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EXPERIMENTAL INVESTIGATION OF HYDRODYNAMIC FORCES ACTING ON A SHIP IN THE VICINITY OF A QUAY WALL

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ABSTRACT

The results of systematic ship model tests investigating the effect of lateral restrictions of the navigation area on manoeuvring behaviour are discussed, with special attention to hydrodynamic phenomena affecting a ship which is moving laterally towards a vertical boundary. A distinction is made between cushion forces, including interaction with effects due to low forward speed and propeller actions, acting on the ship in steady conditions, and non-stationary forces, affecting the ship's dynamics during acceleration and deceleration phases. The potential contribution of such test results to the development of an efficient mathematical model for simulating berthing manoeuvres is discussed.

NOMENCLATURE

$a(\omega)$	added inertia coefficient	
a	acceleration	(m/s^2)
$A_0^{(j)}$	transfer function coefficient	
$A_1^{(j)}$	transfer function coefficient	
$b(\omega)$	hydrodynamic damping coefficient	
B	ship's beam	(m)
$B_1^{(j)}$	transfer function coefficient	
C_B	block coefficient	(-)
$[F_h]$	hydrodynamic force vector	(N, Nm)
h	water depth	(m)
$h(t)$	impulse response function	
k	exponential factor for cushion effect	(-)
k_n	exponential factor for propeller influence on cushion effect	(-)
$K(t)$	retardation function	
L_{pp}, L	ship's length between perpendiculars	(m)
n	propeller rate	(1/s, rpm)
N	yawing moment	(Nm)
N^*	$= N \div (\frac{1}{2}\rho v^2 L^3)$: nondimensional yawing moment	(-)
m	ship's mass	(kg)
$q_{M,F,A}$	quay clearance (lateral distance between ship's side and quay wall) midships, fore, aft	(m)
t	time	(s)
T	ship's draught	(m)
T	propeller thrust	(N)
$T(\omega)$	transfer function	
t_0	starting time of acceleration phase during captive quay wall approach tests	(s)
t_1	starting time of steady phase	(s)
t_2	starting time of deceleration phase	(s)
t_3	end of deceleration phase	(s)
u	ship's forward speed component	(m/s)
u_B	ship's speed component parallel with bank	(m/s)
v	ship's lateral speed component	(m/s)
v_B	ship's speed component perpendicular to bank	(m/s)
v_l	steady lateral speed	(m/s)
V	magnitude of speed vector	(m/s)
$[x]$	ship's position vector	(m, rad)
Y	lateral force	(N)
Y_B	lateral force due to bank effect	(N)
Y_C	lateral force due to cushion effect	(N)
Y_{C0}	Y_C at zero quay clearance	(N)
Y_O	lateral force in open water	(N)
Y^*	$= Y \div (\frac{1}{2}\rho v^2 L^2)$: nondimensional lateral force	(-)
$\alpha^{(j)}$	transfer function damping parameter	(1/s)
β	drift angle (=atan(-v/u))	(deg)
ψ_B	angle between ship's axis of symmetry and quay wall	(deg)
$\xi^{(j)}$	weight factor	(-)
λ	damping coefficient for high frequency	
μ	added inertia for high frequency	
ω	frequency	(1/s)
$\omega_0^{(j)}$	transfer function frequency parameter	(1/s)

1. INTRODUCTION

In channels, canals, harbours and other types of restricted waters, a ship's behaviour is affected by the presence of lateral restrictions of the navigation area, such as banks and quay walls. The latter may influence the hydrodynamic forces and moments acting on the ship hull, due to effects of different origin:

- the motion of the ship parallel to the bank causes hydrodynamic actions known as *bank suction*, although rejection may also occur in very shallow water;
- these bank suction forces are affected by propeller actions, which - in case of positive thrust - always result into a force on the ship's aft body directed towards the bank;
- the lateral force acting on a ship hull moving laterally at constant speed towards a solid boundary increases with

decreasing bank clearance; this phenomenon is widely knows as *cushion effect*;

- in case of contact between the ship and the quay wall, e.g. by means of fenders, accelerations and decelerations may be very large; hydrodynamic *memory effects* occur, which implies that a quasistatical approach is no longer valid. In the vicinity of a quay wall, these effects depend on the distance between ship and quay wall.

In this paper, the attention is focused to hydrodynamic phenomena affecting a ship which is moving laterally towards a vertical boundary. These phenomena were investigated experimentally at Flanders Hydraulics (Antwerp, Belgium) by means of two types of model tests:

- captive model tests, during which the model was forced to follow a straight course at constant forward and lateral speed, followed by a sudden deceleration;
- free model tests during which the model was pulled by a lateral force towards a vertical wall, resulting into a variable lateral speed.

The phenomenon of the cushion effect occurring in such conditions will be discussed, including interaction with effects due to (low) forward speed and propeller actions. It will also be evaluated whether the data collected during the deceleration phase of such tests are sufficient for deriving an efficient mathematical model for simulating berthing manoeuvres.

2. EXPERIMENTAL PROGRAM

2.1. Captive model tests

Systematic model test series were carried out in the *Towing tank for manoeuvres in shallow water* at *Flanders Hydraulics* in Antwerp, Belgium, in order to investigate hydrodynamic forces acting on a ship approaching a vertical quay wall. The experimental facilities consist of a shallow water tank (total length 88 m, width 7 m, maximum water depth 0.5 m), equipped with a computer controlled towing carriage and planar motion system. A vertical wall was mounted into the tank over a length of 20 m at a lateral distance of 1 m from one of the tank walls. The experiments were carried out with a 1:64 scale model of a panamax bulk carrier (L_{pp} = 235 m; B = 32.24 m; T = 12.25 m; C_B = 0.828) at three under keel clearance values (h/T = 1.5, 1.2, 1.1).

Four types of tests were executed:

(a) pure sway tests (u=0, v=constant, n=0);
(b) drift tests (u=constant, v=constant, n=0);
(c) pure sway tests with propeller action (u=0, v=constant, n=constant);
(d) drift tests with propeller action (u=constant, v=constant, n=constant);

The tests consisted of three phases (figure 1):

- an acceleration phase ($t_0 \leq t \leq t_1$), during which the lateral and, in case of test types (b) and (d), the forward acceleration are continuous functions of time;
- a steady phase ($t_1 \leq t \leq t_2$) with constant values for u and v;
- a deceleration phase ($t_2 \leq t \leq t_3$), characterised by a constant negative acceleration.

Most tests were carried out with a steady lateral speed v_1 = 0.16 m/s (full scale), a few tests of type (a) also with v_1 = 0.40 m/s (full scale). Tests (b) and (d) were executed with a forward speed u = 0.8 m/s (full scale), yielding a drift angle β of 11.3 deg; during tests (c) and (d), maximum propeller rate was applied.

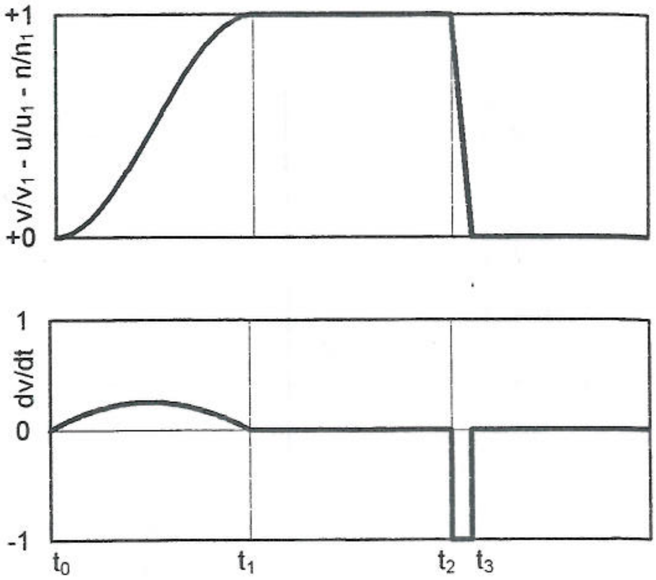

Figure 1. Captive quay wall approach tests: time history of ship model kinematics

Other tests parameters were:

- the final quay clearance q_M, measured amidships (0.1 - 1.0 B);
- the orientation ψ_B with respect to the quay wall (-12 to +12 deg, depending on the final quay clearance).

