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PREDICTION OF PARAMETRIC ROLLING FOR A CONTAINER SHIP IN REGULAR AND IRREGULAR WAVES USING A FULLY NONLINEAR TIME DOMAIN POTENTIAL FLOW METHOD

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Abstract. In this paper numerical simulations of parametric rolling have been performed. SAFEDOR, an EU funded benchmark study on the capability of different methods to predict such motion, was replicated here, in order to assess the quality of SHIPFLOW MOTIONS for the evaluation of this phenomenon. The code is a fully nonlinear 3D unsteady potential flow method. Since viscosity is not implicitly accounted for by a potential flow method, two different techniques are used here to introduce viscous damping coefficients in the roll motion equation. The results obtained with this method are aligned with the results from the best performing methods analyzed in the benchmark, showing a satisfactory match with experimental results.

1 Introduction

Although studies on parametric roll have been carried out since the middle of the last century, they have mainly been focusing on fishing vessels and small coastal cargo carriers in following seas. After an accident in the late nineties where a large container ship suffered significant cargo loss and structural damaged while sailing in head sea, see [1], parametric rolling has increased the attention of researchers and international authorities. In fact, even relatively small amplitude waves can trigger this phenomenon which can lead to severe roll amplitudes.

Parametric roll is induced by a periodic change in the transverse stability. This change is due to large variations of the water plane area in head and following seas and can be significant for ships with bow flare and overhanging stern. In the last twenty years, especially concerning container ships and ferries, which can be characterized by these kinds of stern and bow features, parametric roll has become an important aspect considered thoroughly in the design phase. Numerical methods that allow for a correct prediction of parametric roll have become important tools.

In this paper, the 3-D fully nonlinear time domain potential flow method SHIPFLOW MOTIONS has been used as a basis for the study. The method has shown to give accurate predictions of ship motions in head sea, see for instance [2]. Its capability is extended and has been used here to simulate parametric roll in head and following waves. The method employs the fully nonlinear boundary conditions on the body and free surface, as well as fully coupled rigid body motions. The evolution in time is performed with fourth-order Adam-Bashforth-Moulton method. The forces acting on the ship are obtained by integrating the fluid pressure on the instantaneous wetted surface. Since roll motion is usually heavily influenced by viscosity and roll damping has a primary role in the phenomena of parametric rolling, damping coefficients are added in the roll motion equation. There are various techniques available to predict these coefficients, see for example [3]. For this paper, two formulations have been followed. One proposed by Watanabe and Inoue, presented in [3], has been used to estimate roll damping starting from geometrical and inertial characteristics and a parameter identification technique to obtain these coefficients from roll-decay model tests has been applied to a partial set of simulations, where model tests were available.

The numerical simulations presented here reproduce a benchmark study (SAFEDOR, see [4]) for a container ship, where solutions from different numerical methods were compared with model test results. Semi-captive tests were carried out in head and following seas, for monochromatic and three-component regular waves as well as for irregular waves. The benchmark study had two objectives: the first was to assess the capability of the different codes to simulate the resonance occurrence of parametric roll and the second was to evaluate the quality of the predictions in terms amplitude of the roll motion.

2 Mathematical Model and Numerical Approach

The method used in this study is based on potential flow theory. This means that the fluid is assumed to be homogeneous, inviscid, incompressible and irrotational. Under this hypothesis there exists a scalar quantity referred to as velocity potential ϕ, representing the velocity field of the fluid and which satisfies Laplace's equation:

$$\nabla^2 \phi = 0 \tag{1}$$

On the free surface, the fully nonlinear kinematic and dynamic boundary conditions are applied:

$$\frac{D\mathbf{x}}{Dt} = \nabla\phi \tag{2}$$

where $\mathbf{x} = (x, y, z)$ is the position of a fluid particle on the free surface and

$$\frac{D\phi}{Dt} = -gz + \frac{1}{2}\nabla\phi \cdot \nabla\phi - \frac{p_a}{\rho} \tag{3}$$

where g is the gravitational acceleration, p_a is the atmospheric pressure and ρ is the fluid density. The material derivative is defined as

$$\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + \nabla\phi \cdot \nabla \tag{4}$$

