EFFECTS OF A MUDDY BOTTOM ON THE STRAIGHT-LINE STABILITY

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Abstract: In the period 2001-2004 an extensive experimental research program has been carried out which enabled the development of a mathematical model for ships manoeuvring in various muddy bottom conditions. Real-time simulation runs based on this mathematical model resulted into a redefinition of the nautical bottom concept of the harbour of Zeebrugge. This paper introduces a new mathematical ship manoeuvring model taking the characteristics of the mud layer into account. The developments for the hull related forces are discussed and applied to the calculation of the straight-line stability criterion.

Keywords: ship control, linear equations, controllability, manoeuvrability.

1. INTRODUCTION

As many ports, the harbour of Zeebrugge, Belgium, suffers from sedimentation and the formation of fluid mud layers. Maintenance dredging works are needed in order to maintain safe shipping traffic to the harbour and access channels. To carry out the necessary harbour manoeuvres without major problems, a ship needs a minimum under keel clearance.

The under keel clearance is defined as the minimum distance between the bottom of a ship and the bed of a river or sea. However, when this bottom is covered with a fluid mud layer it is difficult to determine where the actual bottom is located, as traditional survey techniques appear to be inadequate. If the interface between the water and the fluid mud layer is considered as the bottom, it is even possible to navigate with *negative* under keel clearance. For this reason the nautical bottom concept has been introduced. According to PIANC, the nautical bottom is defined as *the level where physical characteristics of the bottom reach a critical limit beyond which contact with a ship's keel causes either damage or unacceptable effects on controllability and manoeuvrability* (PIANC, 1997).

The critical limit used in the definition of the nautical bottom is usually linked to a critical mud-density, which in Zeebrugge was defined at 1.15 ton/m³, a figure depending on the local rheological characteristics of the mud layer.

Several interested parties were in favour of an increase of this critical density, as it would have positive effects on the dredging efficiency. On the other hand an increase of critical density would also result in possible contact between the ships' keel and the mud layer. It was not clear whether the latter would result into unacceptable effects.

To investigate the effects of a fluid mud layer on the bottom on ship behaviour, a comprehensive research program has been carried out including systematic series of captive manoeuvring tests in the *Towing tank for manoeuvres in shallow water* (co-operation Flanders Hydraulics – Ghent University), the development of a mathematical model (Delefortrie, *et al.*, 2005a) and the execution of real-time simulation runs in a full mission bridge simulator.

As a consequence an increase of the critical density to 1.20 ton/m³ resulted possible and has been implemented in the harbour of Zeebrugge, together with restrictions concerning the penetration of a ship's keel into the fluid mud layer. This new concept is currently being evaluated with the execution of large scale measurements on the container vessels calling at Zeebrugge harbour.

2. THE EXPERIMENTAL PROGRAM

Flanders Hydraulics Research (Antwerp, Belgium), the hydraulic research station of the Flemish Authorities, is particularly concerned with investigation of ship hydrodynamics in relation with the concept, adaptation and operation of navigation areas.

To assess the manoeuvring behaviour of ships in confined waterways, two full mission bridge ship-manoeuvring simulators have been installed for research and training.

Fig 1. Flanders Hydraulics Research: towing tank for captive manoeuvring tests in shallow water.

In order to provide the mathematical model of the simulator with realistic data, especially in the (very) shallow water range, the availability of experimental facilities was considered as a requirement. At present these facilities consist of a shallow water towing tank (88 m * 7 m * 0.6 m), equipped with a planar motion carriage, a wave generator and an auxiliary carriage for ship-ship interaction tests, see Figure 1. Thanks to computerised control and data-acquisition, the facilities are operated in a fully automatic mode.

Table 1. Bottom conditions.