Besides quay wall approach tests, extensive bank suction test series have been carried out, during which the ship model follows a track parallel to the quay wall. The test results are beyond the scope of this paper, but were consulted for test result analysis.

2.2. Free model tests

Experiments have also been performed with a 1:70 scale model of a third generation container carrier (L_{pp} = 247.0 m, B = 32.3 m, T = 12.0 m, C_B = 0.68) pulled laterally by means of two falling weights until it was stopped by two springs, acting as fenders (figure 2). These tests were carried out at two under keel clearances (h/T = 1.2, 1.1) and six quay wall configurations, characterized by different values for quay clearance fore and aft of the ship model in its final position (see Table 1).

Table 1

test series	q_A/B	q_F/B	
TA	7.0	7.0	open water
TB	1.0	1.0	parallel to quay wall
TC	0.5	0.5	
TD	0.185	0.185	
TE	1.0	0.0	oblique w.r.t. quay wall
TF	0.0	1.0	

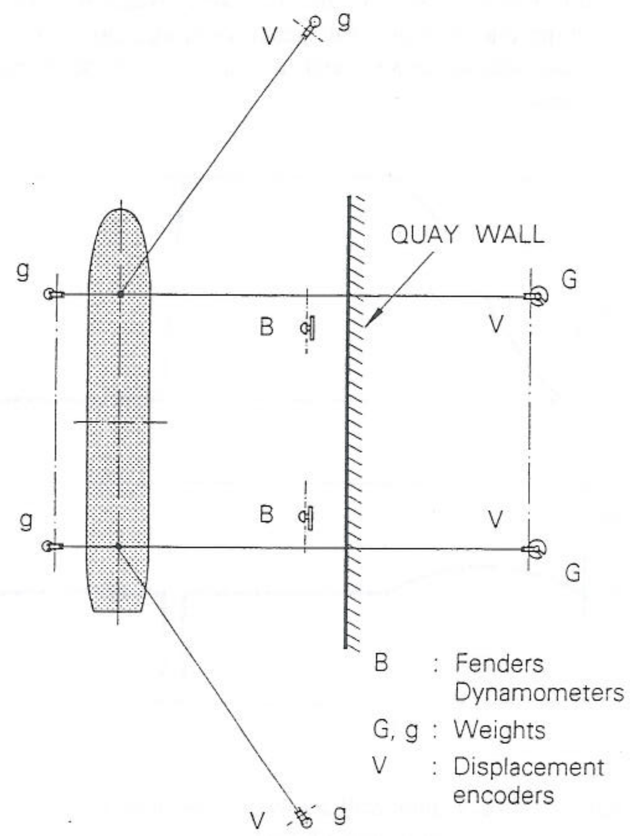

Figure 2. Experimental setup for quay approach tests with free models.

Several combinations of weights pulling the model towards the springs were applied, in order to impose four different lateral speed ranges (0.15 - 0.50 m/s, full scale).

3. HYDRODYNAMIC MEMORY EFFECTS

3.1. Mathematical model

A manoeuvring simulation model is usually based on a quasi-statical approach, assuming that hydrodynamic forces acting on a ship only depend on the instantaneous velocities and accelerations. This approach is acceptable in case of slow manoeuvres, but so-called memory effects cannot be neglected if relatively large accelerations take place, which may occur due to collisions, groundings, berthing to quay walls protected by fenders, tug assisted manoeuvres.

In order to increase the realism of the simulated manoeuvres, these memory effects were integrated into the mathematical model of the ship handling and manoeuvring simulator at Flanders Hydraulics. The non-stationary hydrodynamic forces are calculated by means of impulse response functions h(t) or the related retardation functions K(t):

$$\begin{aligned}\left[F_h(t)\right] &= \int_{-\infty}^{+\infty}[h(t)][x(t-t)]dt \\ &= [\mu][x(t)]+[\lambda][x(t)]+\int_{-\infty}^{t}[K(t-t)][x(t)]dt\end{aligned} \qquad (1)$$

[μ] and [λ] denoting the high frequency limits for added mass and hydrodynamic damping coefficients, respectively, the latter being zero. The retardation functions, which can be considered as the time domain characteristics of the manoeuvring ship, are related to the frequency domain characteristics :

$$\begin{aligned}[K(t)] &= \frac{2}{\pi}\int_0^{\infty}\left([b(\omega)]-[\lambda]\right)\cos\omega t\ d\omega \\ &= -\frac{2}{\pi}\int_0^{\infty}\left([a(\omega)]-[\mu]\right)\omega\ \sin\omega t\ d\omega \\ &= \frac{1}{2\pi}\int_{-\infty}^{\infty}[T(\omega)]\,e^{i\omega t}\ d\omega\end{aligned} \qquad (2)$$

T(ω) being a complex transfer function, defined as:

$$[T(\omega)] = i\omega\left([a(\omega)]-[\mu]\right)+\left([b(\omega)]-[\lambda]\right) \qquad (3)$$

In [1], following approximation was proposed for the elements of [T(ω)] in the vicinity of a quay wall:

$$T(\omega)=\sum_{j=0}^{2}\xi^{(j)}T^{(j)}(t)=\sum_{j=0}^{2}\xi^{(j)}\frac{i\omega B_1^{(j)}}{(i\omega)^2+i\omega A_1^{(j)}+A_0^{(j)}} \qquad (4)$$

$T^{(0)}$ being the transfer function for open water (i.e. laterally unrestricted shallow water) conditions. The weight factor $\xi^{(0)}$ ($= 1 - \xi^{(1)} - \xi^{(2)}$) decreases when the quay clearance becomes smaller and equals 1 in open water.

Expression (4) for T(ω) leads to following expressions for added mass and hydrodynamic damping coefficients:

$$a(\omega)=\sum_{j=0}^{2}\xi^{(j)}\left(\mu^{(j)}+\frac{B_1^{(j)}\left(A_0^{(j)}-\omega^2\right)}{\left(A_0^{(j)}-\omega^2\right)^2+\omega^2A_1^{(j)2}}\right) \qquad (5)$$

$$b(\omega)=\sum_{j=0}^{2}\xi^{(j)}\frac{B_1^{(j)}A_1^{(j)}\omega^2}{\left(A_0^{(j)}-\omega^2\right)^2+\omega^2A_1^{(j)2}} \qquad (6)$$

while following expression is obtained for the retardation function:

