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FROM SURF-RIDING TO LOSS OF CONTROL AND CAPSIZE : A MODEL OF DYNAMIC BEHAVIOUR OF SHIPS IN FOLLOWING / QUARTERING SEAS

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ABSTRACT

Surf-riding is investigated in quartering waves with consideration of Froude Krylov and diffraction wave excitations. Detailed stability analysis is carried out for the obtained multi-degree of freedom dynamical system, with attention on clarifying the specific route leading from surf-riding to broaching. The findings constitute a step towards developing operational and design guidelines for minimising the risk of capsize in astern seas.

INTRODUCTION

According to the statistics of the Japanese *Maritime Safety Agency*, in the period between 1988 and 1992, 588 Japanese fishing vessel capsizes were reported, an appalling account considering the number of lives lost and the cumulative value of properties ruined, [1]. It has been known that when a vessel encounters from astern a relatively regular wave system with large amplitude, its stability is tested in three qualitatively different ways, [2]. Pure loss of stability on a wave crest, an essentially static mode, can arise, if simply the submerged part of the hull does not suffice to keep the vessel upright. Purely dynamic modes 'bearing' instability are equally possible ; low-cycle resonance, the parametric built-up of large roll which can be explained succinctly with "Mathieu's equation", and also, broaching-to. The broaching route remains the most intriguing, mainly because at its very essence lurks a combination of instabilities in different directions, requiring therefore detailed multi-degree of freedom models for explaining it. It is postulated that, in order to develop a sufficient description of a vessel's behaviour undergoing broaching, one should begin with the surge motion, so as to be able to realise the so-called *"state of surf-riding"*, a stationary condition thought of by many as a pre-cursor to broaching, according to which the vessel is forced to advance with speed equal to the wave celerity. Surge should be coupled to the other 'horizontal' motions, sway and yaw, so as to take into account the lateral stability of the vessel on the wave. Roll motion should also be included, not only because it represents the very direction of capsize, but also because it is important to know how the vessel's heeling affects stability in other directions.

There is a number of additional elements which should come supplementary to the above framework. Consideration of the effect of the rudder, mainly in generating yaw and drift and in several occasions undesirable roll, is indispensable. Influential is also the method of steering, which can range from no steering, to manual and to automatic, and so is the degree of variation of roll restoring according to the position on the wave. Last but not least, as the motions are of large amplitude, it is essential to include in the model the necessary non-linear terms and retain the couplings connecting motions in different directions.

A mathematical model applying the above concept has been developed, [3], [4] and it is used here for analysing the dynamic stability in waves of a purse seiner vessel. The specific form of the mathematical model is summarised in Appendix 1. Large-scale model testing has been undertaken since summer 1994, partially supported by the Japanese Shipbuilding Research Association, including free-running and constrained model tests in the new Marine Dynamics Basin of the National Research Institute of Fisheries Engineering of Japan, [5]. Experimentally derived hydrodynamic coefficients and wave forces have been made available. With this paper it is intended, first, to identify the states of surf-riding of this vessel at arbitrary heading and examine their stability. Then, to understand how these vary when one moves from a purely Froude-Krylov wave excitation to diffraction and then to the actual experimental wave force data. Finally, to search for mechanisms which can lead the vessel out of surf-riding and force it towards a turn possibly acompanied by capsize.

THE SOURCE OF INSTABILITY ; STATE-OF-THE-ART

As to the very cause of loss of steerability in waves, Japanese research in early eighties after examination of a number of alternative scenarios, concluded with the interpretation that, the vessel is statically overpowered by the excess of wave moment, which, at a threshold wave height and length can no longer be counterbalanced by the rudder, even when the latter is set at the position of maximum lift, [6]. Along this line of thinking, [7] provided a calculation method based on the identification of the eigenvectors corresponding to the (unstable) critical point of static balance of forces at 35 deg rudder. These could be used for assessing whether the initial condition of the vessel in relation to the unstable equilibrium would lead the vessel to broach or not. Recently, [3], [4], applying continuation methods it has been shown that the points of static equilibrium are connected in state space, and that they are associated with a variety of stability properties, sometimes allowing even more complex forms of behaviour, such as self-excited oscillations during surf-riding. These findings have motivated to look also for purely dynamical sources of instability, pointing at inception angles lower than those of maximum rudder lift.

