end-terms, and *CatCenteno* has the option to use cross-flow method.

4.1 Heave and pitch motions

The results obtained from the variable hull spacing models are interesting, especially regarding the interaction schemes implemented with the Software used. Apart from this general tendency for different Froude numbers and headings can be reasonable found.



a)Heave, Fn0.4 b)Pitch, Fn0.4



c)Heave, Fn0.8 d)Pitch, Fn0.8

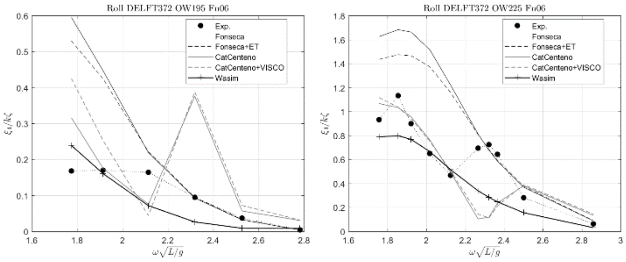
Figure 1-Heave and Pitch RAO examples, a)&b) El Pardo; c)&d) NPL4b S/L=0.4.

The results here included are representative of the general results. On Figure 2 a), it is possible to observe the tendency of over-prediction in heave of methods that include interaction effects, especially for the two-dimensional interaction scheme. However, *Wasim* shows better precision for the general cases. Figure 2 c) exemplifies a type of result found, where the forward speed is high and the hull spacing is big, in these cases it was found that *CatCenteno* can show discontinuities on the curves. Inclusion of end-terms in *Fonseca* shows good fitting to experimental results with resonance peaks very similar; *Wasim* keeps showing good especially predicting the frequency range of resonant peaks for very high speeds.

Pitch motions in catamarans are not so well predicted for the general cases, *Wasim* has the best curve fit and interestingly *Fonseca* without interaction shows reasonable curves but the resonance frequencies are not well predicted being slightly shifted to the experimented ones. Presence of secondary humps in the responses also indicate the existence of non-linearities in this mode of motion.

4.2 Roll motion

From the chosen experimental works available only three models are subjected to oblique waves, *MARINTEK*, *Delft 372* and *El Pardo*. This is possibly justified by the difficulties in creating experimental set-ups for these cases, which are in most of the cases conducted with self propelled models including autopilots that do not assure the same heading during the run, (Hermundstad 1995) identifies this problematic.



a)$\beta = 195°$ b) $\beta = 225°$

Figure 2-Roll RAO examples, DELFT372 Fn=0.6.

Roll motions are less in number of computations, however it was observed that inclusion of any type of interaction is beneficial to RAO curves results. *Wasim* computations show better agreement regarding the shape of curves, and in some cases *CatCenteno* also show good fitting curves. *Fonseca* computations, without interaction and with post-processing to compute roll motion of twin-hulls, show well behaved curves but always with bigger values along the frequency domain.

4.3 Root Mean Square Error

Using performance metric RMSE (Root Mean Square Error), a general overview of the computational results is achieved. In Table 4 the averaged results of all the computations is showed, such values are for heave, pitch and roll and next to them the standard deviation. These results show that for heave motions the closer to the experimented results are obtained using *Wasim*. For pitch motions two software have equal error value, *Fonseca+ET* and *CatCenteno+visco*. For roll computations *Wasim* has the lowest value.

$$e_j = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - H_i)^2} \tag{4}$$

Table 4-Averaged motions RMSE.

RMSE	$\overline{e_3}$	σ_3	$\overline{e_5}$	σ_5	$\overline{e_4}$	σ_4
Fonseca	0.25	0.20	0.25	0.16	0.37	0.36
Fonseca+ET	0.25	0.19	0.21	0.09	0.29	0.24
CatCenteno	0.43	0.29	0.28	0.14	0.18	0.10
CatCenteno+ visco	0.26	0.15	0.21	0.08	0.17	0.07
Wasim	0.23	0.15	0.24	0.17	0.15	0.09

