MOTIONS OF RECTANGULAR BARGES

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MOTIONS OF RECTANGULAR BARGES

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ABSTRACT

In the present paper the applicability of the relatively simple ordinary strip-theory for the prediction of the frequency characteristics of the motions of rectangular barges is investigated.
Special attention is paid to the formulation of the wave loads at a restricted waterdepth. The classic approach and the present approach for the determination of the diffraction part of the wave loads has been described.
The results of the calculations according to these two approaches are compared with some results of an extensive series of model tests of rectangular barges with a range of length-breadth and breadth-draught ratios. With both approaches a fair agreement has been found for the heave and pitch responses. But the present approach results in much better predictions for roll motions.
It is concluded that the ordinary strip-theory method can be used safely for a first estimation of the motions of rectangular barges with a length-breadth ratio of 3.0 or higher.

NOMENCLATURE

B	breadth of the model
FK_i'	two-dimensional Froude-Krilov force or moment in the direction i; this is the load in the direction i on a cross section, caused by the undisturbed wave
Fn	Froude number = $V/(g \cdot L)^{1/2}$
GM	metacentric height
I_{xx}	solid mass moment of inertia
KG	height of the centre of gravity above the keel
L	length of the model
M_{ii}'	two-dimensional potential hydrodynamic mass coefficient of motion i
M_{ij}'	two-dimensional potential hydrodynamic mass coupling coefficient of motion j into motion i
N_{ii}'	two-dimensional potential hydrodynamic damping coefficient of motion i
N_{ij}'	two-dimensional potential hydrodynamic damping coupling coefficient of motion j into motion i
OG	height of the centre of gravity above the still water level
T	local or midship draught of the model
T_φ	natural roll period
V	forward speed of the model
X_{wi}'	two-dimensional exciting wave force or moment
bG	height of the centre of gravity above the centroid of the cross section
g	acceleration of gravity
h	water depth
k	wave number = $2 \cdot \pi / \lambda$
k_{yy}	radius of inertia for pitch of the solid mass of the model
$k_{\varphi\varphi}$	radius of inertia for roll of the solid and hydrodynamic mass of the model
p	pressure
t	time
y_w	local half breadth at the waterline
z	heave displacement
Φ_w	wave potential
∇	volume of displacement
ϵ	phase lag
φ	roll angle
κ	non-dimensional roll damping coefficient
λ	wave length
μ	wave direction
ρ	density of water
θ	pitch angle
ω	circular wave frequency
ω_e	circular frequency of encounter
ζ	elevation of the wave surface
ζ_a	regular wave amplitude
ζ_{wi}^*	the equivalent "direction i" component of the orbital velocity of the waterparticles in the undisturbed wave, relative to the cross section

For the coordinate systems and the axes reference is given to figure 4 in Appendix I.

INTRODUCTION

Barges play an important role in offshore operations. They are used in varied forms such as transportation, launching, mounting derrick, pipelaying and also for storage and production. The workability of these barges is often obtained from their motion characteristics in waves, when towed to or moored at the work location. For a proper assessment of the workability, accurate computational methods for the prediction of the motions are required.

In the present paper the applicability of the relatively simple ordinary strip-theory for the predictions of the frequency characteristics of the motions is investigated. Special attention is paid to the formulation of the wave loads at a restricted water depth.

In strip-theory calculations, the wave loads on a ship are found by integrating the two-dimensional loads on the cross sections of a restrained ship over the ship length. These loads consist of a Froude-Krilov part and a diffraction part.

The present approach expands the Froude-Krilov force or moment in deep water waves in series. The dominating term in the relevant part of the series delivers equivalent directional components of the orbital acceleration and velocity. These components are then used to calculate the diffraction part of the wave loads.

In the classic approach, as generally presented for deep water in the literature, for each cross section an average pressure level is found in such a manner that the pressure at this level delivers the Froude-Krilov force or moment. This level is used to calculate the diffraction part of the wave loads.

The two approaches are described here. The results of the calculations are compared with some results of an extensive series of model tests in deep water, involving different rectangular barge models with varying length-breadth and breadth-draught ratios.

For the heave and pitch motions, the differences between the results of the two approaches are very small and a fair agreement with the experimental data has been found.

For the roll motions the present approach delivers a fair agreement. The results are much better than those obtained by using the classic approach, which does not include the contribution of the potential coefficients for roll into the diffraction part of the wave moment.