Mud type	Density (kg/m³)	Dynamic viscosity (Pa s)	Layer thickness		
			0.75 m "1"	1.50 m "2"	3.00 m "3"
"d"	1100	0.03	D/E	D/E	D/E/U
"c"	1150	0.06	D	D	D
"b"	1180	0.10	D	D	D
"f"	1200	0.11	-	D	-
"h"	1210	0.19	D/E	D/E	D
"e"	1260	0.29	-	D	-
"g"	1250	0.46	-	D/E	D/E
"S"	solid bottom				

A homogeneous artificial mixture, consisting of two types of chlorinated paraffin and petroleum, has been used to simulate the mud layer. In total seven bottom layers of a different viscosity and density have been utilized to carry out captive manoeuvring runs at different under keel clearances, see Tables 1 and 2.

The selected density-viscosity combinations were based on measurements of density and rheology profiles carried out in the outer harbour of Zeebrugge in 1997-98. A mud layer configuration is defined by two characters: a letter (b,…,h) denoting the material characteristics and a figure (1, 2, 3) representing the layer thickness. Tests carried out above a solid bottom are referred to as “S”. “x” in Table 2 represents any mud layer corresponding with Table 1.

Table 2. Under keel clearances (referred to the solid bottom)

h/T	D	E	U1	U2	U3
1.07	S				
1.10	S,x	S,x	S	S	S
1.15	S,x	S,x			
1.26	S,x2,x3		d3		
1.32	S,x2,x3		d3		
1.35			S	S	S
1.50	S				
2.00	S		S	S	S
2.50	S				

The letters D, U (container carriers) and E (tanker) in Table 1 denominate the ship models that have been used. More details can be found in Table 3. Most runs have been carried out making use of model D of a 6000 TEU container carrier, because of the importance of container traffic for the harbour of Zeebrugge.

Table 3. Ship models.

Model	D	E	U1/U2/U3
Scale	1/75	1/75	1/80
L_{PP} (m)	289.8	286.8	331.8
B (m)	40.25	46.77	42.82
T (m)	13.50	15.50	14.54 / 13.5 / 12
C_B	0.59	0.82	0.655 / 0.645 / 0.632
A_R (m²)	60.96	98.34	83.13
# blades	5	5	6
D_P (m)	8.145	7.733	8.46
P/D (-)	0.97	0.65	1.00
AEP (-)	0.8	0.62	0.96

3. MATHEMATICAL MODEL

For each tested combination of ship, mud layer and under keel clearance a mathematical ship manoeuvring model has been developed (Delefortrie, *et al.*, 2005a). This model has been used to carry out the simulation runs, but can still be enhanced. At present the model consists of separate sets of coefficients for each combination of under keel clearance and bottom condition. To be able to simulate intermediate conditions a new mathematical ship manoeuvring model taking the characteristics of the mud layer into account is being developed.

With the aim of assessing the straight-line stability the present paper will only focus on the hull components of the sway force and the yaw moment of this new model.

3.1 The solid bottom case

For each under keel clearance the hull forces were modelled using the following expressions, where the functions of β, γ and χ are tabulated for a discrete number of values:

$$Y_H = (Y_{\dot v} - m)\dot v + (Y_{\dot r}(\beta) - m x_G)\dot r - mur + \frac{1}{2}\rho LT \left\{ \begin{array}{c} (u^2+v^2)Y'(\beta) + \\ \left(u^2 + \left(\frac{1}{2} rL\right)^2\right) Y'(\gamma) + \\ \left(v^2 + \left(\frac{1}{2} rL\right)^2\right) Y'(\chi) \end{array}\right\} \qquad (1)$$

$$N_H = (N_{\dot v} - m x_G)\dot v + (N_{\dot r}(\beta) - I_{zz})\dot r - m x_G ur + \frac{1}{2}\rho L^2 T \left\{ \begin{array}{c} (u^2+v^2)Y'(\beta)x_Y(\beta) + \\ \left(u^2 + \left(\frac{1}{2} rL\right)^2\right) N'(\gamma) + \\ \left(v^2 + \left(\frac{1}{2} rL\right)^2\right) N'(\chi) \end{array}\right\} \qquad (2)$$

For most of the hydrodynamic derivatives and functions in (1-2), in the following denoted by F, a linear relationship with the non-dimensional under keel clearance parameters T / (h-T) and L / (h-T) appears to result into adequate approximations:

$$F = F_{deep} + \frac{P}{h-T}\xi_1 \qquad (3)$$

In (3) P denotes either the ship's length or its draft; ξ_1 represents a constant - or a function of other kinematical parameters - taking the under keel clearance effect into account. Examples of this relationship can be found in Figures 2 – 4.