On the rigid body surface a Neumann type impermeability condition is given, taking into account body motion:

$$\frac{\partial\phi}{\partial n} = \mathbf{n} \cdot (\mathbf{u} + \boldsymbol{\omega} \times \mathbf{r}) \tag{5}$$

where $\mathbf{u}$ and $\boldsymbol{\omega}$ are the translational and angular velocities, $\mathbf{r}$ is the position of the point where the condition is applied with respect to the center of rotation and $\mathbf{n}$ is the unit normal vector pointing into the fluid domain. A Neumann type impermeability condition is applied also on the bottom surface of the domain:

$$\frac{\partial\phi}{\partial n} = 0 \tag{6}$$

The boundary value problem, defined by Equation (1) and by the boundary conditions, Equations (2), (3), (5) and (6), is solved by means of a boundary element method, placing constant strength sources on quadrilateral panels both on the hull and free surface, see [5]. The evolution of the free surface is obtained through a *Mixed Euler-Lagrangian* (MEL) method, as described in [6]. The time stepping is performed with a fourth order Adam-Bashforth-Moulton method.

On the boundaries of the numerical domain a blending zone is introduced. The purpose of this zone is twofold: it dampens out the perturbed solution obtained in the inner part of the domain with respect to the undisturbed solution of the outer part, where the velocity potential is known *a priori*, while at the same time functions as a wave generator.

Once the solution of the boundary value problem is obtained at each time step, *i.e.* the velocity potential is evaluated on all the panels and the fluid velocity on the hull is known. Knowing the velocity potential and the fluid velocity, is possible to obtain compute the pressure using the unsteady Bernoulli equation. Integrating the pressure on the instantaneous wetted surface, forces and moments acting on the hull are known and it is thus possible to solve ship motions equations. Considering the uncoupled equations for sake of simplicity, even though they are included in the method, we have:

$$m\ddot{\mathbf{x}} = \mathbf{F} = -\iint_{S_b} p\mathbf{n}\, dS \tag{7}$$

$$I\ddot{\boldsymbol{\gamma}} = \mathbf{M} = -\iint_{S_b} p\big(\mathbf{r} \times \mathbf{n}\big)\, dS \tag{8}$$

being $\ddot{\mathbf{x}}$ the acceleration of the center of gravity along the axis, $\ddot{\boldsymbol{\gamma}}$ the angular accelerations and $\mathbf{n}$ the normals to each panel on the hull.

Since the method is based on the hypothesis of potential flow, viscosity is not included in the calculations. The error introduced by such approximation can usually be neglected for motions such as heave and pitch. On the other hand, roll motion is generally heavily influenced by viscous effects. The term that is more affected by viscosity in the roll motion equation is the damping term. It is therefore necessary to account for viscosity in some way. The most common way to account for such effects is through damping coefficients, $B(\dot{\varphi})$, that are included in the roll motion equation. If we consider the equation for *One Degree of Freedom* (1DOF), without the coupling terms with other motions, we have:

$$I_{xx}\ddot{\varphi} = -\iint_{S_b} p\big(\mathbf{r} \times \mathbf{n}\big) \cdot \mathbf{i}\, dS - B(\dot{\varphi}) \tag{9}$$

It is possible to find in literature many ways to express the damping model, see for instance [7]; the most common are:

$$B(\dot{\varphi}) = B_l\dot{\varphi} + B_q|\dot{\varphi}|\dot{\varphi} + B_c\dot{\varphi}^3 \tag{10}$$

$$B(\dot{\varphi}) = B_l\dot{\varphi} + B_q|\dot{\varphi}|\dot{\varphi} \tag{11}$$

$$B(\dot{\varphi}) = B_l\dot{\varphi} + B_c\dot{\varphi}^3 \tag{12}$$

and the choice of one model instead of another can be justified by different considerations on the physics and mathematical details. In order to perform the simulations, it is necessary to evaluate such coefficients, once that a model is chosen. In the present paper, two methodologies, each one based on different models from the above, are used to evaluate damping coefficients. The first one follows a different form of Equation (11), where only the quadratic term is considered. It is based on regression analysis and was proposed by Watanabe and Inoue (W-I), see [3]. This method uses geometrical and inertial characteristics of a ship to estimate the quadratic term B_q:

$$B_q = h[1.42\frac{C_B T}{L} + 0.01]f(Fn, \Lambda) \tag{13}$$

where h is a function that depends on the forms and mass distribution of the ship, Fn is the Froude number and Λ is the tuning ratio, between the encounter frequency of the incoming waves and the natural roll frequency. The other method used here, a *Parameter Identification Technique* (PIT), to obtain damping coefficients analyzes model test results, using either time series of roll decay or frequency domain curve of beam sea. Given some input values φ, the equation of motion, written as a sum of components, is numerically solved. Damping and restoring coefficients in this equation are systematically varied to minimize the square error:

$$\chi^2(\mathbf{p}) = \sum_{i=1}^{N_{data}} \big(\varphi(i) - \hat{\varphi}(i, \mathbf{p})\big)^2 \tag{14}$$

In this way it is possible to find the best set of parameters $\mathbf{p}$ that gives the best fit between the input values φ and the numerically evaluated values $\hat{\varphi}(\mathbf{p})$. It is possible to chose the damping model from Equations (10), (11) or (12) which best suits the specific need. Here, a linear plus cubic model was chosen, as the one of Equation (12). For a deeper insight of this method, see [8]. Since the PIT evaluates the damping coefficients starting from model test results, and thus these values are tailored for each ship, we can expect a better evaluation of such terms, compared with the more generic one proposed by Watanabe and Inoue.

3 Numerical Simulations

Numerical simulations have been performed here to replicate the EU funded project SAFEDOR, an international benchmark study aimed to assess the performance of different numerical codes for the prediction of parametric roll. The ship tested is a container ship and model experiments were carried out in two different model basins. In order to have a better control over the parameters that characterize and affect parametric roll, semi-captive tests were performed. This makes it easier to benchmark numerical simulations against experimental tests since uncertainties and bias are reduced. The whole set of tested cases is given in Table 1, where H and T are wave height and period. Ship properties are given in Table 2. Note that cases 1 and 12 are roll decay tests and irregular waves are obtained with a JONSWAP spectrum with an overshoot parameter $\gamma = 3.3$.

In order to properly replicate the benchmark study, the same input information was used. The only inputs given were the test matrix of Table 1 and the roll decay time series. In the same way as almost half the participants did during the study, the time series of roll decay were used to tune the roll inertial properties. Unfortunately, for this paper only the time series of roll decay from the first half of tests were available, *i.e.* only the case with $GM = 1.38\,m$. Since the roll radius of inertia in the benchmark report is the same between the two sets of simulations, the error expected from this lack of information is negligible. On the other hand, the PIT uses model test results to obtain the damping coefficients: the coefficients are tuned on the roll decay curve and then used to simulate the parametric roll cases. This means that damping coefficients have been evaluated with the Watanabe-Inoue formulation for both sets, while with the PIT for the first set only.

Table 1: Experimental tests

Test	GM	Heading	Fn	H_1	T_1	H_2	T_2	H_3	T_3	Description
01	1.38	-	0.00	-	-	-	-	-	-	Roll Decay
02	1.38	180°	0.08	3.6	10.63	-	-	-	-	1 Harmonic
03	1.38	180°	0.08	5.7	10.63	-	-	-	-	1 Harmonic
04	1.38	180°	0.12	3.6	10.63	-	-	-	-	1 Harmonic
05	1.38	180°	0.12	5.7	10.63	-	-	-	-	1 Harmonic
06	1.38	180°	0.12	2.4	10.63	2.4	9.66	2.4	11.55	3 Harmonics
07	1.38	180°	0.12	4.0	10.63	1.0	9.66	1.0	11.55	3 Harmonics
08	1.38	180°	0.12	5.0	10.63	-	-	-	-	Irregular
09	1.38	160°	0.12	3.6	10.63	-	-	-	-	1 Harmonic
10	1.38	160°	0.12	5.7	10.63	-	-	-	-	1 Harmonic
11	1.38	160°	0.12	4.0	10.63	1.0	9.66	1.0	11.55	3 Harmonics
12	1.00	-	0.00	-	-	-	-	-	-	Roll Decay
13	1.00	0°	0.08	3.6	8.00	-	-	-	-	1 Harmonic
14	1.00	0°	0.08	6.0	8.00	-	-	-	-	1 Harmonic
15	1.00	0°	0.04	3.6	8.00	-	-	-	-	1 Harmonic
16	1.00	0°	0.04	6.0	8.00	-	-	-	-	1 Harmonic
17	1.00	0°	0.04	2.4	8.00	2.4	7.11	2.4	8.89	3 Harmonics
18	1.00	0°	0.08	2.4	8.00	2.4	7.11	2.4	8.89	3 Harmonics
19	1.00	0°	0.08	5.0	8.00	-	-	-	-	Irregular
20	1.00	180°	0.08	5.0	12.12	-	-	-	-	1 Harmonic
21	1.00	180°	0.12	5.0	12.12	-	-	-	-	1 Harmonic
22	1.00	180°	0.08	4.0	12.12	1.0	10.77	1.0	13.47	3 Harmonics