It is concluded that the ordinary strip-theory method can be used safely for a first estimation of the motions of rectangular barges with a length-breadth ratio of 3.0 or higher.

TWO-DIMENSIONAL WAVE LOADS

Attention will be paid here to the right hand terms of the equations of motions of a sailing ship or barge. For a description of the determination of the left hand terms reference is given to [1]. According to Haskind the exciting wave forces and moments, defined by a Froude-Krilov part and a diffraction part, on a restrained cross section of a ship in waves will be of the following form:

$$X_{wi}' = \frac{D}{Dt}\left[M_{ii}' \cdot \dot{\zeta}_{wi}^{*} \right] + N_{ii}' \cdot \dot{\zeta}_{wi}^{*} + FK_i'$$

with:

$$\frac{D}{Dt} = \left[\frac{\partial}{\partial t} - V \cdot \frac{\partial}{\partial x_b} \right]$$

Froude-Krilov Loads and Orbital Motions

The two-dimensional Froude-Krilov force or moment FK_i' is calculated by an integration of the directional pressure gradient or the directional component of the orbital acceleration in the undisturbed wave over the cross sectional area of the hull. The axes system and these phenomena have been given in Appendix I. Equivalent directional components of the orbital acceleration and velocity, derived from the Froude-Krilov force or moment, are used to calculate the diffraction part of the wave force or moment.

The present approach expands the Froude-Krilov force or moment in deep water with $\lambda >> 2\pi \cdot y_w$ and $\lambda >> 2\pi \cdot T$ in series. So an approximation of this force or moment will be found.

With the Froude-Krilov force or moment and the dominating term in the relevant part of the series, equivalent directional components of the orbital acceleration and velocity are found.

The classic approach, see for instance [2] and [3], defines an average pressure level in such a manner that the pressure at this level delivers the Froude-Krilov force or moment. This average pressure level is used to obtain equivalent directional components of the orbital acceleration and velocity.

In the derivation of these components the area and the moments of a cross section are used:

$$A = 2 \cdot \int_{-T}^{0} y_b \cdot dz_b \qquad S_y = 2 \cdot \int_{-T}^{0} y_b \cdot z_b \cdot dz_b$$

$$I_y = 2 \cdot \int_{-T}^{0} y_b \cdot z_b^2 \cdot dz_b \qquad I_z = 2/3 \cdot \int_{-T}^{0} y_b^3 \cdot dz_b$$

Also has been defined for the surge, sway, heave and roll motions:

$$\ddot{\zeta}_{wi}' = \frac{D}{Dt}\left[\dot{\zeta}_{wi}' \right] \qquad \text{for } i = 1, 2, 3, 4$$

Orbital Motions in the Surge Direction

The Froude-Krilov force in the surge direction is given by:

$$FK_1' = -\int_{-T}^{\zeta} \int_{-y_b}^{+y_b} \frac{\partial p}{\partial x_b} \cdot dy_b \cdot dz_b$$

$$= +\rho \cdot \int_{-T}^{\zeta} \int_{-y_b}^{+y_b} \ddot{\zeta}_{w1}^{*} \cdot dy_b \cdot dz_b$$

After neglecting the second order terms, this can be written as:

$$FK_1' = -\rho \cdot A_{ch} \cdot k \cdot g \cdot \cos\mu \cdot \zeta_a \cdot \sin(\omega_e t - kx_b \cos\mu)$$

with:

$$A_{ch} = 2 \cdot \int_{-T}^{0} \frac{\sin(-ky_b \sin\mu)}{-ky_b \sin\mu} \cdot \frac{\cosh k(h+z_b)}{\cosh kh} \cdot y_b \cdot dz_b$$

When expanding the Froude-Krilov force in deep water with $\lambda >> 2\pi \cdot y_w$ and $\lambda >> 2\pi \cdot T$ in series, it is found:

$$FK_1' \approx -\rho \cdot \left[A + S_y \cdot k + I_y \cdot \tfrac{1}{2} k^2 + \ldots \right] \cdot$$

$$\cdot k \cdot g \cdot \cos\mu \cdot \zeta_a \cdot \sin(\omega_e t - kx_b \cos\mu)$$

The acceleration term "$k \cdot g \cdot \cos\mu \cdot \zeta_a$" here is the amplitude of the longitudinal component of the relative orbital acceleration in deep water at $z_b=0$.