ANALYSIS

Vessel details and calculation method

Table 1 : Vessel particulars

type	:	Purse seiner
L_{BP}	:	34.50 m
B	:	7.60 m
T_f	:	2.84
T_a	:	3.14
C_b	:	0.652
LCB	:	1.742 (aft)
GM	:	0.755 m
A_R	:	3.487 m^2

The details of the considered vessel are summarised in Table 1. The calculation of wave forces on the basis of the so-called Froude-Krylov assumption, seems to fall short in relation to the real wave force, mainly as regards the phase and magnitude of the yaw moment and sometimes also the magnitude of the sway force. The differences in magnitude can prove quite substantial, with a possibility of reaching a multiplier as high as *2.5*, while phase lags up to *20%* of the wave's length are not unusual, [8], [9]. In general, the actual wave yaw momment is leading the Froude-Krylov moment, the latter presenting its peaks at the wave crest or trough. Consideration of diffraction improves upon this situation, although the calculation still cannot be considered satisfactory. What is really essential to know, however, is how the states of surf-riding predicted on the basis of a Froude-Krylov calculation, would qualitatively vary, first if an increase in the maginitude of the excitation comparable to the effect of difraction on loads was introduced, and then how influential the phase lag of the wave's yaw moment could prove to be. This would allow in turn, to pinpoint towards and isolate the key factors affecting the stability of the vessel. The method adopted for calculating diffraction effects is the one proposed in [8]. A comparison between calculated and measured wave forces is presented in Fig 1.