$$K(t)=\sum_{j=0}^{2}K^{(j)}(t) \qquad (7)$$

with

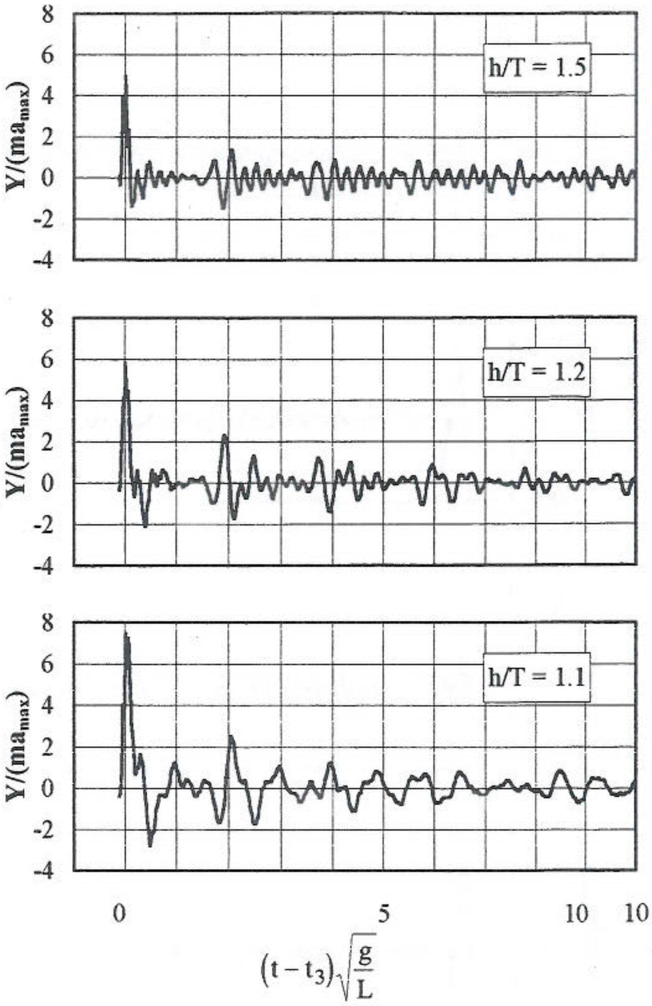

Figure 3. Captive quay wall approach tests with panamax bulk carrier model ($q_M/B = 0.1$, $u = 0$, $n = 0$): lateral force during and after deceleration test. Influence of water depth.

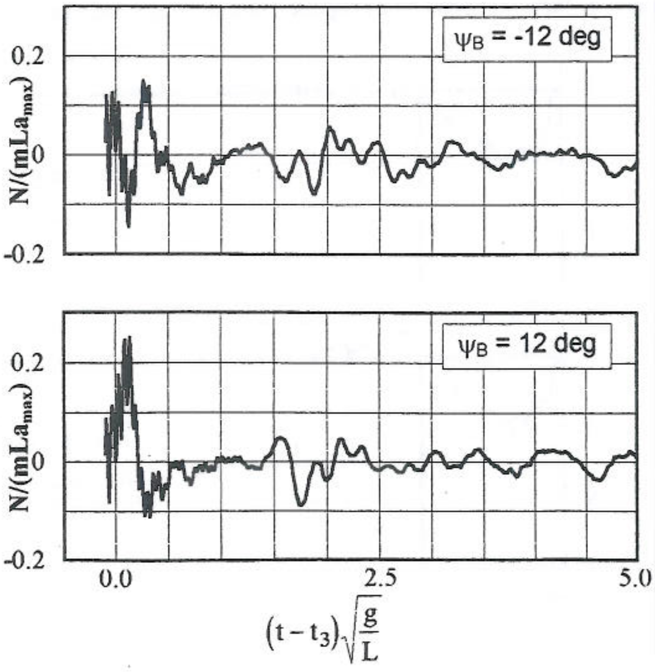

Figure 5. Captive quay wall approach tests with panamax bulk carrier model ($q_M/B = 1.0$, $h/T = 1.2$, $u = 0$, $n = 0$): yawing moment during and after deceleration test. Influence of orientation with respect to quay wall.

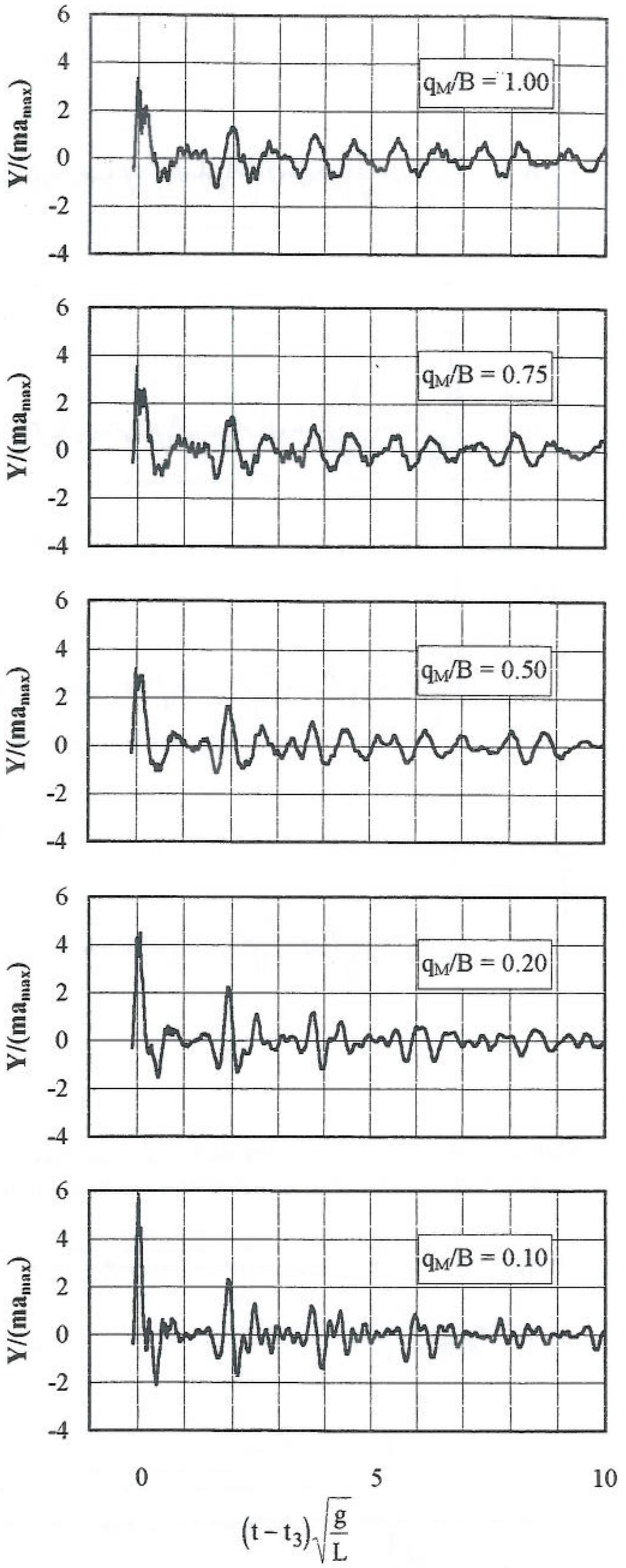

Figure 4. Captive quay wall approach tests with panamax bulk carrier model ($h/T = 1.2$, $u = 0$, $n = 0$): lateral force during and after deceleration test. Influence of water depth.