The dominating first term in this series consists of a mass and an acceleration.
This mass term "$\rho \cdot A$" is used to obtain from the total Froude-Krilov force an equivalent longitudinal component of the orbital acceleration of the water particles:

$$FK_1' = \rho \cdot A \cdot \ddot{\zeta}_{w1}^*$$

This holds that the equivalent longitudinal components of the orbital acceleration and velocity are equal to the values at $z_b=0$ in a wave with a reduced amplitude ζ_{a1}^*:

$$\ddot{\zeta}_{w1}^* = -k \cdot g \cdot \cos\mu \cdot \zeta_{a1}^* \cdot \sin(\omega_e t - kx_b \cos\mu)$$

$$\dot{\zeta}_{w1}^* = +k \cdot g/\omega \cdot \cos\mu \cdot \zeta_{a1}^* \cdot \cos(\omega_e t - kx_b \cos\mu)$$

with:

$$\zeta_{a1}^* = \frac{A_{ch}}{A} \cdot \zeta_a$$

This equivalent acceleration and velocity will be used in the diffraction part of the wave force too.

In the classic approach an average pressure level $z_b=-T_1^*$ in the fluid is defined in such a manner that the pressure at this level delivers the Froude-Krilov force. For this, first a vertical integration has been carried out, followed by a horizontal one while keeping the pressure constant.

$$FK_1' = -\rho \cdot 2y_w/k \cdot \frac{\sin(-ky_w \sin\mu)}{-ky_w \sin\mu} \cdot$$

$$\cdot \left[1 - \frac{\sinh k(h-T_1^*)}{\cosh kh} \right] \cdot k \cdot g \cdot \cos\mu \cdot \zeta_a \cdot$$

$$\cdot \sin(\omega_e t - kx_b \cos\mu)$$

With the expression for the Froude-Krilov force, found before, it follows:

$$\frac{\sinh k(h-T_1^*)}{\cosh kh} = 1 - \frac{-ky_w \sin\mu}{\sin(-ky_w \sin\mu)} \cdot \frac{A_{ch}}{2y_w/k}$$

This means that the mass term "$\rho \cdot A$" in the series expansion is used again to obtain an equivalent longitudinal component of the orbital acceleration of the water particles from the total Froude-Krilov force.
This holds that in the classic approach the reduced wave amplitude ζ_{a1}^* is given by:

$$\zeta_{a1}^* = \frac{2y_w/k}{A} \cdot \frac{\sin(-ky_w \sin\mu)}{-ky_w \sin\mu} \cdot$$

$$\cdot \left[1 - \frac{\sinh k(h-T_1^*)}{\cosh kh} \right] \cdot \zeta_a$$

So for the equivalent orbital motions in the surge direction, it is clear that the present approach will produce the same results as the classic approach.

Orbital Motions in the Sway Direction

The Froude-Krilov force in the sway direction is given by:

$$FK_2' = -\int_{-T}^{\zeta} \int_{-y_b}^{+y_b} \frac{\partial p}{\partial y_b} \cdot dy_b \cdot dz_b$$

$$= +\rho \cdot \int_{-T}^{\zeta} \int_{-y_b}^{+y_b} \ddot{\zeta}_{w2}^* \cdot dy_b \cdot dz_b$$

The derivations for sway are conformable to those given for surge, when replacing there "$k \cdot g \cdot \cos\mu \cdot \zeta_a$" by "$k \cdot g \cdot \sin\mu \cdot \zeta_a$".

Orbital Motions in the Heave Direction

The Froude-Krilov force in the heave direction is given by:

$$FK_3' = -\int_{-T}^{\zeta} \int_{-y_b}^{+y_b} \frac{\partial p}{\partial z_b} \cdot dy_b \cdot dz_b$$

$$= +\rho \cdot \int_{-T}^{\zeta} \int_{-y_b}^{+y_b} (g + \ddot{\zeta}_{w3}^*) \cdot dy_b \cdot dz_b$$

After neglecting the second order terms, this can be written as:

$$FK_3' = -\rho \cdot \left[-2y_w/k \cdot \frac{\sin(-ky_w \sin\mu)}{-ky_w \sin\mu} + A_{sh} \right] \cdot$$

$$\cdot k \cdot g \cdot \zeta_a \cdot \cos(\omega_e t - kx_b \cos\mu)$$

with:

$$A_{sh} = 2 \cdot \int_{-T}^{0} \frac{\sin(-ky_b \sin\mu)}{-ky_b \sin\mu} \cdot \frac{\sinh k(h+z_b)}{\cosh kh} \cdot y_b \cdot dz_b$$