The choice of the under keel clearance parameter can be explained as follows: the water has to find a way out through a volume with a length equal to the ship's length and a height equal to the absolute under keel clearance (h-T). An increase of the ship's length and a decrease of the absolute under keel clearance narrow the passage in a vertical sense, while enlarging it in a longitudinal sense, resulting in larger hydrodynamic (reaction) forces.

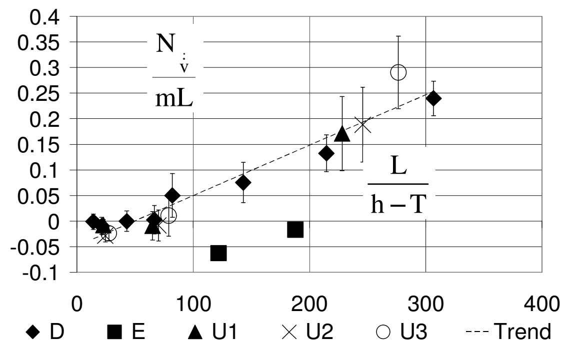

Fig 2. Sway acceleration derivative for the yaw moment, ship models D, E and U. Stopped propeller, u > 0. Trend for ship model D.

For the three ship models the same mathematical formulation may be used. The non-dimensional deep water values for the container carriers D and U have comparable magnitudes.

A linear relationship with the under keel clearance parameters cannot be used in all cases. Figure 3 shows the lateral force as a function of the yawing angle for different under keel clearance. As already reported by Delefortrie, *et al.* (2005a) the hydrodynamic lateral force due to yaw rate has an opposite sign at extreme shallow under keel clearances. This lateral force increases from deep to shallow water to reach a maximum. If the under keel clearance decreases further, the lateral force will decrease again and even take an opposite sign in extreme shallow water conditions; such an effect can only be modelled using a non-linear (e.g. quadratic) relationship of the under keel clearance parameter:

$$F = F_{deep} + \frac{P}{h-T}\xi_1 + \left(\frac{P}{h-T}\right)^2 \xi_2 \qquad (4)$$

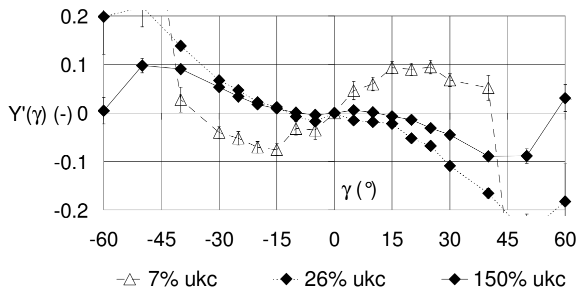

Fig 3. Yaw function for the sway force, ship model D, stopped propeller, navigating ahead.

Finally it resulted more convenient to model $x'_Y(\beta)$, being the application point of the sway force $Y'(\beta)$, as a function of the under keel clearance parameter, rather than $N'(\beta)$. A concluding example is given in Figure 4 for the sway added mass.

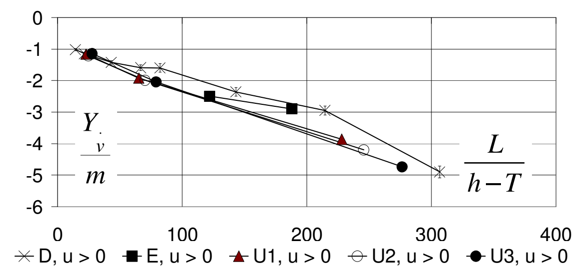

Fig 4. Sway added mass, ship models D, E, U, u > 0, 0 rpm.