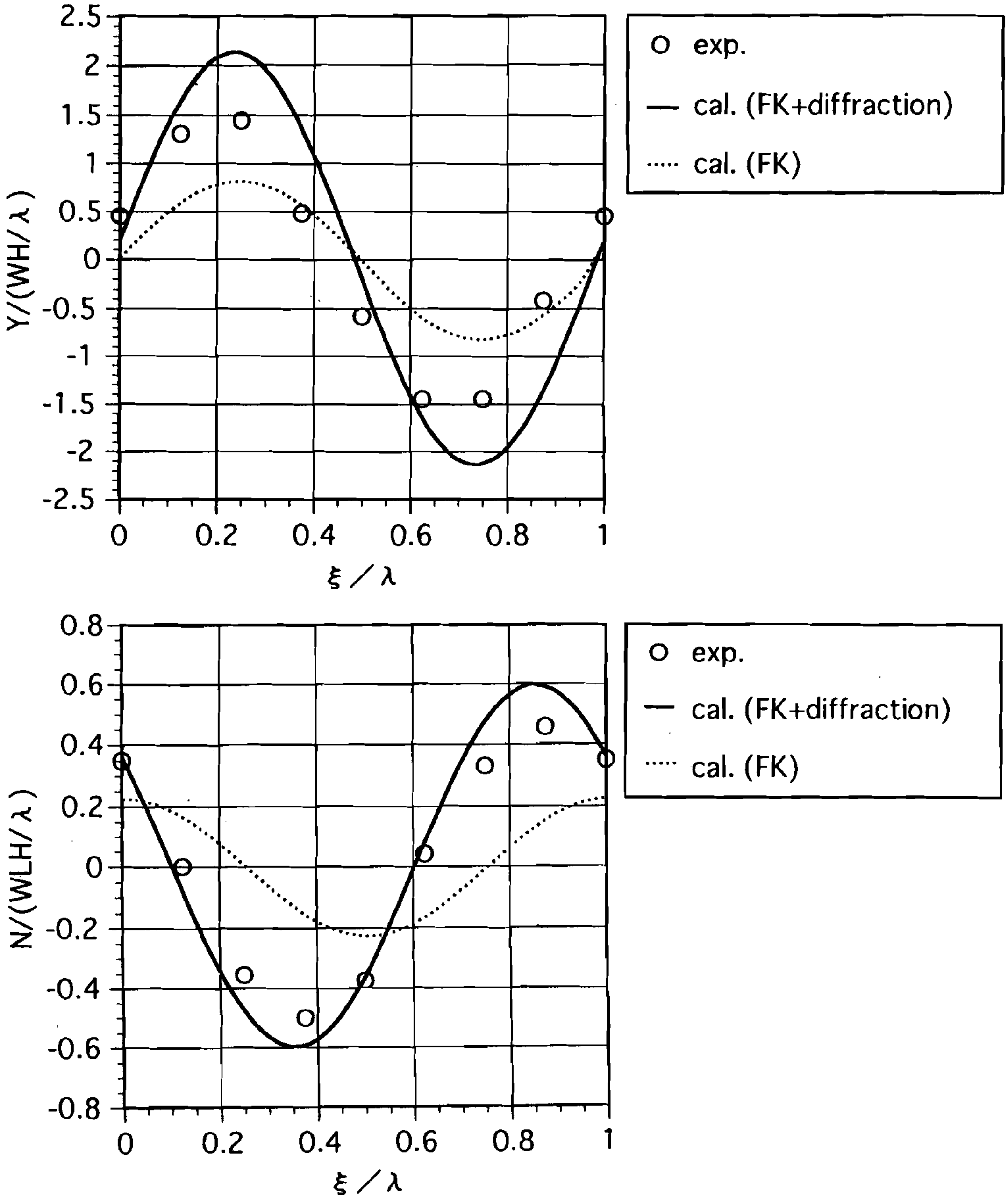


Fig 1: Wave excitation

States of surf-riding and analysis of stability

A typical layout of the states of surf-riding assuming as control parameter the rudder angle δ is shown in Fig 2, for wave length to ship lentgh ratio $\lambda/L = 2.0$ and wave steepness $H/\lambda = 1/30$ (H : wave height) with wave diffraction included. For this specific wave they occupy almost all the control parameter's domain of variation ,i.e., *-35 deg*,

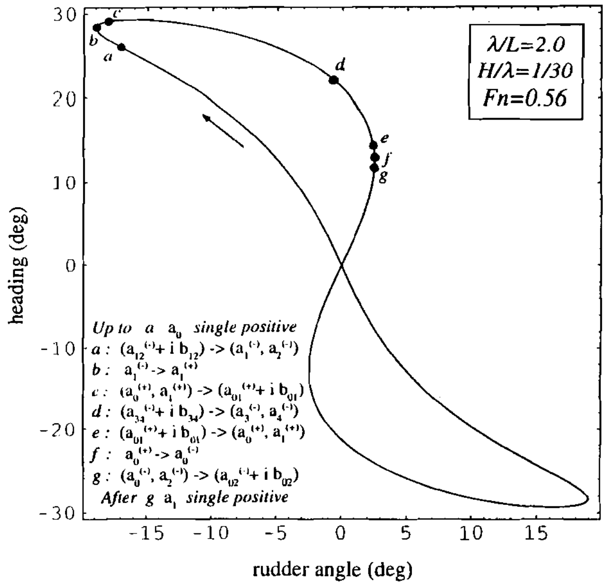
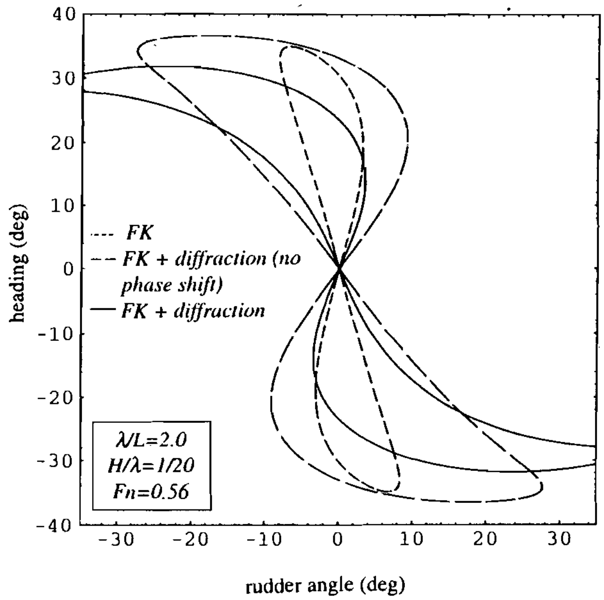