When expanding the Froude-Krilov force in deep water with $\lambda >> 2\pi \cdot y_w$ and $\lambda >> 2\pi \cdot T$ in series, it is found:

$$FK_3' \approx -\rho \cdot \Big[\{-2y_w/k\} + \{A+S_y \cdot k + I_y \cdot \tfrac{1}{2}k^2 + \ldots\} \Big] \cdot \cdot k \cdot g \cdot \zeta_a \cdot \cos(\omega_e t - kx_b \cos\mu)$$

The acceleration term "$k \cdot g \cdot \zeta_a$" here is the amplitude of the vertical component of the relative orbital acceleration in deep water at $z_b=0$.

The first part of this series represents a quasi-static restoring spring term due to the elevation of the wave surface.
The dominating first term in the second part of this series consists of a mass and an acceleration.
This mass term "$\rho \cdot A$" is used to obtain from the second part of the Froude-Krilov force an equivalent vertical component of the orbital acceleration of the water particles:

$$FK_3' = 2\rho g y_w \cdot \zeta + \rho \cdot A \cdot \ddot{\zeta}_{w3}^*$$

This holds that the equivalent vertical components of the orbital acceleration and velocity are equal to the values at $z_b=0$ for a wave with a reduced amplitude ζ_{a3}^*:

$$\ddot{\zeta}_{w3}^* = -\tanh(kh) \cdot k \cdot g \cdot \zeta_{a3}^* \cdot \cos(\omega_e t - kx_b \cos\mu)$$

$$\dot{\zeta}_{w3}^* = +\tanh(kh) \cdot k \cdot g/\omega \cdot \zeta_{a3}^* \cdot \sin(\omega_e t - kx_b \cos\mu)$$

with:

$$\zeta_{a3}^* = \frac{A_{sh}}{A \cdot \tanh(kh)} \cdot \zeta_a$$

This equivalent acceleration and velocity will be used in the diffraction part of the wave force too.

In the classic approach an average pressure level $z_b=-T_3^*$ in the fluid is defined in such a manner that the pressure at this level delivers the total Froude-Krilov force. So the restoring spring term will be included.
For this, first a vertical integration has been carried out, followed by a horizontal one while keeping the pressure constant.

$$FK_3' = \rho \cdot 2y_w/k \cdot \frac{\sin(-ky_w \sin\mu)}{-ky_w \sin\mu} \cdot \frac{\cosh k(h-T_3^*)}{\cosh kh} \cdot \cdot k \cdot g \cdot \zeta_a \cdot \cos(\omega_e t - kx_b \cos\mu)$$

With the expression for the Froude-Krilov force, as found before, it follows:

$$\frac{\cosh k(h-T_3^*)}{\cosh kh} = 1 - \frac{-ky_w \sin\mu}{\sin(-ky_w \sin\mu)} \cdot \frac{A_{sh}}{2y_w/k}$$

This means that the spring term in the series expansion is used as a mass term, to obtain an equivalent vertical component of the orbital acceleration of the water particles from the total Froude-Krilov force:

$$FK_3' = -\rho \cdot 2y_w/k \cdot \ddot{\zeta}_{w3}^*$$

This holds that in the classic approach the reduced wave amplitude ζ_{a3}^* is given by:

$$\zeta_{a3}^* = \frac{kg}{\omega^2} \cdot \frac{\sin(-ky_w \sin\mu)}{-ky_w \sin\mu} \cdot \frac{\cosh k(h-T_3^*)}{\cosh kh} \cdot \zeta_a$$

So for the equivalent orbital motions in the heave direction, the present approach will produce results different from the classic approach.

<u>Orbital Motions in the Roll Direction</u>

The Froude-Krilov moment in the roll direction is given by:

$$FK_4' = -\int_{-T}^{\zeta}\int_{-y_b}^{+y_b} \Big[-\frac{\partial p}{\partial y_b} \cdot z_b + \frac{\partial p}{\partial z_b} \cdot y_b\Big] \cdot dy_b \cdot dz_b$$

$$= +\rho \cdot \int_{-T}^{\zeta}\int_{-y_b}^{+y_b} \Big[-\ddot{\zeta}_{w2}^* \cdot z_b + (g+\ddot{\zeta}_{w3}^*) \cdot y_b\Big] \cdot dy_b \cdot dz_b$$