Considering the Froude number at which the catamarans are tested and the hull spacing, which combined represent the interaction level between the demi-hulls. Using Equation 3, $Int.$ coefficient is calculated at the natural heave frequency for each tested condition. Comparing this with RMSE values it is found that using the three-dimensional method, *Wasim*, results in a wide interval of interaction coefficients, ranging from $Int. = 0$ until $Int. = 0.83$. Considering the correspondent Froude numbers these results show the same wide range, with $Fn = 0.2$ until $Fn = 0.8$. These values show that computations using Wasim are the most reliable ones for any condition. Other interaction schemes using Strip Theory methods can also result in lower RMSE values too. It is shown that *CatCenteno* accounting for viscous effects gives low RMSE values for high Froude numbers, $Fn > 0.6$. Regarding the interaction coefficients these range from $Int. = 0.2$ until $Int. 0.72$. Indicating reduction of errors when accounting for viscous effects giving a relatively high range of interaction at which the results are acceptable. Good results using this method do not include hull spacing value of $S/L = 4$. Some cases using two-dimensional approach without cross-flow method had low RMSE, with $Int. = 0.72$ until $Int. = 0.81$, however they are only three and at very low Froude number, $Fn = 0.2$. For the case of no-interaction, using *Fonseca*, low RMSE values can be found when including end-terms, such cases are for relatively high Froude numbers, from $Fn = 0.53$ till $Fn = 0.8$. In combination with big hull spacings the interaction coefficient ranges from $Int. = 0$ until $Int. = 0.56$. This means that the computations from simple strip theory can perform well when considering catamarans at high speed. If end-terms are not included acceptable results can be found too, however the range of Froude number becomes lower, with $Fn = 0.2$ until $Fn = 0.6$. These low speeds indicate that even when interaction is relatively high, single hull strip theory well implemented, can give good results.

5 STUDY ON MODEL ERRORS

With significant experimental data collected and compared with computations, further post-processing of transfer functions is done using uncertainty models. To do so, two levels of model errors are used with differentiation on the frequency dependency.

5.1 Frequency independent error

In (Guedes Soares 1991) several types for the uncertainty models are introduced; unbiased, constant, linear and quadratic. It follows that differences between numerical results and experimental data are obtained for each computed frequency. These differences can represent a systematic error or the model error of the method. The knowledge of these models can improve the obtained results by compensating them. Being so the model can be considered a function $\phi(\omega)$ that when multiplied by the method result $H(\omega)$ gives the improved result. It is still important to consider the experimental error, which should have an average deviation tending to zero due its unpredictable nature, $\epsilon(\omega)$.

$$\hat{H}(\omega) = \phi(\omega) \cdot H(\omega) + \epsilon(\omega) \tag{5}$$

For the model error ϕ a polynomial function can be defined, considering different degrees results in better fitting of the model error in the frequency domain.

For the simpler case of frequency independent model error, this function is constant that can be defined by finding the minimum of the square error when applying the model error.

$$Q = \sum_i (X_i - aH_i)^2 = \sum_i \epsilon^2 \tag{6}$$

$$\hat{a} = \frac{\sum_i X_i H_i}{\sum_i H_i^2} \tag{7}$$

Averaged results for the constant model error are showed in Table 5. In this general view of results, the method that needs less linear correction is *CatCenteno* when including viscous effects, with values closer to one for a random variable. The general view also gives the idea that pitch motion is less constant in results, for all the methods. The standard deviation of frequency independent model errors is relatively higher than for the heave motion. And for roll motion the same high standard deviation values are found when using higher order of interaction schemes, however keeping an average of satisfactory result. The conclusion is that when including interaction in roll motion results do not need a correction but are very inconstant, possibly due to test conditions.

Table 5-Averaged values for FIME.

FIME	$\overline{a_3}$	σ_3	$\overline{a_5}$	σ_5	$\overline{a_4}$	σ_4
Fonseca	0.95	0.13	0.88	0.21	0.55	0.17
Fonseca+ET	1.03	0.14	1.09	0.24	0.62	0.17
CatCenteno	0.81	0.16	0.89	0.21	0.82	0.21
CatCenteno+ visco	0.97	0.15	1.00	0.20	1.00	0.54
Wasim	0.91	0.13	0.86	0.16	1.12	0.39

5.2 Frequency dependent model error

The following formulation is based on Model Correction Factor (MCF) methods, which considers the influence of deviation between ideal or calculated and realistic results of any model reflecting that real situation. In this case it is considered catamaran motions the real situation, with experiments as realistic results and motions computations as the calculated values that try to predict the complexity of the real problem, (Ang, Tang e others 2007).

$$MCF(\omega_i) = \frac{X_i}{H_i}(\omega_i) \qquad (8)$$

When applying the MCF to all the computations the result is a relatively dense cloud of data, in order to separate results a differentiation is created using influence variables of motions transfer functions.