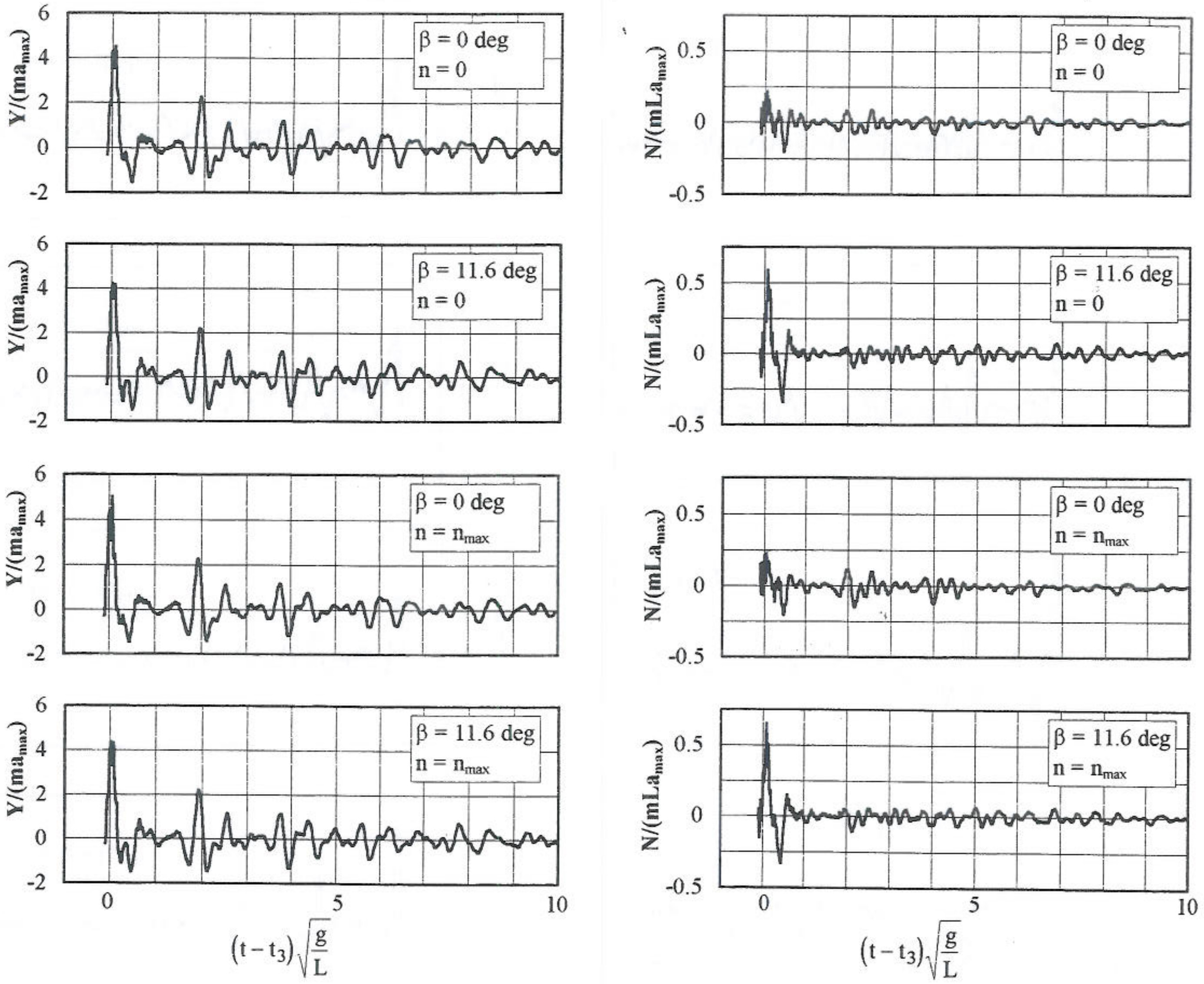

Figure 6. Captive quay wall approach tests with panamax bulk carrier model ($q_M/B = 0.2$, $h/T = 1.2$, $\psi_B = 0$ deg): lateral force and yawing moment during and after deceleration phase. Influence of forward speed and propeller rate during steady phase.

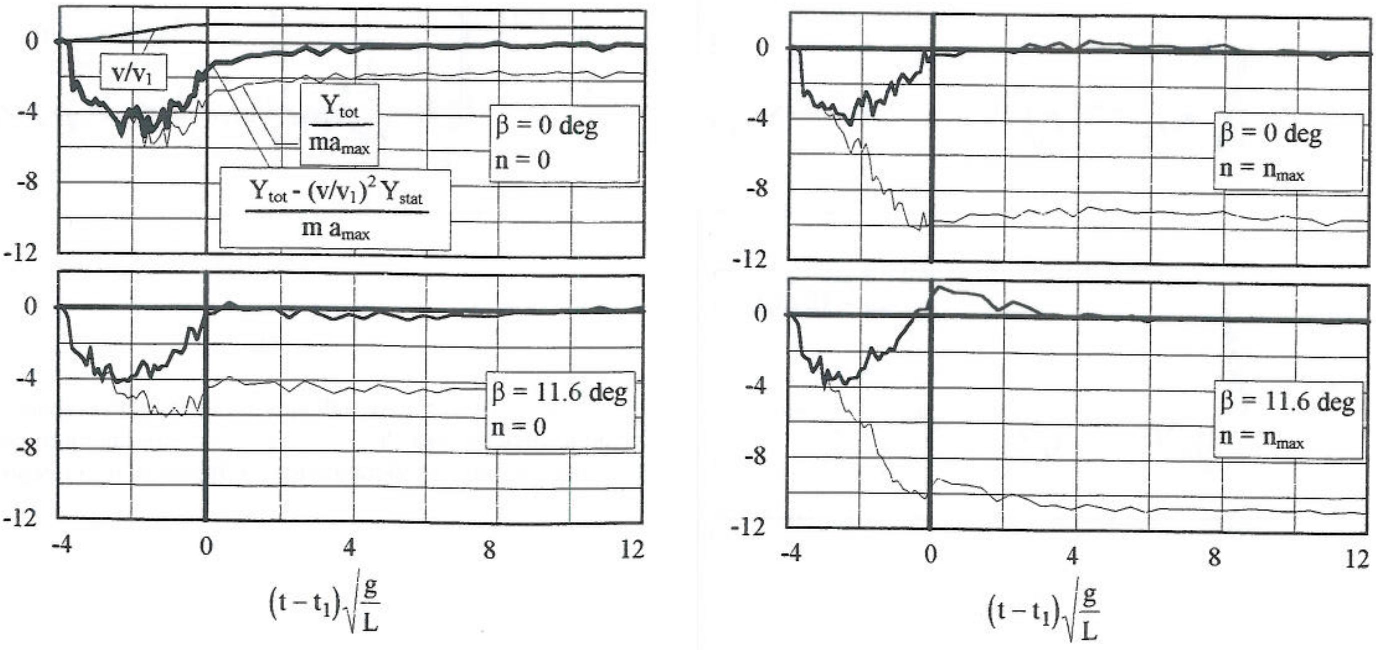

Figure 7. Captive quay wall approach tests with panamax bulk carrier model ($h/T = 1.2$): lateral force during and after acceleration phase. Influence of forward speed and propeller rate during steady phase.

$$
\begin{aligned}
&K^{(j)}(t)\\
&= \xi^{(j)} B_1^{(j)} e^{-\alpha^{(j)} t}\left(\cos\omega_0^{(j)} t - \frac{\alpha^{(j)}}{\omega_0^{(j)}}\sin\omega_0^{(j)} t\right) \text{ if } A_0^{(j)} - \alpha^{(j)^2} > 0\\
&= \xi^{(j)} B_1^{(j)} e^{-\alpha^{(j)} t}\left(1 - \alpha^{(j)} t\right) \qquad \text{if } A_0^{(j)} - \alpha^{(j)^2} = 0\\
&= \xi^{(j)} B_1^{(j)} e^{-\alpha^{(j)} t}\left(\cosh\omega_0^{(j)} t - \frac{\alpha^{(j)}}{\omega_0^{(j)}}\sinh\omega_0^{(j)} t\right)\\
&\qquad \text{if } A_0^{(j)} - \alpha^{(j)^2} < 0
\end{aligned}
\tag{8}
$$

where

$$\alpha^{(j)} = \frac{1}{2} A_1^{(j)} \tag{9}$$

$$\omega_0^{(j)^2} = \left| A_0^{(j)} - \alpha^{(j)^2} \right| \tag{10}$$

The transfer function parameters $\xi^{(j)}$, $A_0^{(j)}$, $A_1^{(j)}$, $B_1^{(j)}$ (j=1,2) depend on the position of the ship referred to the quay wall, i.e. on distance and orientation. An algorithm has been developed for an optimal determination of these parameters if the added mass and hydrodynamic damping coefficients are known functions of frequency.