Table 2: Ship Particulars

L_{pp}	$150.0\,m$
B	$27.2\,m$
T	$8.5\,m$
C_b	0.667
C_p	0.678
GM tests $1 \div 11$	$1.38\,m$
GM tests $12 \div 22$	$1.00\,m$
k_{xx}	$9.96\,m$

Given the wide range covered by the test matrix, different type of responses were expected, as shown in [4]. Since the aim of the study presented here was to compare the current method with the methods evaluated in the benchmark, the same way to analyze the results was followed. In the case of a reached steady state, the mean value of roll amplitude for the stationary response had been taken. This is typically the case for one harmonic waves. When the simulations were performed for group waves, a sort of stationary responses were obtained but without steady state. Finally, for the irregular waves, the responses were chaotic. In the two latter cases, the amplitudes of the whole simulation record were averaged, excluding the transient part where the motion was not fully developed. Comparing the values of roll amplitude obtained in this way with model test results, it is possible to compare the quality of the predicted amplitude. To have some terms of comparison, the standard deviation σ and the correlation coefficient r were used in the benchmark study. Being x_i the mean amplitude of the $i-th$ case, $\overline{x}_i$ the corresponding amplitude of the model test and $\widehat{x}_i = x_i - \overline{x}_i$, standard deviation and correlation coefficient are evaluated with:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(\widehat{x}_i - \widehat{x}_m)^2}{n-1}} \tag{15}$$

$$r = \frac{cov(x, \overline{x})}{\sigma_x \sigma_{\overline{x}}} \tag{16}$$

where $\widehat{x}_m$ is the difference between the mean value of the amplitudes of numerical results and model tests. Standard deviation and correlation coefficient were evaluated for each method, allowing to rank them and to find the best performing ones. The main aim of the study, however, was to verify whether or not the different methods were able to predict the occurrence of parametric rolling, regardless of the value of the amplitude simulated. In order to evaluate the successful detection of parametric rolling, a critical roll amplitude was introduced in the study. An event is marked as successful when numerical and model test results coincide with respect of the critical roll amplitude. Choosing a critical roll amplitude equal to $x_{cr} = 0.5°, 1.0°, 1.5°, 2.0°$, a success rate was evaluated for each method and for each critical value:

$$P = \frac{1}{n}\sum_{i=1}^{n} q_i \tag{17}$$

where:

$$q_i = \begin{cases} 1 & \text{if}\,(x_i - x_{cr})(\overline{x}_i - x_{cr}) \geq 0 \\ 0 & \text{if}\,(x_i - x_{cr})(\overline{x}_i - x_{cr}) < 0 \end{cases} \tag{18}$$

Once the success rate was evaluated for each critical value, the mean was taken to define the best performing methods. For a deeper insight on the ranking of the methods and on data processing, see [4].

4 Numerical Results

In this section numerical results are presented. Before running the tests for the evaluation of parametric rolling, roll decay tests were simulated. Time series of roll decay can be seen in Figure 1. Both approaches to obtain damping coefficients were used and compared. As can be noticed, since the PIT uses the model test results to get the damping coefficients, the simulations performed with such coefficients are more accurate. Nevertheless, there is a good agreement between model test and numerical simulations with both methods. Since model test for roll decay were also used to tune inertia properties of the ship, there is an almost perfect match between simulated and tested roll frequencies.