5.2.1 *Linear correlation study*

In this case the objective is to quantify the possible linearity between multiple variables and the control variable RMSE of the motions results. The methods used in motions computations are separated and five variables are chosen; β heading angle, Fn Froude number, C_B block coefficient, C_{wl} water line coefficient and S/L demi-hull spacing. The values inside Tables 6, 7 and 8, show the dependency of RMSE results and the variables, were the values above 0.50 are highlighted. This represents the closer to linear correlations that are found.

Table 6-Linear correlation coefficients for heave.

$\mathbf{CC_3}$	**β**	**Fn**	$\mathbf{C_B}$	$\mathbf{C_{wl}}$	**S/L**
Fonseca	0.34	0.59	-0.31	-0.28	-0.17
Fonseca+ET	0.34	0.53	-0.33	-0.32	-0.20
CatCenteno	0.21	0.75	-0.37	-0.28	0.07
CatCenteno+visco	0.27	0.61	-0.31	-0.26	0.27
Wasim	0.09	0.64	-0.22	-0.13	0.14

Table 7-Linear correlation coefficients for pitch.

$\mathbf{CC_5}$	**β**	**Fn**	$\mathbf{C_B}$	$\mathbf{C_{wl}}$	**S/L**
Fonseca	0.35	0.76	-0.20	-0.14	-0.02
Fonseca+ET	0.30	0.57	-0.51	-0.56	0.06
CatCenteno	0.16	0.71	-0.27	-0.15	0.09
CatCenteno+visco	0.24	0.51	-0.34	-0.24	0.21
Wasim	0.14	0.57	-0.13	0.00	0.03

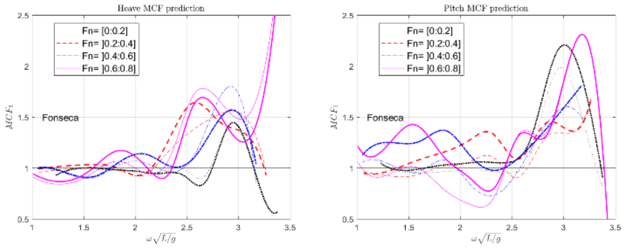
Table 8-Linear correlation coefficients for roll.

$\mathbf{CC_4}$	**β**	**Fn**	$\mathbf{C_B}$	$\mathbf{C_{wl}}$	**S/L**
Fonseca	-0.59	-0.04	0.14	0.64	-0.33
Fonseca+ET	-0.53	-0.06	0.09	0.61	-0.28
CatCenteno	-0.04	0.45	-0.21	0.20	0.09
CatCenteno+visco	0.50	0.53	-0.42	-0.28	0.42
Wasim	-0.12	-0.04	-0.09	0.33	-0.05

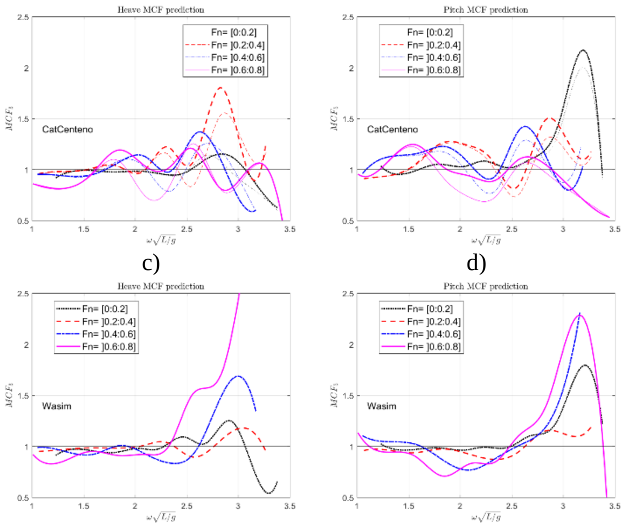
For heave and pitch motions it is predictable that possible correlation between results and Froude number could exist for all methods. This is very reasonable due to the importance of such variable in the different formulations. Strong influence of the block coefficient and the waterline coefficient in pitch motion can be found too, in the results of strip theory when included the end-terms. This is due to the prevailing hydrostatic forces, characteristic of the method. However, since it is not found on the rest of methods this coefficient will not be studied.