3.2. Experimental observations

General considerations. Analysis of the results of the captive model tests described in paragraph 2.1 leads to a better qualitative understanding of the significance of the parameters determining non-stationary forces and moments acting on a ship model in a non-steady motion. Following parameters will be considered: water depth (h/T), average quay clearance (q_M/B), orientation with respect to the bank, drift angle (β), propeller action. Both the acceleration and deceleration phases will be discussed, although non-steady phenomena can be observed more clearly during the latter, due to the larger acceleration magnitudes experienced by the ship model. Moreover, the quay clearance parameter was only varied systematically during the deceleration phase.

Water depth. Figure 3 shows the influence of h/T on the time record of the lateral force acting on the decelerating ship model. It is clear that the under keel clearance significantly affects the magnitude of the extrema, as well as their time of occurrance. Dominating frequencies appear to decrease with decreasing water depth.

Average quay clearance. As expected, the distance from the ship's side to the quay wall is a significant parameter. Figure 4 shows that dominating frequencies increase with decreasing quay clearance, while the magnitude of the extrema increases. This effect becomes significant for quay clearance values smaller than half the ship's beam.

Orientation with respect to the bank. The angle between the quay wall and the ship's longitudinal axis of symmetry does not appear to have significant influence on the lateral force. The effect on the yawing moment, on the other hand, can be observed very clearly (figure 5): nonzero values for ψ_B result into additional damped oscillating time functions.

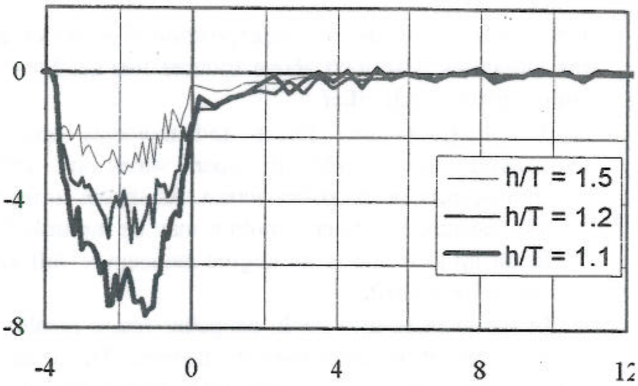

Figure 8. Captive quay wall approach tests with panamax bulk carrier model (β = 0, n = 0): lateral force (Y / ma_{max}) during and after acceleration phase. Influence of water depth.

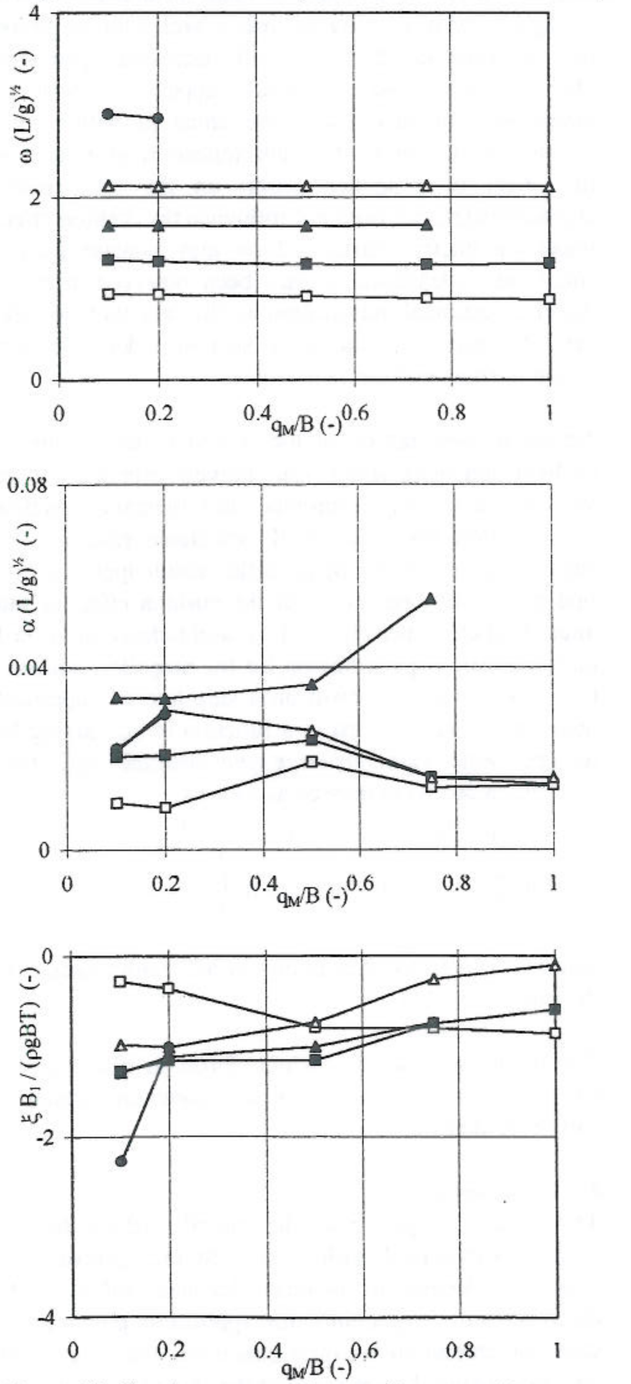

Figure 10. Captive quay wall approach tests with panamax bulk carrier model (u=0, n=0, h/T = 1.2). Lateral force due to lateral motion: influence of quay clearance on transfer function parameters.

Effect of propeller action. Superposition of propeller action to the situations described above induces two kinds of effects, counteracting each other.

- The hydrodynamic forces and moments acting on a swaying ship model in open water are influenced significantly by propeller action. As shown in figure 13a, the resistance to lateral motion may be multiplied with a factor up to 6 due to an engine manoeuvre 'full ahead' in case of pure drift.
- In the vicinity of a bank, propeller action results into an attraction of the stern towards the bank. This bank suction force significantly increases with decreasing water depth (figure 14).

Figure 13a shows that due to bank suction the lateral force acting on a ship moving towards a bank with the propeller at full rate generally decreases with decreasing quay clearance. On the other hand, Y^* always appears to have a larger magnitude compared with the situation without propeller action: the vicinity of the bank appears to eliminate partially the effect of propeller action on the open water drift characteristics, but does not influence the cushion effect. As a result, the lateral resistance force may increase again at very small quay clearance, as has been observed at h/T = 1.1. Another practical implication is the fact that no advantage can be taken from the bank suction induced by propeller action during berthing manoeuvres.

Although combination of forces and moments due to drift, cushion and bank effects qualitatively explains the relationship between quay clearance and dynamics qualitatively, superposition does not yield acceptable results. The bank suction forces induced by propeller action appear to be amplified by the combination with the cushion effect at moderate under keel clearance (h/T = 1.5), and reduced at lower h/T. A more realistic approximation for the propeller induced lateral force and yawing moment on a ship laterally approaching a quay wall should consist of a function of q_M varying between the open water value for large quay clearance and zero for $q_M = 0$, which can be expressed as follows:

$$\frac{Y(\beta,n,\frac{q_M}{B},\frac{h}{T})-Y(\beta,n=0,\frac{q_M}{B},\frac{h}{T})}{Y(\beta,n,\frac{q_M}{B}\to\infty,\frac{h}{T})-Y(\beta,n=0,\frac{q_M}{B}\to\infty,\frac{h}{T})}=1-e^{-k_n\frac{q_M}{B}} \tag{15}$$

where k_n is a factor depending on h/T, with typical values in the range 0.5 - 1.0.