Fig 2 : Stability transitions

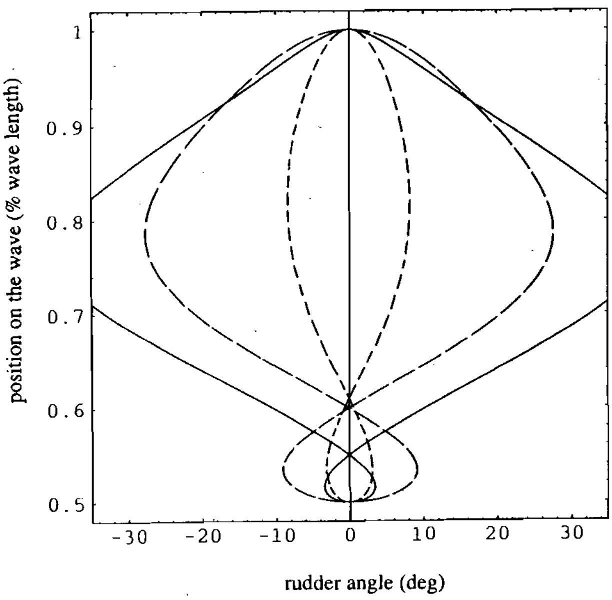
to *35 deg* rendering surf-riding possible for headings up to nearly *30 deg*. The occurring stability transitions are also shown in this picture. In general, for the unsteered vessel, all states were found unstable. More specifically, near to the wave trough we have a sequence of saddle points (one single positive eigenvalue and all others negative or, if complex, with negative real part). At about 26 deg heading, shown as point *a* of Fig 2, there is the first transition with a pair of complex conjugate eigenvalues with negative real part splitting into two real negative eigenvalues. The one of these turns positive at the slightly higher heading of 28 deg, point *b*, which corresponds to the *turning (or limit) point* of the curve. So at this region two different positive eigenvalues exist. At the point *c* the two real positive eigenvalues merge into a complex pair, always with positive real part. At *d* another pair of conjugate eigenvalues, having negative real part, gives rise to two negative real, while, at *e*, the complex pair with the positive real part turns into two different positive reals. The first of these, changes to negative at the nearby point *f*, signifying entry of the region of the wave crest, which is dominated by saddle-type instability in the surge direction.

Effect of the increased excitation amplitude and phase lag due to diffraction

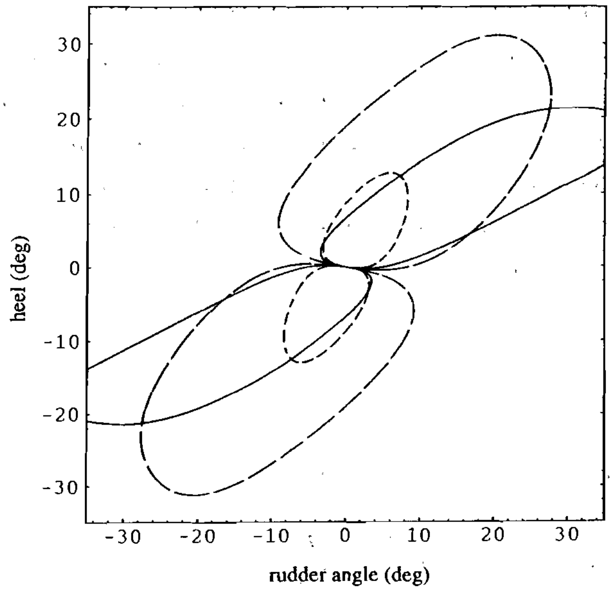
Figs 3a, 3b, and 3c indicate first the geometric variation of the states of surf-riding as one moves from the *Froude-Krylov* force towards excitation amplitudes comparable in size to inclusion of diffraction, and from there to the incorporation of the phase shift in yaw. The wave characteristics are, $\lambda/L=2.0$, and $H/\lambda=1/20$, while the propeller is set so as to produce a nominal Froude number of 0.56 (exactly equal to the wave celerity). The increase in magnitude of the excitation, 'opens up' the parameter's domain allowing surf-riding up to *28.0 deg* rudder angle, as compared to the initial angle of only *9 deg*. It allows also to realise surf-riding up to slightly higher headings (from *35 deg* to *37 deg*). An almost proportional magnification of heeling takes also place, with the maximum stepping up from *11.5 deg* to *31.0 deg*.



(3a)



(3b)



(3c)

Fig 3: Surf-riding with Froude-Krylov and with diffraction

Addition of the phase shift produces important qualitative effects on this picture. At first the wave trough becomes less repulsive in yaw (the positive eigenvalue reduces in value) while the states of surf-riding can no longer constitute a closed curve. Likewise, surf-riding is now viable for the whole parameter domain (from *-35* to *+35 deg*). However, the range of headings were surf-riding can exist shrinks to a maximum of *31 deg* to either side.