5.2.2 *Average model correction factor*

Due to the correlation study, data can be treated by differentiating the MCF in terms of Froude number. This is done by creating 4 intervals of Froude numbers regarding the experimental data available. With the data that is included in each Froude number interval the average of MCF within a frequency interval is calculated and the resulting value plotted. Because of the end-terms at post-processing of *Fonseca* results and inclusion of viscous effects by the cross-flow at *CatCenteno*, thin and thick curves are in the figures. The thick lines are the improved methods and the thin lines base methods. Because *Wasim* does not include such post-processing calculations it is only showed thick lines. In all the figures there is a horizontal line at 1 which helps to indicate if the computations are under or over-predicted.



a) b)



c) d)

e) f)

Figure 3-MCF prediction for heave and pitch motions, a)&b) *Fonseca*; b)&c) *CatCenteno*; e)&f) *Wasim*; left: Heave, right: Pitch.

The no-interaction results can be found in Figure 4 a) & b), using *Fonseca* software. Generally under-predicted results since the values are present largely above horizontal line. For higher speeds worst results are obtained at high frequency and with more oscillations along the frequency domain.

Model correction factor values for the case of computations using *CatCenteno* are showed in Figure 4 b) & c). The results when including a two-dimensional interaction scheme show different characteristics regarding the resonance peaks, and the general behaviour of the curve is more inconstant. The over-prediction is found near the resonance peaks and the inclusion of cross-flow brings these values closer to one.

The last set of figures, e) and f), refers to the computations of averaged MCF for *Wasim* results. The overall results are better having values closer to 1, at the relevant frequency domain. The figure shows a slightly over-prediction of heave motion at all Froude numbers. The high speed combined with high frequencies gives very high values of MCF and it is considered to be the same situation of close to zero response values. In this case the location of resonance frequencies is not well observed for heave results, but only for pitch where it is represented by lower values of the curves. This values show bigger over-predictions with the increase of speed and become wider, ranging a bigger interval of frequencies.

The sequence of results show that there is improvement on MCF when accounting for interaction. In general, heave predictions come with MCF values closer to one and with results that can indicate the discrepancies at resonance frequencies. As for pitch the values show that this motion is not so well predicted, for the strip theories it comes under-predicted and for panel method used over-predicted. Inclusion of end-terms in *Fonseca* do not necessary bring better results, especially due to the lack of interaction of the method, while viscous effects in *CatCenteno* do bring some improvement in results but only for the very high Froude numbers, however location of resonance frequencies is not so easy to observe due to wider ranges in frequency. The figures have also showed the correlation result between the tested values, RMSE and the ship's speed. This difference is observed by the amplitude and peaks locations of MCF curves, representing the resonance frequencies and differences in motions amplitudes.

6 RESULTS CONCLUSIONS

Heave motion results are better predicted than pitch motions for catamarans. Resonance frequencies are generally well predicted by the three methods however it appears to exist a limit when strip theory based codes fail to give the same type of curve at resonance peak, $Fn > 0.6$. The experimented peaks are wider than the predictions of strip theory codes, while *Wasim* show resulting curves in better agreement.

Pitch motions in catamarans are not so well predicted for the general cases, *Wasim* has the best curve fit and interestingly *Fonseca* without interaction shows reasonable curves but the resonance frequencies are not well predicted being slightly shifted to the experimented ones. Presence of secondary humps in the responses also indicate the existence of non-linearities in this mode of motion.