After neglecting the second order terms, this can be written as:

$$FK_4' = -\rho \cdot \Big[-C_{yw}/k - S_{ych}/k + I_{zsh} \Big] \cdot \cdot k^2 \cdot g \cdot \sin\mu \cdot \zeta_a \cdot \sin(\omega_e t - kx_b \cos\mu)$$

with:

$$C_{yw} = 2 \cdot \frac{\dfrac{\sin(-ky_w \sin\mu)}{-ky_w \sin\mu} - \cos(-ky_w \sin\mu)}{(ky_w \sin\mu)^2} \cdot y_w^3$$

$$S_{ych} = 2 \cdot \int_{-T}^{0} \frac{\sin(-ky_b \sin\mu)}{-ky_b \sin\mu} \cdot \frac{\cosh k(h+z_b)}{\cosh kh} \cdot \cdot y_b \cdot z_b \cdot dz_b$$

$$I_{zsh} = 2 \cdot \int_{-T}^{0} \frac{\dfrac{\sin(-ky_b \sin\mu)}{-ky_b \sin\mu} - \cos(-ky_b \sin\mu)}{(ky_b \sin\mu)^2} \cdot \cdot \frac{\sinh k(h+z_b)}{\cosh kh} \cdot y_b^3 \cdot dz_b$$

When expanding the Froude-Krilov moment in deep water with $\lambda >> 2\pi \cdot y_w$ and $\lambda >> 2\pi \cdot T$ in series, it is found:

$$FK_4' \approx -\rho \cdot \Big[\{-2/3 \cdot y_w^3/k\} - \{S_y/k + I_y + \ldots\} + + \{I_z + \ldots\}\Big] \cdot \cdot k^2 \cdot g \cdot \sin\mu \cdot \zeta_a \cdot \sin(\omega_e t - kx_b \cos\mu)$$

The acceleration term "$k^2 \cdot g \cdot \sin\mu \cdot \zeta_a$" in here is the amplitude of the roll component of the relative orbital acceleration in deep water at $z_b=0$.

The first part of this series represents a quasi-static restoring spring term due to the wave slope.

The second part of this series represents the contribution of the Froude-Krilov force of sway into the roll moment.
The third part of this series represents the pure roll moment, caused by the vertical component of the orbital acceleration. The dominating term in this part consists of a mass moment of inertia and an angular acceleration. This mass moment of inertia term "$\rho \cdot I_z$" is used to obtain from the third part of the Froude-Krilov moment an equivalent roll component of the orbital acceleration of the water particles:

$$FK_4' = \rho \cdot 2/3 \cdot y_w^3 \cdot k \cdot g \cdot \sin\mu \cdot \zeta - \rho \cdot S_y \cdot \ddot{\zeta}_{w2}^* + \rho \cdot I_z \cdot \ddot{\zeta}_{w4}^*$$

This holds that the equivalent roll components of the orbital acceleration and velocity are equal to the values at $z_b=0$ for a wave with a reduced amplitude ζ_{a4}^*:

$$\ddot{\zeta}_{w4}^* = -\tanh(kh) \cdot k^2 \cdot g \cdot \sin\mu \cdot \zeta_{a4}^* \cdot \sin(\omega_e t - kx_b \cos\mu)$$

$$\dot{\zeta}_{w4}^* = +\tanh(kh) \cdot k^2 \cdot g/\omega \cdot \sin\mu \cdot \zeta_{a4}^* \cdot \cos(\omega_e t - kx_b \cos\mu)$$

with:

$$\zeta_{a4}^* = \frac{I_{zsh}}{I_z \cdot \tanh(kh)} \cdot \zeta_a$$

This equivalent angular acceleration and velocity will be used in the diffraction part of the wave moment too.

From the classic approach has been found that $T_1^*=T_2^*=T^*$ and for deep water that $T_3^*=T^*$.
It is supposed in this approach that also the diffraction part of the wave moment for roll acts at the level $z_b=-T^*$ in the fluid.
Then an equivalent roll component of the orbital acceleration is obtained from the equivalent lateral component of the orbital acceleration at this level $-T^*$:

$$\ddot{\zeta}_{w4}^* = \ddot{\zeta}_{w2}^* \cdot k \cdot \tanh k(h-T^*)$$

This holds that in the classic approach the reduced wave amplitude ζ_{a4}^* is given by:

$$\zeta_{a4}^* = \frac{2y_w/k}{A} \cdot \frac{\sin(-ky_w \sin\mu)}{-ky_w \sin\mu} \cdot \frac{\tanh k(h-T^*)}{\tanh kh} \cdot \left[1 - \frac{\sinh k(h-T^*)}{\cosh kh} \right] \cdot \zeta_a$$

So for the equivalent orbital motions in the roll direction, the present approach will produce results different from the classic approach.