Consideration of experimentally-derived wave excitation

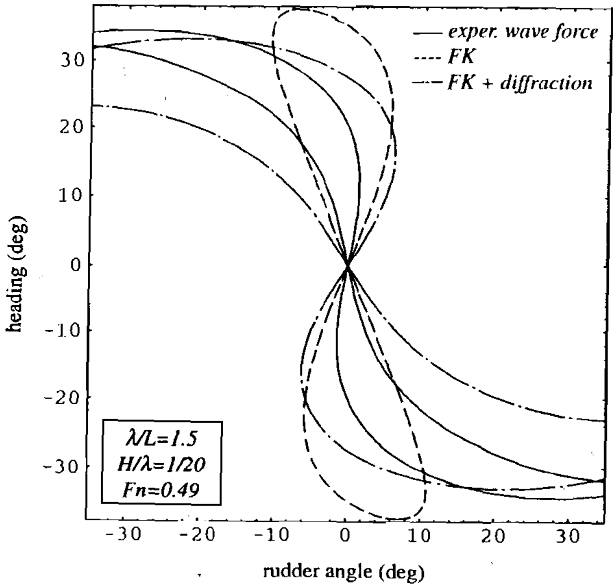
Fig 4 compares the surf-riding curves obtained respectively with Froude-Krylov, Froude-Krylov+diffraction, and real wave force, at $\lambda/L=1.5$ *and* $H/\lambda=1/20$. Although the qualitative pattern is invariant,there is substantial quantitative difference, calling for more attention on the calculation of wave loads.

Effect of propeller rate

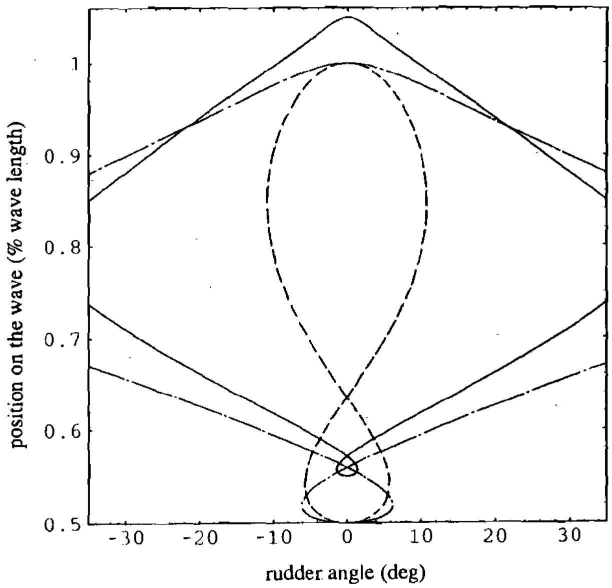
Surf-riding is very dependent on the propeller's rate of rotation (represented by the nominal Froude number, *Fn*) as shown in Fig 5. Reducing *Fn* causes the domain of headings up to which surf-riding is realisable, to shrink considerably.

From surf-riding to loss of control and capsize

To realise surf-riding in a stable way, active steering is in principle necesssary. This



(4a)



(4b)

Fig 4 : Surf-riding corresponding to experimental wave force

would cause the stabilisation of a certain range of surf-riding states located nearer to the wave trough, the exact extent of which would depend on the particular steering characteristics. Fig 6 demonstrates the case of a vessel with proportional and differential control on which, while in a steady surf-riding condition, the propeller rate was slightly reduced. In total *4* cases are considered, the matrix of two different initial headings (*10 deg* and *23.5 deg*) and two final nominal Froude numbers (*0.56 -> 0.48* and *0.56 -> 0.40*). From Fig 5 it is possible to derive that, both at $Fn = 0.40$ and *0.48*