Roll motions are less in number of computations, however it was observed that inclusion of any type of interaction is beneficial to RAO curves results. *Wasim* computations show better agreement regarding the shape of curves, and in some cases *CatCenteno* also show good fitting curves. *Fonseca* computations, without interaction and with post-processing to compute roll motion of twin-hulls, show well behaved curves but always with bigger values along the frequency domain.

With the previous observations and interaction intervals together with the average RMSE computed, it is concluded that the best method to apply in catamaran motions studies is *Wasim*. However, *Fonseca* including end-terms can perform good for longitudinal motions, with some discrepancies in the location of resonance frequencies.

Other important observation is the failure to find a linear correlation of FIME results and the variables defined in the chapter. However, when changing the control variable to RMSE an acceptable degree of correlation with Froude number is found. For roll motion this was not found, limiting the motion error study. Because of this it can be concluded that application of a constant model error, which is not frequency dependent is not sufficient for the case of catamaran motion computations.

With FDME result the tendency of results follows the previous observations, showing better predictions using *Wasim.* However, it is also shown relevance of Froude number, since frequencies at which errors are more significant are close to natural encounter frequencies.

The results using no-interaction methods for catamaran motions can perform well when comparing a generic metric like RMSE. However, the lack of some degree of interaction gives errors at resonance frequencies. *CatCenteno* only gives good results when including with cross-flow. Such empiric method could be applied to higher level of interactions and therefore improving their results. Which is possible in *Wasim* by increasing the critical damping.

7 REFERENCES

Ang, Alfredo Hua Sing, Wilson H. Tang, and others. 2007. *Probability concepts in engineering: emphasis on applications in civil & environmental engineering.* Vol. 1. Wiley New York.

Bertram, Volker. 2012. *Practical ship hydrodynamics.* Elsevier.

Bunnik, T., Daalen Van, G. Kapsenberg, Y. Shin, R. Huijsmans, G. B. Deng, G. Delhommeau, M. Kashiwagi, and B. Beck. 2010. "A comparative study on state-of-the-art prediction tools for seakeeping." *28th ONR Symposium on Naval hydrodynamics.*

Castiglione, Teresa, Frederick Stern, Sergio Bova, and Manivannan Kandasamy. 2011. "Numerical investigation of the seakeeping behavior of a catamaran advancing in regular head waves." *Ocean Engineering* (Elsevier) 38: 1806-1822.

Centeno, R., N. Fonseca, and C. Guedes Soares. 2000. "Prediction of motions of catamarans accounting for viscous effects." *International shipbuilding progress* 47: 303-323.

Chan, H. S. 1993. "Prediction of motion and wave loads of twin-hull ships." *Marine structures* (Elsevier) 6: 75-102.

Dhavalikar, Sharad S. 2011. "Comparative Study of Seakeeping Analysis Results From Various Methods." *ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering.* 217-223.

Faltinsen, O., and Rui Zhao. 1991. "Numerical predictions of ship motions at high forward speed." *Phil. Trans. R. Soc. Lond. A* (The Royal Society) 334: 241-252.

Faltinsen, Odd Magnus. 2005. *Hydrodynamics of high-speed marine vehicles.* Vol. 474. Cambridge university press Cambridge.

Fang, Chih Chung, and Hoi Sang Chan. 2004. "Investigation of seakeeping characteristics of high-speed catamarans in waves." *Journal of Marine Science and Technology* 12: 7-15.

Fang, Chih-Chung, H. S. Chan, and A. Incecik. 1996. "Investigation of motions of catamarans in regular waves-I." *Ocean engineering* (Elsevier) 23: 89-105.

Fonseca, N., and C. Guedes Soares. 1998. "Time-domain analysis of large-amplitude vertical ship motions and wave loads." *Journal of Ship Research* (SNAME SOCIETY OF NAVAL ARCHITECTS AND MARINE) 42: 139-152.

Frank, Werner. 1967. "Oscillation of cylinders in or bellow the free surface of deep fluids." Tech. rep., Naval Ship Research and Development Center, Washington D. C.

Guedes Soares, C. 1991. "Effect of transfer function uncertainty on short-term ship responses." *Ocean Engineering* (Elsevier) 18: 329-362.

Guedes Soares, C., N. Fonseca, P. Santos, and A. Maron. 1999. "Model tests of the motions of a catamaran hull in waves." *Proceedings of the International Conference on*

Hydrodynamics of High-Speed Craft, Royal Institution of Naval Architects, London.