The dominance of the cushion forces is also valid for the yawing moment (figure 13c); an expression similar to (15) can be introduced.

4.3. Conclusion

Test results suggest that the lateral cushion force effect, nondimensionalized with respect to the approach velocity, appears to depend on the quay clearance and the under keel clearance only. Apparently, the application point of this force does not depend on the quay clearance, and, as a result, does not shift during the approach of the ship to the quay wall.

If berthing manoeuvres are combined with engine manoeuvres, the increase of the lateral force and yawing moment due to propeller action which is observed in open water, gradually vanishes with decreasing quay clearance.

Finally, following expression may be used for modelling the cushion effect:

$$\begin{aligned}Y_C\left(\beta,n,\frac{q_M}{B},\frac{h}{T}\right) &=\\ &=\frac{1}{2}\rho v_B^2L^2\,Y'\left(\beta=\pm\frac{\pi}{2},n=0,\frac{q_M}{B}\to\infty,\frac{h}{T}\right)A\,e^{-k\frac{q_M}{B}}\\ &\quad+\left(1-e^{-k_n\frac{q_M}{B}}\right)\bullet\\ &\quad\bullet\left(Y(\beta,n,\frac{q_M}{B}\to\infty,\frac{h}{T})-Y(\beta,n=0,\frac{q_M}{B}\to\infty,\frac{h}{T})\right)\end{aligned} \tag{16}$$

with a similar expression for the yawing moment N_C.

5. CONCLUSION.

Berthing manoeuvres involving lateral motions of a ship towards a quay wall can only be simulated in a realistic way if the mathematical model of the ship manoeuvring simulator takes account of the cushion effect, leading to an increase of the resistance to lateral motion with decreasing quay clearance, and of the memory effects, which become important if accelerations with large magnitude are involved, as in the case of berthing to fenders. Results of systematic series of captive quay wall approach tests have demonstrated the importance of these effects, and have indicated the relevant parameters.

The retardation functions which can be used for describing the memory effects due to unsteady lateral motion can be identified from the test results; the relevant parameters appear to be clearly related to quay clearance. It was also observed that even if moderate accelerations take place, the effect of nonsteady phenomena may be of importance.

For the cushion effect due to lateral approach of a quay wall, an empirical expression was suggested, taking account of approach speed, forward speed and propeller action, and based on open water test results.

Further developments may involve

- the introduction of a more standardised (minimum) test program for bank related effects, including bank suction, cushion forces and memory effects, during which all relevant parameters are varied and which allows the determination of a reliable and realistic bank force simulation module;
- the study of the effect of yawing motion, which was not considered in this test program;
- investigation of more complex bank or quay geometries.

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1. Laforce E., Vantorre M., 1994, "Application of manoeuvring simulation techniques for dimensioning quaywall fenders", 28th International Navigation Congress (PIANC), Sevilla, Section II, Subject 3, pp. 7-16.

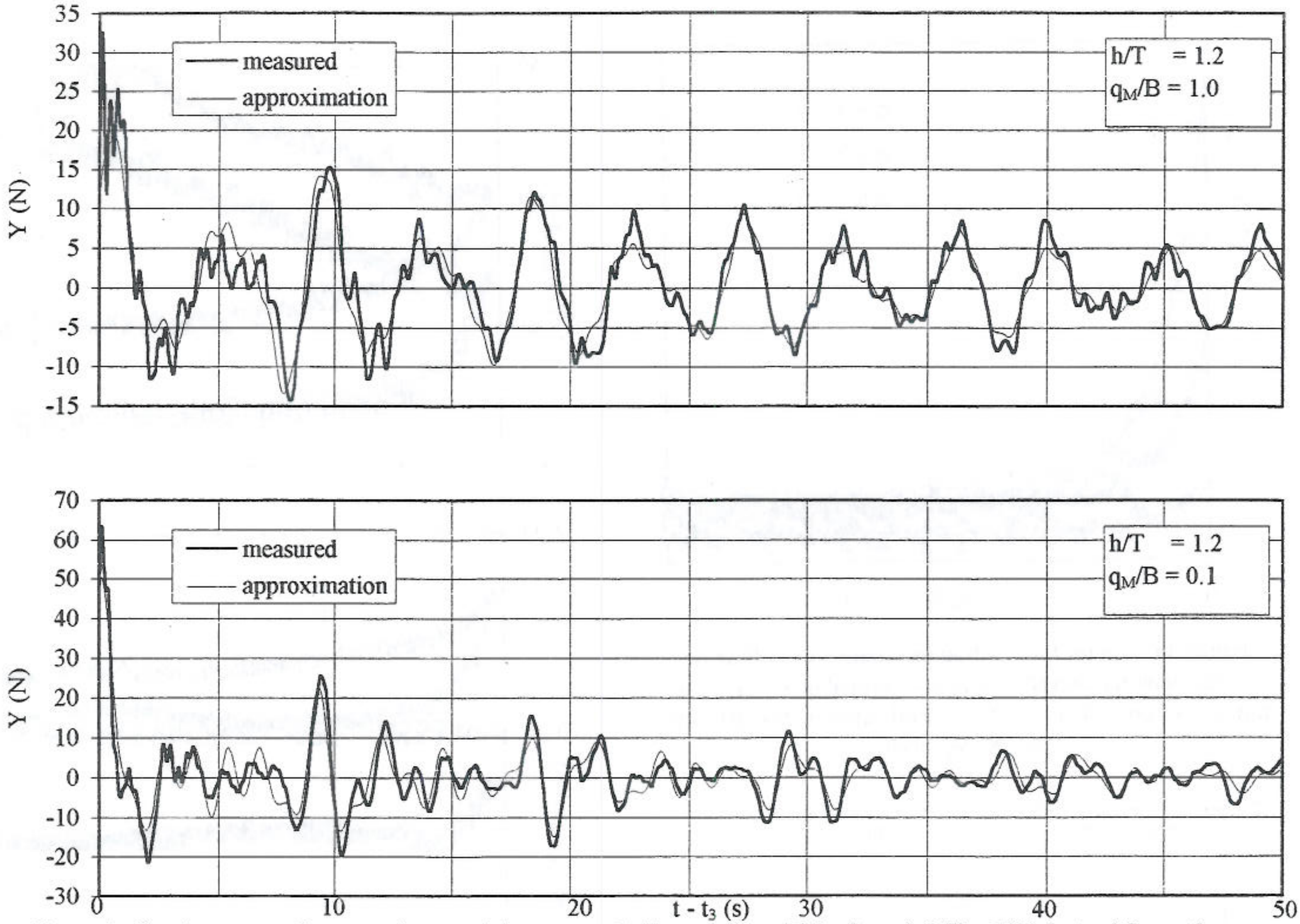


Figure 9. Captive quay wall approach tests with panamax bulk carrier model (u=0, n=0, h/T = 1.2). Lateral force after deceleration : measured time history and approximation.

Drift angle and propeller action. The superposition of a propeller action during the steady phase does not result into significantly different non-stationary dynamics during and after the deceleration phase. The influence of a longitudinal velocity component on the yawing moment acting on the ship model appears to be important, while the effect on the lateral force is rather marginal (see figure 6).

During and immediately after the acceleration phase, a significant influence of propeller action and forward speed on the time history of lateral force is observed, as shown in figure 7. If a purely lateral motion without propeller action is applied, the lateral force only reaches a steady state with some delay; this 'memory effect' is less important if a forward speed is superposed, and is clearly affected by propeller action. Figure 8 shows that this non-stationary phenomenon disappears with increasing under keel clearance.