The equations (1-2) can be linearised to:

$$\begin{aligned} &(Y_{\dot v} - m)\dot v + (Y_{\dot r} - m x_G)\dot r + Y_{uv}uv + (Y_{ur} - m)ur = 0 \\ &N_{\dot v}\dot v + (N_{\dot r} - I_{zz})\dot r + N_{uv}uv + (N_{ur} - m x_G)ur = 0 \end{aligned} \qquad (5)$$

Previous results of the linear manoeuvring derivatives above muddy bottoms have already been reported by Vantorre, *et al.* (2003) and Delefortrie, *et al.* (2005b).

Regression analysis of the effect of the under keel clearance resulted in the following models (a_i to e_i are strictly positive regression coefficients)

$$Y_{\dot v} = -a_1 - b_1 \frac{L}{h-T} \qquad (6)$$

$$\mathrm{Y}_{\dot{r}} = a_2 - b_2 \frac{L}{h-T} \qquad (7)$$

$$\mathrm{N}_{\dot{v}} = -a_3 + b_3 \frac{L}{h-T} \qquad (8)$$

$$\mathrm{N}_{\dot{r}} = -a_4 - b_4 \frac{L}{h-T} \qquad (9)$$

$$\mathrm{Y}_{uv} = -a_5 - b_5 \frac{L}{h-T} \qquad (10)$$

$$Y_{ur} = -a_6 - c_6 \frac{T}{h-T} + d_6 \left(\frac{T}{h-T} \right)^2 \qquad (11)$$

$$N_{uv} = -a_7 + c_7 \frac{T}{h-T} - b_7 \frac{L}{h-T} + e_7 \frac{LT}{(h-T)^2} \qquad (12)$$

$$N_{ur} = -a_8 - c_8 \frac{T}{h-T} \qquad (13)$$

The effect of shallow water on the sign and magnitude of the derivatives has been resumed in Table 4.

Table 4. Influence of the under keel clearance on sign and magnitude of the linear derivatives.

derivative	6000 TEU container
	value at (h=1.1T)/value at (h=2.5T)
$Y_{\dot{v}}$	3.54
$Y_{\dot{r}}$	-26.47
$N_{\dot{v}}$	-7.14
$N_{\dot{r}}$	5.19
Y_{uv}	4.89
Y_{ur}	5.31
N_{uv}	3.02
N_{ur}	2.41

3.2 The muddy bottom case

Be h_2 the thickness of the mud layer and h_1 the height of the upper lying water layer, the total depth can be written as:

$$h = h_1 + h_2 \qquad (14)$$

The bottom material can vary from water over soft mud to consolidated mud. If the mud has large viscosity and density values, like sand or clay, the material will hardly move when a ship passes by and its top can be considered as the actual seabed. In this case equations (6) to (13) can be used to predict the linear manoeuvrability derivatives, with h = h_1.

On the other hand if the material is very fluid the mud layer cannot be considered as a solid bottom. In the limit condition of two equivalent water layers, equations (6 - 13) can be used with h = h_1+h_2. For intermediate situations a parameter Φ can be defined, so that:

$$h = h_1 + \Phi h_2 \qquad (15)$$

Particular values for this fluidization parameter Φ are 0 (hard layer of thickness h_2) and 1 (watery layer of thickness h_2). The fluidization parameter of the mud covering the seabed depends on the following parameters:

- the rheological properties (e.g. viscosity) of the mud: a decrease of the latter logically result into an increased fluidization parameter;
- the under keel clearance referred to the mud-water interface: the fluidization parameter increases when the ship's keel is located closer to the mud or penetrates the mud;
- undulations of the mud layer (see Figure 5).

The latter affect the manoeuvring behaviour of the vessel, and may even lead to a negative fluidization parameter, especially when the ship navigates with positive under keel clearance above the mud layer.