Hermundstad, Ole Andreas. 1995. “Theoretical and experimental hydroelastic analysis of high speed vessels.” Ph.D. dissertation, The Norwegian Institute of Technology.

Hudson, D. A., W. G. Price, and P. Temerel. 1995. “Seakeeping performance of high speed displacement craft.” *FAST'95: 3rd Int. Conf. on Fast Sea Transportation.*

Journee, J. M. J., and L. J. M. Adegeest. 2003. “Theoretical manual of strip theory program "SEAWAY for Windows".” *TU Delft Report* 1370.

Kring, David Charles. 1994. “Time domain ship motions by a three-dimensional Rankine panel method.” Ph.D. dissertation, Massachusetts Institute of Technology.

Lee, C. M., H. D. Jones, and R. M. Curphey. 1973. “Prediction of motion and hydrodynamic loads of catamarans.” *Marine Technology* 10: 392-405.

Lee, Choung M., and Richard M. Curphey. 1977. “Prediction of motion, stability and wave load of Small-Waterplane-Area-Twin-Hull ships.” *Transactions Society Naval Architects Marine Engineers* 85: 94-130.

Nestegard, Arne, Vigleik Hansen, Olav Rognebakke, and Bo Cerup-Simonsen. 2008. “Achievements in Applications of Marine Hydrodynamics.” *ASME 2008 27th International Conference on Offshore Mechanics and Arctic Engineering.* 319-326.

Ohkusu, Makoto. 1970. “On the motion of multihull ships in waves (I).” *Report of Research Institute of Applied Mechanics, Kyushu University* 18.

Ohkusu, Makoto, and Mikio Takaki. 1971. “On the motion of multihull ships in waves (II).” *Report of Research Institute of Applied Mechanics, Kyushu University* 19.

Salvesen, N., E. O. Tuck, and O. Faltinsen. 1970. “Ship motions and sea loads.” *Transactions Society Naval Architects Marine Engineers* 78: 250-287.

Söding, Heinrich, T. U. Hamburg, Volker Bertram, and Germanischer Lloyd. 2009. “A 3-D Rankine source seakeeping method.” *Ship Technology Research* (Taylor & Francis) 56: 50-68.

Temarel, Pandeli, Wei Bai, Anne Bruns, Q. Derbanne, D. Dessi, S. Dhavalikar, N. Fonseca, et al. 2016. “Prediction of wave-induced loads on ships: Progress and challenges.” *Ocean Engineering* (Elsevier) 119: 274-308.

Van't Veer, Adriaan Pieter. 1998. “Behaviour of catamarans in waves.” Ph.D. dissertation, TU Delft, Delft University of Technology.

Van't Veer, Riaan. 1998. “Experimental results of motions and structural loads on the 372 catamaran model in head and oblique waves.” *TU Delft report.*

Van't Veer, Riaan. 1998. “Experimental results of motions, hydrodynamic coefficients and wave loads on the 372 catamaran model.” *TU Delft report.*

Varyani, Kamlesh S., Rama M. Gatiganti, and Miroslaw Gerigk. 2000. “Motions and slamming impact on catamaran.” *Ocean engineering* (Elsevier) 27: 729-747.

Veer, A. P., and F. R. Siregar. 1995. “The interaction effects on a catamaran traveling with forward speed in waves.” *FAST'95: 3rd Int. Conf. on Fast Sea Transportation* (Delft University of Technology, Faculty of Mechanical Engineering and Marine Technology, Ship Hydromechanics Laboratory).

Veritas, Det Norske. 2011. “Sesam user manual WASIM: wave loads on vessels with forward speed.” version: 5.1-01.

Watanabe, I., and C. Guedes Soares. 1999. “Comparative study on the time-domain analysis of non-linear ship motions and loads.” *Marine structures* (Elsevier) 12: 153-170.

Wellicome, J. F., P. Temarel, A. F. Molland, and P. R. Couser. 1995. “Experimental measurements of the seakeeping characteristics of fast displacement catamarans in long-crested head-seas.” Tech. rep., University of Southampton.