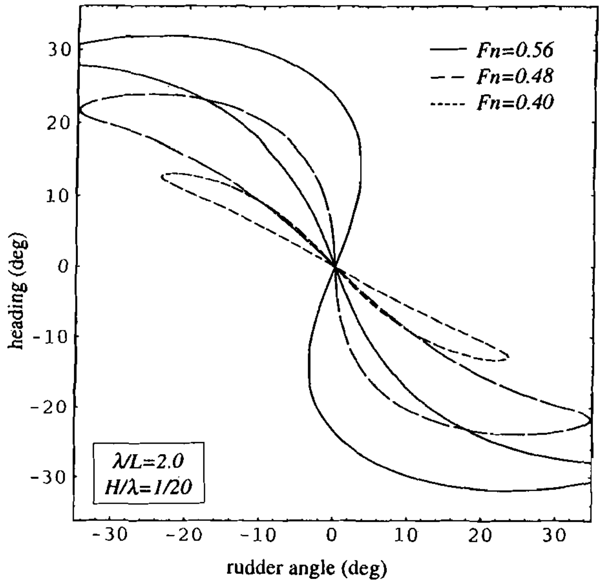


Fig 5 : Effect of the propeller's rate of rotation

there is no steady state corresponding to the larger heading, *23.5 deg*, although such a state exists for $Fn = 0.56$. At this heading therefore, reduction of propeller rate causes escape from surf-riding as a certainty. Due to the 'discontinuity' of the transition and the magnitudes of the excitations this can lead with high probability to broach and capsize, Fig 6. A slightly different picture is obtained at the smaller *10 deg* heading however, as only the 0.56 -> 0.40 transition leads to broach. This occurs because at

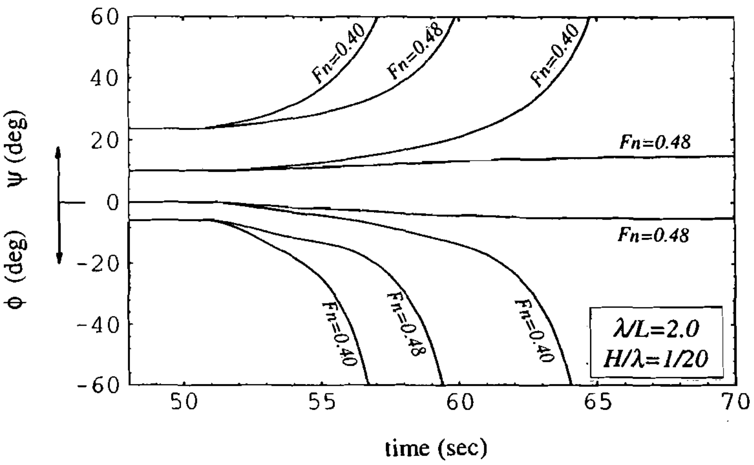


Fig 6 : "Loss of heading" and capsize

$Fn = 0.48$ it is still possible to stay on surf-riding, Fig 5. It must be mentioned however that the mere existence of a corresponding steady-state at the final nominal Froude number, is not adequate to guarantee that the vessel will rest on surf-riding. This is decided only by the position of the initial condition of the vessel, in relation to the attracting domain of the surf-riding state at the lower rate.

CONCLUDING REMARKS

We have analysed the stability of a fishing vessel in surf-riding condition, considering its coupled motions in surge-sway-yaw-roll with and wihout inclusion of autopilot. A specific mechanism leading to broaching with capsize has been illustrated, resulting from reduction of the rate of the propeller while surf-riding. Practically this could be attempted either in order to escape from surf-riding, or, to benefit from the wave force. The possibility of significant differences in magnitude and phase between the Froude-Krylov and real wave yaw moment would play a decisive role in quantifying the operational risk a vessel is faced with, given a specific set of environmental parameters.

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APPENDIX I

The mathematical model is an extended version of a still-water 4-degree-of-freedom manoeuvring model, incorporating the wave excitation terms. For the linear and nonlinear manoeuvring coefficients the corresponding still-water values were used, measured with circular motion tests. The specific form of the mathematical model, written in a general dynamical system's representation and using standard manoeuvring nomenclature is presented below :

$$\dot{u} = G_1/A\ , \quad \dot{v} = G_2/D\ , \quad \dot{r} = G_3/D\ , \quad \dot{p} = G_4/D, \quad \dot{\phi} = p\ , \quad \dot{\psi} = r\ ,$$

$$\dot{x} = u\cos\psi - v\sin\psi\ , \quad \dot{y} = u\sin\psi + v\cos\psi\ , \quad \dot{\delta} = t_\delta\ (-\delta + a_\psi(\psi-\psi_r) + a_r r) \quad \textit{(optional)}$$