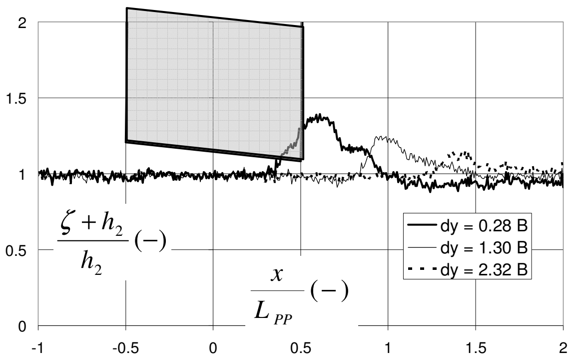

Fig 5. Undulations of the interface at various lateral distances of model D. Mud f2, +3.9% ukc, F_n = 0.088, 0 rpm. The ship is represented taking squat into account.

The effect of the fluidization parameter is illustrated in Figures 6 and 7 using the condition where ship D navigates at an under keel clearance of -1.1% of the ship's draft above mud layer h2. The sway added mass in this condition has the same magnitude as if the ship was navigating above a solid bottom with an under keel clearance of L / (h-T) ≈ 480 or 4.5% of draft above the solid bottom. As a result both represented conditions in Figure 7 are hydro-dynamically equivalent from the sway added mass point of view. The fluidization parameter in this case is 0.5 as can be calculated with equation (15).

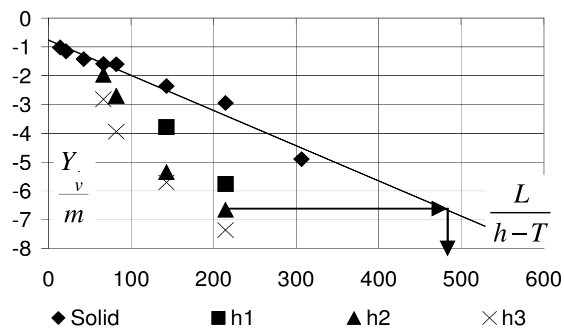

Fig. 6. Sway added mass, ship model D, u > 0, 0 rpm. Illustration of the effect of the fluidization parameter.

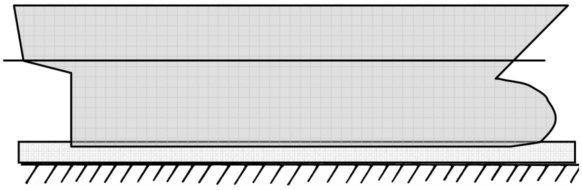

Fig. 7a. Ship model D: -1.1% of draft above a mud layer h2 (10% of draft above the solid bottom)

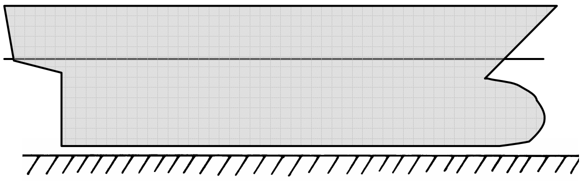

Fig. 7b. Ship model D: 4.5% of draft above the solid bottom.

Fig. 8 shows the fluidization parameter for different mud layers. The value in the abscissa represents the penetration of the keel into the mud layer, defined as:

$$\Pi = \frac{T - h_1}{h_2} \qquad (16)$$

taking positive values in case the ship's keel is penetrating into the mud layer.

A linear relationship can be observed. The actual fluidization depends further on the thickness of the mud layer and the dynamic viscosity μ of the mud, so that in general the fluidization can be written as:

$$\begin{aligned}\Phi = &\left(a_0 + \mu a_\mu\right)\Pi + \\ &\Phi_{00} + \mu\Phi_{0\nu} + \frac{h_2}{T}\left[\Phi_{h0} + \mu\Phi_{h\mu}\right]\end{aligned} \qquad (17)$$

Φ is always smaller than 1 for the hull forces, so that the value of under keel clearance related parameters – referred to the solid bottom – increases with a mud layer on the bottom of the seabed.