3.3. Verification of the mathematical model.

Deceleration phase. It was evaluated whether the lateral force acting on the ship model during and after the deceleration phase of captive quay approach tests could be approximated by means of (1), in which the retardation function K was expressed as a sum of exponentially decaying harmonic or hyperbolic time functions, (7)-(8). It was concluded that a fair agreement can be obtained if this sum is extended to four to five terms instead of two or three; figure 9 shows some examples.

The parameters determining the functions (8) obviously have a clear relationship with the quay clearance, as shown in figure 10, displaying the parameters determining the damped harmonic components of the lateral force. The figure displaying ξB_1 shows that these components increase with decreasing quay clearance, except for the component with the lowest frequency. The latter appears to be related to the tank resonance phenomenon, which demonstrates that the influence of the other tank wall, situated at a distance of at least ten times the ship model's beam, cannot be neglected.

It can be concluded that sufficient information can be extracted from a series of captive quay approach test in order to develop a manoeuvring simulation module for calculating non-stationary forces due to lateral accelerations.

Acceleration phase. The memory effects observed during and immediately after the acceleration phase (see figures 7-8) can be simulated by a adaptation of the open water transfer function. Such an approach results into rather unrealistic corresponding frequency domain characteristics, but this should not be considered as an important disadvantage for manoeuvring simulation. It should be born in mind, however, that the physical background is related to the establishment of a steady flow around the laterally moving ship model, rather than to frequency characteristics. Although the phenomenon is only observed at zero forward speed, it could lead to new insight concerning the interpretation of PMM sway test results.

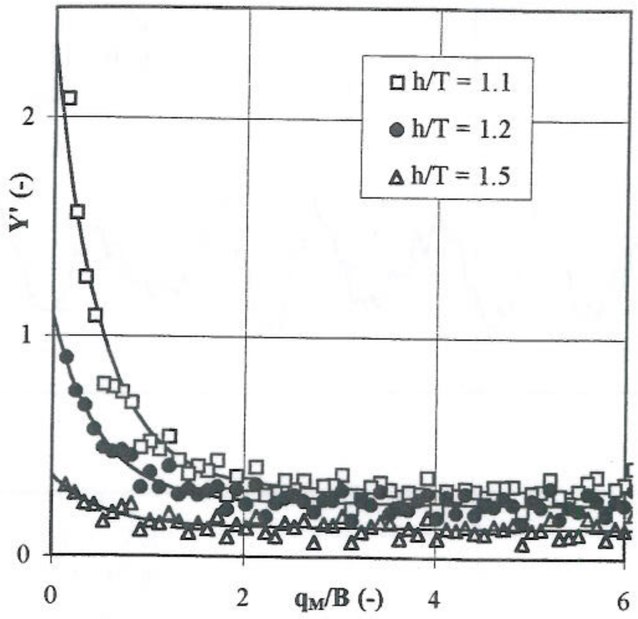


Figure 11. Lateral force acting on a panamax bulkcarrier model moving laterally towards a vertical quay wall as a function of quay clearance for several depth to draught ratios (β=-90 deg, n=0).

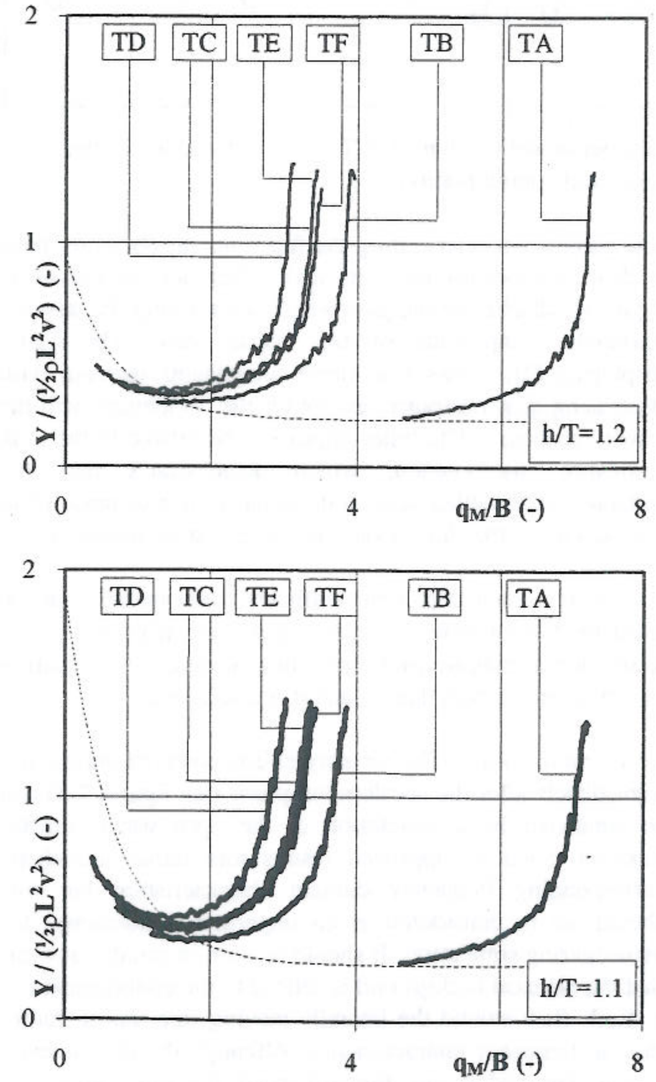
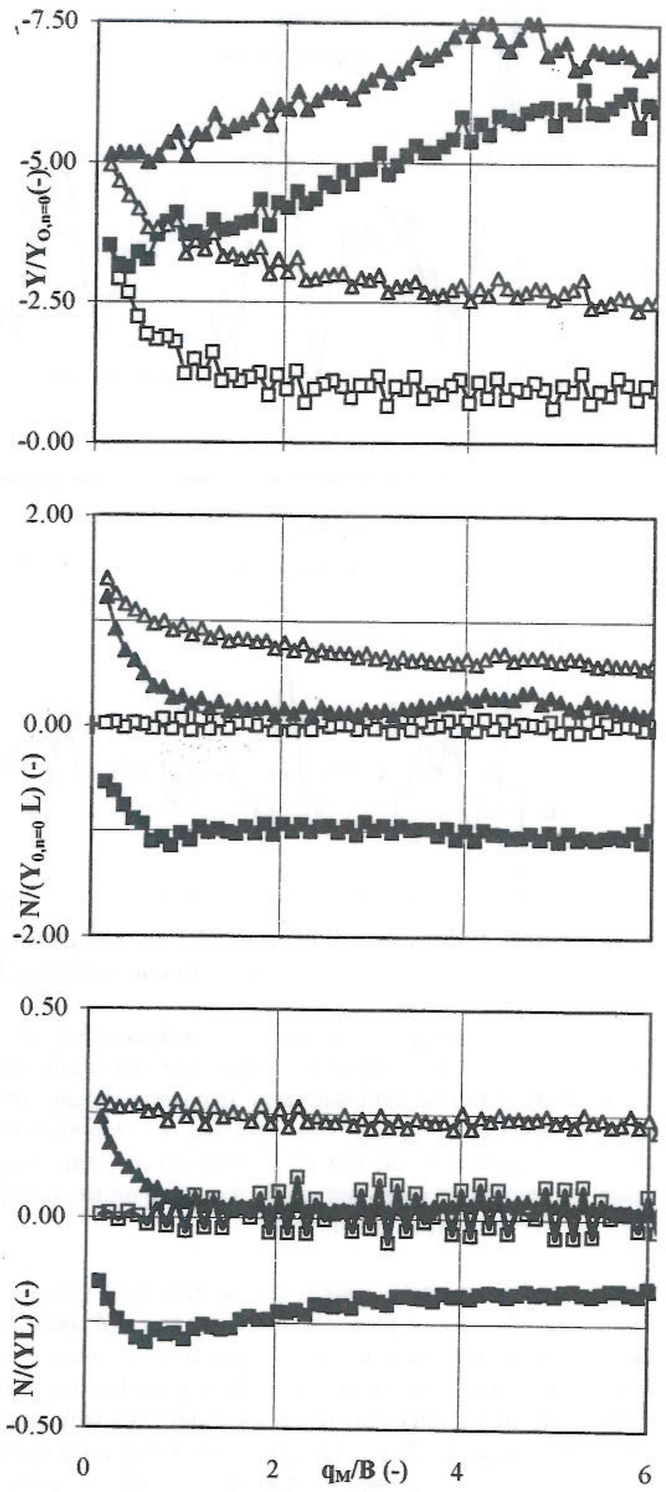


Figure 12. Free quay wall approach test with container carrier model: nondimensional force as a function of quay clearance during acceleration and approach phase.