<u>Total Exciting Wave Forces and Moments</u>

With the previous formulations for the present approach, the two-dimensional exciting wave forces and moments are defined by a Froude-Krilov part and a diffraction part as given below.

Surge:

$$X_{w1}' = +M_{11}' \cdot \ddot{\zeta}_{w1}^* + \left[N_{11}' - V \cdot \frac{dM_{11}'}{dx_b}\right] \cdot \dot{\zeta}_{w1}^* + FK_1'$$

Sway:

$$X_{w2}' = +M_{22}' \cdot \ddot{\zeta}_{w2}^* + \left[N_{22}' - V \cdot \frac{dM_{22}'}{dx_b}\right] \cdot \dot{\zeta}_{w2}^* + FK_2' + M_{24}' \cdot \ddot{\zeta}_{w4}^* + \left[N_{24}' - V \cdot \frac{dM_{24}'}{dx_b}\right] \cdot \dot{\zeta}_{w4}^*$$

Heave:

$$X_{w3}' = +M_{33}' \cdot \ddot{\zeta}_{w3}^* + \left[N_{33}' - V \cdot \frac{dM_{33}'}{dx_b}\right] \cdot \dot{\zeta}_{w3}^* + FK_3'$$

Roll:

$$X_{w4}' = +M_{44}' \cdot \ddot{\zeta}_{w4}^* + \left[N_{44}' - V \cdot \frac{dM_{44}'}{dx_b}\right] \cdot \dot{\zeta}_{w4}^* + FK_4' + OG \cdot X_{w2}' + M_{42}' \cdot \ddot{\zeta}_{w2}^* + \left[N_{42}' - V \cdot \frac{dM_{42}'}{dx_b}\right] \cdot \dot{\zeta}_{w2}^*$$

Pitch:

$$X_{w5}' = -X_{w1}' \cdot bG - X_{w3}' \cdot x_b$$

Yaw:

$$X_{w6}' = +X_{w2}' \cdot x_b$$

However, in the classic approach, as for instance given for deep water by Vughts [3], the terms:

$$M_{44}' \cdot \ddot{\zeta}_{w4}^* + \left[N_{44}' - V \cdot \frac{dM_{44}'}{dx_b}\right] \cdot \dot{\zeta}_{w4}^*$$

are omitted in the diffraction part of the exciting wave moment for roll X_{w4}'. When using the Haskind relations to obtain the exciting wave moment for roll, these terms should not be included.

The total exciting wave forces and moments on the ship are found by an integration of the two-dimensional values over the length:

$$X_{wi} = \int_L X_{wi}' \cdot dx_b \qquad \text{for } i = 1, \ldots 6$$

MODEL DEFINITION AND TESTING PROGRAM

The model experiments have been carried out at the Delft Shiphydromechanics Laboratory in Towing Tank number I with a width of 4.20 meter and a waterdepth of 2.31 meter. These tank dimensions dictated the dimensions of the model. Tank wall interference should be as low as possible and the consequences of blockage have to be within the accuracy of the measurements.

The dimensions of the tested models of rectangular barges are given in table I.

"Model A" has a length-breadth ratio of 3.0. To investigate the consequences of tank wall interference on the motions in waves, a geometrically similar "Model B" with half the size of "Model A" has been tested too. "Model C" has a length-breadth ratio of 5.0 and "Model D" is a barge model with a square waterline. All models have been tested at an even keel condition, so with zero trim.
However, the experiments with "Model C" and "Model D" are not completed yet.