Note that the viscosity of the mud layer has been selected as significant for the mud composition. However, it should be borne in mind that the rheologic behaviour of mud cannot be characterised by one single parameter.

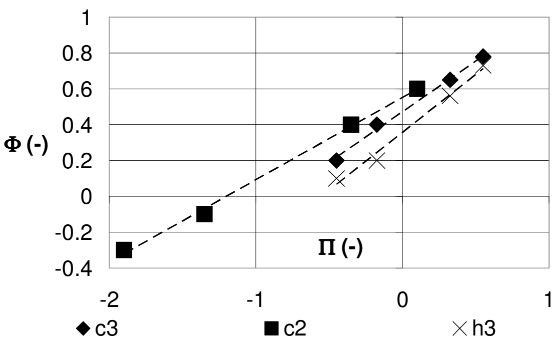

Fig. 8. Fluidization for the sway added mass, ship model D, u > 0, 0 rpm.

4. CONTROLLABILITY

4.1 Definition

The eigenvalues of the set of equations (5) have been calculated, (The Manoeuvring Committee, 2002):

$$\sigma_{1,2} = -\frac{B \pm \sqrt{B^2 - 4AC}}{2A} \qquad (15)$$

using following notations:

$$A = \left(Y_{\dot v} - m\right)\left(N_{\dot r} - I_{zz}\right) - \left(Y_{\dot r} - mx_G\right)N_{\dot v} \qquad (16)$$

$$\begin{aligned}B = &Y_{uv}\left(N_{\dot r} - I_{zz}\right) + \left(Y_{\dot v} - m\right)\left(N_{ur} - mx_G\right) \\ &-\left(Y_{ur} - m\right)N_{\dot v} - \left(Y_{\dot r} - mx_G\right)N_{uv}\end{aligned} \qquad (17)$$

$$C = Y_{uv}\left(N_{ur} - mx_G\right) - \left(Y_{ur} - m_1\right)N_{uv} \qquad (18)$$

A ship is characterised by straight line stability if the real part of the stability indices is negative. A and B being positive, this is the case if C>0.

4.2 Effect of the under keel clearance

The effect of under keel clearance on the controllability can be assessed by replacing the hydrodynamic derivatives in (16-18) with their corresponding expressions (6-13). Both Y_{uv} and N_{ur} are already negative in deep water conditions, and will be more negative in shallow water, see Table 4, so the first term in (18) will always be positive and larger in shallow water conditions.

N_{uv} is always negative and will be more negative in shallow water. In deep water Y_{ur} is small and negative, but its absolute value increases with decreasing water depth, and becomes even larger than the ship's mass. The second term in (18) will therefore be positive in extreme shallow water conditions and negative in deep water conditions. The ship has thus more stability with decreasing under keel clearance, as C will be more positive with decreasing under keel clearance. Ship D, which is slightly unstable in deep water conditions, will be stable in shallow water.

4.3 Effect of the bottom condition

The effect of the bottom condition can also be assessed using the corresponding expressions (6-13) in (16-18). In case of a mud layer the depth h needs to be replaced by the equivalent depth (15), which takes the fluidization parameter into account. As stated in paragraph 3.2 the fluidization parameter is always smaller than 1, so that – for a same under keel clearance above the solid bottom – the presence of a mud layer will further increase the straight line stability of the ship. Figure 9 shows some examples for the stability index σ_1.

The stability indices are complex numbers, taking account of the negative value for the discriminant, see Figure 10. Although the ship is very stable, the equilibrium will be reached with oscillating damping.

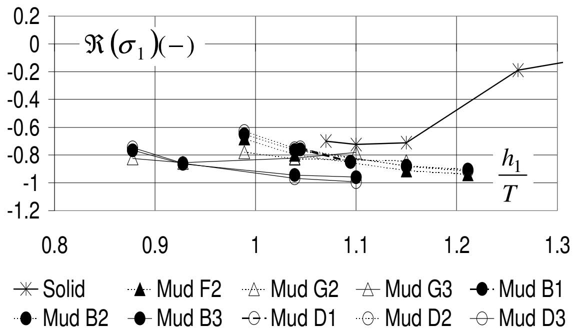

Fig 9. Ship model D: real coefficient of the stability index: influence of bottom characteristics and under keel clearance.