In Figures 2 and 3 the mean roll amplitudes, evaluated as described in the previous section, are shown. As said, for the set of tests with $\overline{GM} = 1.0\,m$ the computations were done using only the damping coefficients obtained with the Watanabe and Inoue formulation, since the roll decay test was not available and thus it was not possible to get the coefficients using the parameter identification technique. Since it is not easy to see a trend from these figures, standard deviation and correlation coefficient are used to assess the quality of the predicted amplitudes. In Table 3 it is possible to compare the correlation coefficient r and standard deviation σ obtained using the current method. These values are evaluated for each set of tests using both the techniques to get the damping coefficients and they can be compared with the values from the benchmark: both the mean values for the overall benchmark study and for the four best performing methods are shown. It is important to stress that the values obtained for the simulations where the PIT was used to evaluate the damping coefficients are referred only to first set of simulations. As can be seen, the method used here is aligned with the best performing methods in the benchmark study.

In Table 4 the success rate P is presented and compared with the overall and with the results of the best performing methods in order to assess the efficiency of the method when it comes to the prediction of the occurrence of parametric rolling. Values are shown for each critical roll amplitude and the mean of these values, P_m, is presented as well. In the table are also shown the values of P for the overall benchmark and for the four best performing methods, expressed only through the mean value since data for each point were not available. Again, the values obtained from the numerical simulations using the PIT to get the damping coefficients are referred only to the first set of tests. Results obtained with the current method are at the same level of the best performing methods from the benchmark.

5 Discussion

The current fully nonlinear potential flow method is used to replicate a benchmark study on parametric roll. In the benchmark study, the best performing methods both in terms of occurrence and amplitude prediction are identified. Numerical simulations presented here show a general good agreement with model test results. In terms of the

Table 3: Correlation coefficient and standard deviation.

	σ	r
PIT tests $2 \div 11$	4.64°	0.74
W-I tests $2 \div 11$	4.71°	0.74
W-I tests $13 \div 22$	6.63°	0.67
W-I tests $2 \div 22$	6.13°	0.62
Overall	10.5°	0.37
Best Performing	6.4°	0.64

Table 4: Success rate as a function of the critical rolling angle.

	$P\|_{x_{cr}=0.5°}$	$P\|_{x_{cr}=1.0°}$	$P\|_{x_{cr}1.5°}$	$P\|_{x_{cr}=2.0°}$	P_m
PIT tests $2 \div 11$	1.0	1.0	0.7	0.7	0.85
W-I tests $2 \div 11$	1.0	1.0	0.7	0.7	0.85
W-I tests $13 \div 22$	0.7	0.8	0.8	0.8	0.78
W-I tests $2 \div 22$	0.85	0.9	0.75	0.75	0.81
Overall	*na*	*na*	*na*	*na*	0.62
Best Performing	*na*	*na*	*na*	*na*	0.78

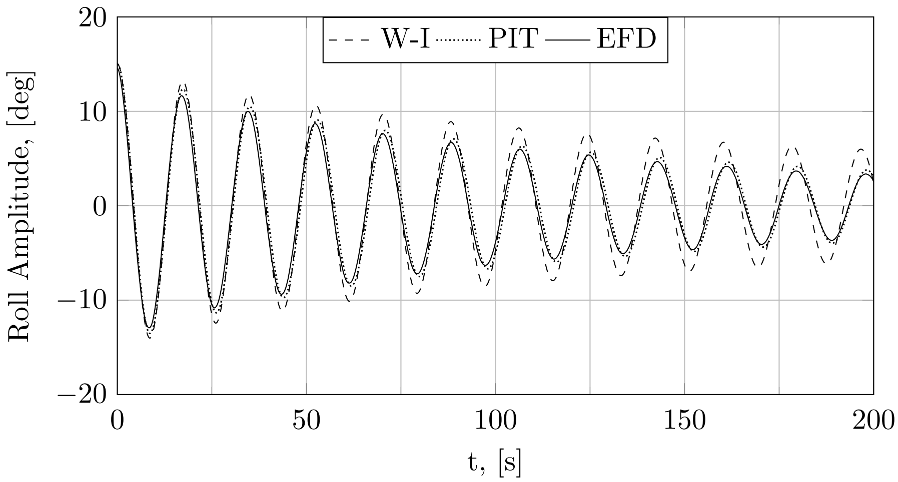

Figure 1: Roll decay for the case with $\overline{GM} = 1.38\,m$.