	L/B = 3				L/B = 3			L/B = 5			L/B = 1		
Model:	A1	A2	A3	A4	B1	B2	B3	C1	C2	C3	D1	D2	D3
B/T (-)	5.00	7.50	10.00	13.33	5.00	7.50	10.00	5.00	6.67	10.00	5.00	6.67	10.00
L (m)	2.250	2.250	2.250	2.250	1.125	1.125	1.125	2.000	2.000	2.000	0.750	0.750	0.750
B (m)	0.750	0.750	0.750	0.750	0.375	0.375	0.375	0.400	0.400	0.400	0.750	0.750	0.750
T (m)	0.150	0.100	0.075	0.056	0.075	0.050	0.038	0.080	0.060	0.040	0.150	0.113	0.075
KG (m)	0.151	0.099	0.074	0.056	0.075	0.050	0.046	0.080	0.076	-	0.150	0.115	0.074
KG/T (-)	1.003	0.990	0.993	1.005	1.000	1.000	1.227	1.000	1.267	-	1.000	1.022	0.980
GM (m)	0.237	0.420	0.588	0.798	0.119	0.209	0.285	0.127	0.176	-	0.237	0.358	0.589
k_{yy}/L (-)	0.252	0.252	0.251	0.256	0.250	0.250	0.250	0.250	0.250	-	0.457	0.405	0.403
$k_{\varphi\varphi}/B$ (-)	0.473	0.491	0.520	-	0.458	0.502	0.504	0.461	0.503	-	0.488	0.505	0.567
T_φ (s)	1.461	1.139	1.021	-	0.999	0.826	0.710	1.038	0.960	-	1.510	1.270	1.111
κ (-)	0.049	0.101	0.140	-	0.061	0.113	0.163	0.053	0.086	-	0.028	0.052	0.094

Table I Survey of Tested Models

In regular head waves, the heave and pitch motions and the added resistance due to waves have been measured at four Froude numbers; Fn = 0.00, 0.05, 0.10 and 0.15 respectively. The models were not free to surge.
In regular beam waves, the heave and roll motions have been measured at zero forward speed only. The models were not free to sway. The linear non-dimensional roll damping coefficients κ have been obtained from the free rolling experiments and are given in table I for a roll angle amplitude of 3 degrees.

It is noticed that the measurements of the incoming waves were influenced by reflection of the waves from the model. This leads to the spreading in the experimental data. Besides this, some of the incoming short waves showed also a non-harmonic behaviour which particularly can affect the roll motions.

VALIDATION OF STRIP-THEORY AND EXPERIMENTS

The measured barge motions have been compared with the theoretical predictions of both the present and the classic approach for the wave loads, made by a strip-theory ship motions PC program, named "SEAWAY-DELFT" [4]. This program calculates, among others, for six degrees of freedom the motions and the added resistances due to waves of monohull ships or barges in a seaway. The preliminary results of a comparitive study are presented here.

Heave and Pitch Motions in Regular Head Waves

The models were not free to surge, so the motions are defined by coupled heave and pitch equations:

$$(\rho\cdot\nabla+a_{33})\cdot\ddot{z} + b_{33}\cdot\dot{z} + c_{33}\cdot z + a_{35}\cdot\ddot{\theta} + b_{35}\cdot\dot{\theta} + c_{35}\cdot\theta = X_{w3}$$

$$(I_{yy}+a_{55})\cdot\ddot{\theta} + b_{55}\cdot\dot{\theta} + c_{55}\cdot\theta + a_{53}\cdot\ddot{z} + b_{53}\cdot\dot{z} + c_{53}\cdot z = X_{w5}$$

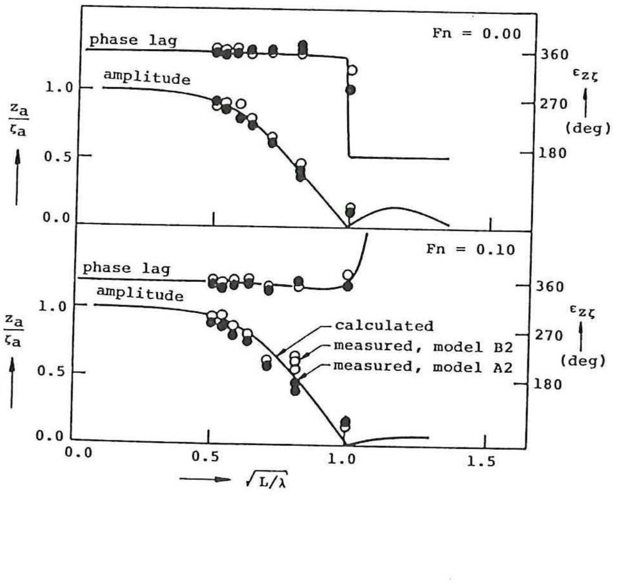
with:

$$z = z_a\cdot\cos(\omega_e t+\epsilon_{z\zeta})$$

$$\theta = \theta_a\cdot\cos(\omega_e t+\epsilon_{\theta\zeta})$$

A conformal mapping method, using a Lewis transformation of the cross section forms to the unit circle, has been used here to calculate the hydrodynamic mass and damping coefficients a_{ij} and b_{ij} by the Ursell-Tasai method. The coefficients c_{ij} follow from the geometry of the model.
No significant differences have been found for the vertical barge motions in head waves, calculated by the present and the classic approach for the wave loads.