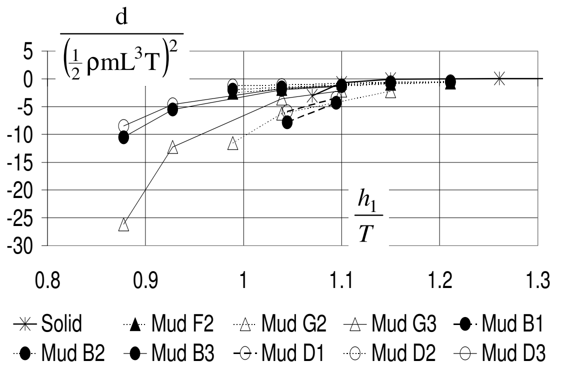

Fig 10. Ship model D: discriminant of quadratic equation for stability indices. Influence of bottom characteristics and under keel clearance.

5. CONCLUSIONS

A new mathematical model for ship manoeuvring is currently being developed, taking the under keel clearance and the presence of a mud layer into account. When navigating above muddy bottom conditions a hydrodynamic equivalent solid bottom condition can be defined. This phenomenon has been expressed with a fluidization parameter, which takes the proportion of the mud behaving like water, into account.

The hydrodynamic derivatives increase with decreasing under keel clearance. For a same under keel clearance above a solid bottom this effect is larger with the presence of a mud layer. Consequently both a smaller under keel clearance and the presence of a mud layer have a positive effect on the ship's straight line stability, although equilibrium is reached with oscillations.

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SYMBOLS

A	Coefficient of σ^2 (stability indices eqn)	(kg^2m^2)
AEP	expanded area ration of propeller	(-)
A_R	rudder area	(m²)
a_i	Regression coefficient; i=0..8,ν	(-)
B	ship's beam	(m)
	coefficient of σ^1 (stability indices eqn)	(kg^2m)
C	Coefficient of σ^0 (stability indices eqn)	(kg^2)
C_B	block coefficient	(-)
D	propeller diameter	(m)
d	discriminant (stability indices eqn)	(kg^4m^2)
F	force component	(N)
h	depth	(m)
h_1	water depth (free surface to interface)	(m)
h_2	thickness of mud layer	(m)
I_{zz}	moment of inertia about vertical axis	$(kg\ m^2)$
L, L_{pp}	ship's length between perpendiculars	(m)
m	ship's mass	(kg)
P	propeller pitch	(m)
r	yaw rate (>0 clockwise)	(rad/s)
t	time	(s)
T	ship's draft	(m)
u	longitudinal speed component (>0 forwd)	(m/s)
v	lateral speed component (>0 to starboard)	(m/s)
x_G	longitudinal position of centre of gravity	(m)
x_r, x_v, x_Y	longitudinal position of application point of forces due to yaw, sway, sway	(m)
Y	lateral force (>0 to starboard)	(N)
N	yawing moment (>0 clockwise)	(Nm)
Y_q, N_q	hydrodynamic derivative; q= $\dot{v}$, $\dot{r}$, uv, ur	
β	drift angle (= - arctan v/u)	(deg)
γ	yaw angle (= arctan 0.5rL/u)	(deg)
δ	rudder angle	(deg)
ζ	rise of interface	(m)
μ	mud dynamic viscosity	(Pa.s)
ξ	under keel clearance effect	
Π	keel penetration into mud	(-)
$\sigma_{1,2}$	stability index	(s^{-1})
ρ	density	(kg/m^3)
Φ	fluidization parameter	(-)
Φ_{ij}	Regression coefficient; i=0,h; j=0,ν	(-)
χ	correlation angle (= arctan 0.5rL/v)	(deg)

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