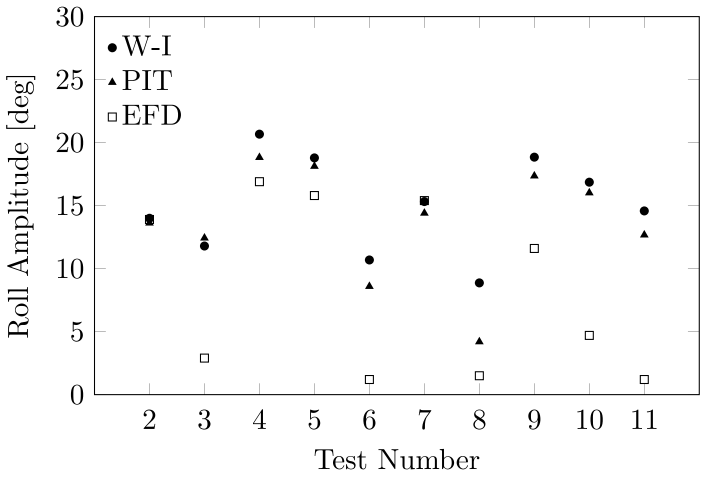

Figure 2: Mean roll amplitudes for set of tests with $\overline{GM} = 1.38\,m$.

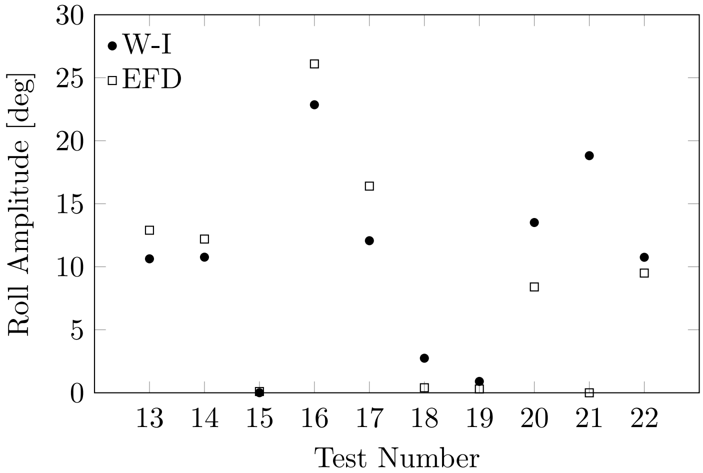

Figure 3: Mean roll amplitudes for set of tests with $\overline{GM} = 1.0\,m$.

ability of the method to replicate the resonance occurrence of parametric roll, results are aligned with the mean value of the best performing methods. The success rate represents the accuracy in the predictability of the phenomenon and the results presented show that we can expect a correct detection of parametric roll eight times out of ten. Furthermore, the difference between the two sets of simulations is rather small, suggesting that the accuracy of the prediction does not depend on loading condition and waves. Not only, results are similar in terms of predictability also between simulations performed with different damping coefficients. Regarding the quality of the amplitude of the simulated conditions, measured with standard deviation and correlation coefficient, results show a satisfactory match with model tests, being aligned again with the best performing methods. The difference between the values obtained using different methods for the evaluation of damping coefficients is small as well. The discrepancy between σ and r for the tests $2 \div 11$ and $13 \div 22$ is due to the big difference in amplitude in the test number 21, where no roll motion was experienced in the basin and the simulated condition has an amplitude around $\phi \cong 19°$. However, the ratio between encounter and natural roll frequencies is $\omega_e/\omega_\phi = 2.13$. One of the conditions that triggers parametric rolling is that such ratio has to be in the following range: $\omega_e/\omega_\phi \cong 2/n$ with n integer. It can be said then that this case lays on the edge of possible parametric rolling. From a design point of view though, the current method is on the safe side since it would show a possible danger situation when conditions are on the borderline.

To sum up, the current method employed in this paper has proved to be a reliable tool for the prediction of parametric roll and to be aligned with the best performing methods in the benchmark. It is worth mentioning that even with simple methods such as the one proposed by the Watanabe and Inoue for the evaluation of damping coefficients, good results are reached. Furthermore, for a correct prediction of this phenomenon, restoring force characteristics must be evaluated properly. Since forces are evaluated on the instantaneous wetted surface in the method used here with a fully nonlinear approach, a good prediction can generally be expected.

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