,

where $\quad A = (M - X_{\dot{u}}), \quad G_1 = (L_X+X_H+X_W+X_P+X_R)$

$$D = \begin{vmatrix} (m - Y_{\dot v}) & (m\, x_G - Y_{\dot r}) & -mz_G \\ (mx_G - N_{\dot v}) & (I_z - N_{\dot r}) & 0 \\ (z_Y\, Y_{\dot v} - mz_G) & z_Y\, Y_{\dot r} & (I_x - K_{\dot p}) \end{vmatrix} \qquad G_2 = \begin{vmatrix} (L_Y + Y_H + Y_W + Y_P + Y_R) & (m\, x_G - Y_{\dot r}) & -mz_G \\ (L_N + N_H + N_W + N_P + N_R) & (I_z - N_{\dot r}) & 0 \\ (L_K + K_H + K_W + K_P + K_R) & z_Y\, Y_{\dot r} & (I_x - K_{\dot p}) \end{vmatrix}$$

$$G_4 = \begin{vmatrix} (m - Y_{\dot v}) & (m\, x_G - Y_{\dot r}) & (L_Y + Y_H + Y_W + Y_P + Y_R) \\ (mx_G - N_{\dot v}) & (I_z - N_{\dot r}) & (L_N + N_H + N_W + N_P + N_R) \\ (z_Y\, Y_{\dot v} - mz_G) & z_Y\, Y_{\dot r} & (L_K + K_H + K_W + K_P + K_R) \end{vmatrix} \quad G_3 = \begin{vmatrix} (m - Y_{\dot v}) & (L_Y + Y_H + Y_W + Y_P + Y_R) & -mz_G \\ (mx_G - N_{\dot v}) & (L_N + N_H + N_W + N_P + N_R) & 0 \\ (z_Y\, Y_{\dot v} - mz_G) & (L_K + K_H + K_W + K_P + K_R) & (I_x - K_{\dot p}) \end{vmatrix}$$

$$L_X = m\, r\, v - m\, z_G\, p\, r \quad , \qquad L_Y = -\, m\, r\, u\, , \qquad L_N = -\, mx_G\, ru \quad , \qquad L_K = m\, z_G\, r\, u$$

Hull Forces

$$X_H = (X_{vr} - Y_{\dot v})\, vr - Y_{\dot r}\, r^2 - Res(u)$$

$$Y_H = Y_v\, v\, U + Y_r\, r\, U + Y_{vv}\, v^2 + Y_{vr}\, v\, r + Y_{rr}\, r^2$$

$$N_H = N_r\, r\, U + N_v\, vU + N_{rr}\, r^2 + N_{rrv}\, r^2 v/U + N_{vvr}\, v^2 r/U + N_\phi\, \phi\, U^2 + N_{v\phi}\, v\phi\, U + N_{r\phi}\, r\phi\, U$$

$$K_H = K_p\, p + R(\phi, x) - z_Y\, (Y_v\, vU + Y_r\, rU + Y_{vv}\, v^2 + Y_{vr}\, vr + Y_{rr}\, r^2) \qquad \text{where } U = (u^2 + v^2)^{1/2}$$

Froude-Krylov Wave Forces

$$X_W = -\rho\, g\, (H/2)\, k\, cos\psi \int_L a(\psi)\, e^{-k\, d(x_S)}\, A(x_S)\, sink(x + x_S\, cos\psi)\, dx_S$$

$$Y_W = \rho\, g\, (H/2)\, k\, sin\psi \int_L a(\psi)\, e^{-k\, d(x_S)}\, A(x_S)\, sink(x + x_S\, cos\psi)\, dx_S$$

$$N_W = \rho\, g\, (H/2)\, k\, sin\psi \int_L a(\psi)\, e^{-k\, d(x_S)}\, A(x_S)\, x_S\, sink(x + x_S\, cos\psi)\, dx_S$$

$$K_W = \rho\, g\, (H/2)\, k\, sin\psi \int_L a(\psi)\, e^{-k\, d(x_S)}\, A(x_S)\, z_W\, sink(x + x_S\, cos\psi)\, dx_S$$

Propeller thrust

$$X_p = (1 - t_p)\, \rho\, n^2\, D^4\, K_T(u, v, r)$$

Rudder Forces

$$X_R = -F_N(u, v, r, \delta)\, sin\delta$$

$$Y_R = -(1 + a_H)\, F_N(u, v, r, \delta)\, cos\delta$$

$$N_R = -[1 + a_H(x_H/x_R)]\, x_R\, F_N(u, v, r, \delta)\, cos\delta$$

$$K_R = -(1 + a_H)\, z_R\, F_N(u, v, r, \delta)\, cos\delta$$