	β = 90.0 deg	β = 11.6 deg
n = 0	□	Δ
n = n_{max}	■	▲

Figure 13. Nondimensional representation of lateral force and yawing moment acting on a panamax bulkcarrier model moving towards a vertical quay wall as a function of quay clearance : influence of forward velocity and propeller action (h/T = 1.2).

4. CUSHION EFFECT

4.1. General considerations

Hydrodynamic forces and moments acting on a ship model approaching a quay wall with constant lateral speed v and forward speed u in combination with propeller action (constant propeller rate n) are the result of several influences:

- forces and moments (Y_O, N_O) due to drift in open water, being functions of:
  - the speed vector **V**, characterised by its components (u, v), or its magnitude and argument (V, β);
  - the propeller action;
- bank suction effects (Y_B, N_B) due to:
  - the speed component u_B parallel to the quay wall;
  - the propeller action;
- cushion effects (Y_C, N_C), due to the speed component v_B perpendicular to the quay wall (approach speed).

The results of captive approach manoeuvres were compared with open water oblique towing tests and bank suction tests during which a course parallel to the quay wall was implied, in order to determine the effect of the approach speed.

Due to the limited values of the angle ψ_B between the ship's longitudinal axis and the quay wall ($|\psi_B| \leq 12$ deg), v_B can be approximated by the lateral speed component v. As the effect of the approach speed $v_B \approx v$ is taken into consideration, nondimensional values for lateral force and yawing motion will be defined as follows:

$$Y^* = \frac{Y}{\frac{1}{2}\rho v_B^2 L^2} \quad ; \quad N^* = \frac{N}{\frac{1}{2}\rho v_B^2 L^3} \qquad (11)$$

and will be functions of the drift angle β, the propeller rate n, the quay clearance q_M, the orientation ψ_M with respect to the quay wall, and the depth to draught ratio h/T.

4.2. Experimental observations

Lateral motion towards a quay wall, no propeller action. The nondimensional lateral force Y^*, acting on a ship laterally moving towards a quay wall ($\beta = \pm\frac{1}{2}\pi$) without propeller action (n=0), appears to be independent of the approach speed $V = v \approx v_B$, and can be considered as a function of the relative quay clearance q_M/B and the water depth to draught ratio h/T. No significant influence of the ship model's orientation with respect to the quay wall was observed.

The influence of quay clearance can be approximated as follows:

$$\frac{Y^*\left(\beta = \pm\frac{\pi}{2}, n = 0, \frac{q_M}{B}, \frac{h}{T}\right)}{Y^*\left(\beta = \pm\frac{\pi}{2}, n = 0, \frac{q_M}{B} \to \infty, \frac{h}{T}\right)} = 1 + A\,e^{-k\frac{q_M}{B}} \qquad (12)$$

with $k \approx 2$. The factor $A \equiv Y^*_{C0} \div Y^*_O$, being the ratio between

- the lateral cushion force Y^*_{C0} for zero quay clearance:

$$Y^*_{C0} = Y^*\left(\beta = \pm\frac{\pi}{2}, n = 0, \frac{q_M}{B} \to 0, \frac{h}{T}\right) - Y^*\left(\beta = \pm\frac{\pi}{2}, n = 0, \frac{q_M}{B} \to \infty, \frac{h}{T}\right) \qquad (13)$$

- and the lateral force Y^*_O due to pure sway in open water:

$$Y^*_{O0} = Y^*\left(\beta = \pm\frac{\pi}{2}, n = 0, \frac{q_M}{B} \to \infty, \frac{h}{T}\right) \qquad (14)$$

strongly depends on h/T, as shown in figure 11, representing captive model test results.

For the considered ship type, the yawing moment due to pure lateral motion appears to be negligible in the full range of quay clearances, which means that the application point of the lateral force is located midships.

The conclusions of the captive model test results were also qualitatively confirmed by the free model tests, as illustrated in figure 12, where Y' is plotted as a function of q_M/B. In open water, the ship model is still accelerating at collision time, while due to the presence of the quay wall the ship's speed is already decreasing before touching the springs. The parts of the curves representing the deceleration phases appear to coincide very well, in spite of the variety of speeds and quay wall configurations. Figure 12 also displays a function suggested by expression (12) connecting the minima of the $Y'(q_M/B)$-curves, where inertia forces are not active.

Effect of forward speed. As the nondimensional lateral force $Y' = Y \div (\frac{1}{2}\rho V^2 L^2)$ and yawing moment $N' = N \div (\frac{1}{2}\rho V^2 L^3)$ are functions of the drift angle β, the superposition of a longitudinal speed component affects the open water values for Y' and N' and, therefore, for Y^* and N^*. With decreasing quay clearance, the velocity component u_B parallel to the quay wall induces bank suction effects, but due to the very low speed the latter are not to be considered as significant compared to drift forces and cushion effects. It should also be mentioned here that at very limited under keel clearance bank rejection may take place instead of bank suction.

Compared to the results of pure sway tests, the forward speed component appears to induce a vertical shift of the $Y^*(q_M/B)$-curve (figure 13a), which indicates that the cushion effect only depends on the approach speed v_B. The yawing moment, on the other hand, increases while the ship approaches the quay (figure 13b), but the location of the point of application of the lateral force remains unaffected (figure 13c).

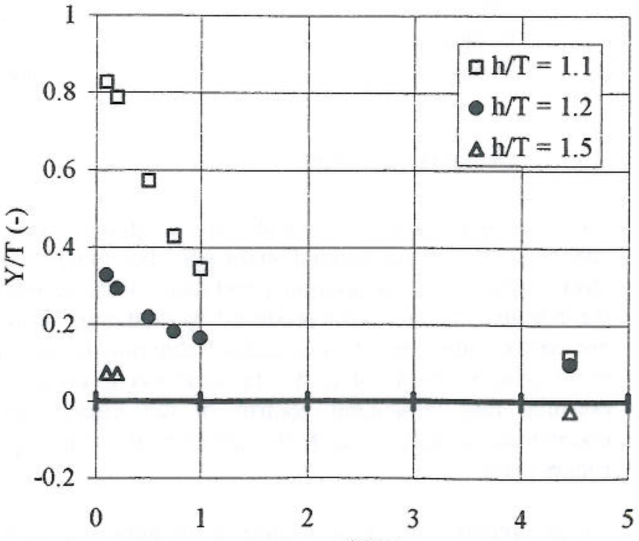


Figure 14. Lateral bank suction force on a panamax bulkcarrier model at zero speed due to propeller action: influence of under keel clearance (u=0, v=0).