The experimental results of Models A, B and C, with their L/B ratios as 3.0 and 5.0 associated with a range of B/T ratios, have been analysed.
The heave responses are predicted fairly well, but the calculated pitch amplitudes are a good ten per cent too low.
However, tank wall interference is an important factor for pitch motions. From all experiments, carried out with the geometrically similar Models A and B, it is concluded that the experimental data of the small Model B, so the model for which less tank wall interference is expected, are much more close to the predicted data. This leads to the conclusion that the pitch motions can also be predicted fairly well by the strip-theory.



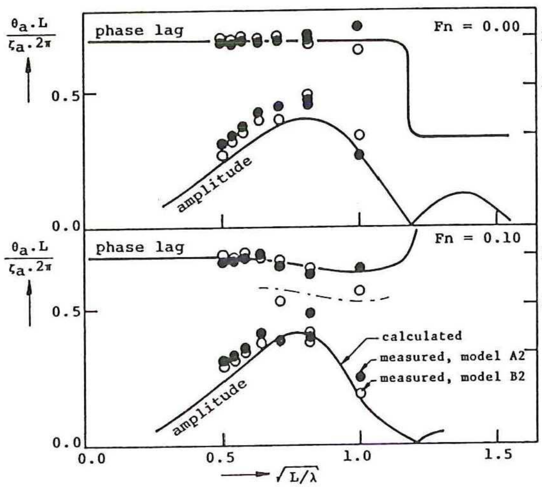


Fig. 1 Measured and Calculated Heave and Pitch Responses at Fn=0.00 and Fn=0.10 in Regular Head Waves

Figure 1 shows a comparison between the measured and the calculated heave and pitch responses at zero forward speed and Fn=0.10 of the geometrically similar Models A2 and B2 with L/B=3.0 and B/T=7.5.

Added Resistance in Regular Head Waves

Two methods have been used to calculate the mean added resistance due to waves. The first method is a radiated energy method [5] and the second method is an integrated pressure method [6].
The calculated data have been compared with the experimental data of Models A, B and C with their L/B ratios is 3.0 and 5.0 associated with a range of B/T ratios. Only the final conclusions are given here.

Generally, at forward speed both methods underestimate the added resistance considerably. At zero forward speed or a very low forward speed only, the integrated pressure method gives fair acceptable results, but the radiated energy method still delivers to high predictions.
This leads to the conclusion that the strip-theory with the integrated pressure method predicts the drift forces fairly well.

Heave and Roll Motions in Regular Beam Waves

The models were not free to sway, so the motions at zero forward speed are defined by the uncoupled heave and roll equations:

$$(\rho \cdot \nabla + a_{33}) \cdot \ddot{z} + b_{33} \cdot \dot{z} + c_{33} \cdot z = X_{w3}$$

$$(I_{xx} + a_{44}) \cdot \ddot{\varphi} + b_{\varphi\varphi} \cdot \dot{\varphi} + c_{44} \cdot \varphi = X_{w4}$$

with:

$$z = z_a \cdot \cos(\omega_e t + \epsilon_{z\zeta})$$

$$\varphi = \varphi_a \cdot \cos(\omega_e t + \epsilon_{\varphi\zeta})$$

$$b_{\varphi\varphi} = b_{44} + b_{44v}$$

The moment of inertia for roll I_{xx} of the solid mass of the model has been obtained during a free rolling test by subtracting the calculated hydrodynamic potential mass moment of inertia a_{44} at the natural freqency from the measured total moment of inertia.
The viscous part of the roll damping b_{44v} has also been obtained from the free rolling test by subtracting the calculated hydrodynamic potential damping b_{44} at the natural freqency from the measured total damping $b_{\varphi\varphi}$. This coefficient b_{44v} is kept constant for all frequencies.
A conformal mapping method, using a Lewis transformation of the cross section forms to the unit circle, has been used here to calculate the hydrodynamic mass and damping coefficients a_{ij} and b_{ij} by the Ursell-Tasai method. The coefficients c_{ij} follow from the geometry of the model.
No significant differences have been found between the calculated heave responses by the present and the classic approach for the wave loads.

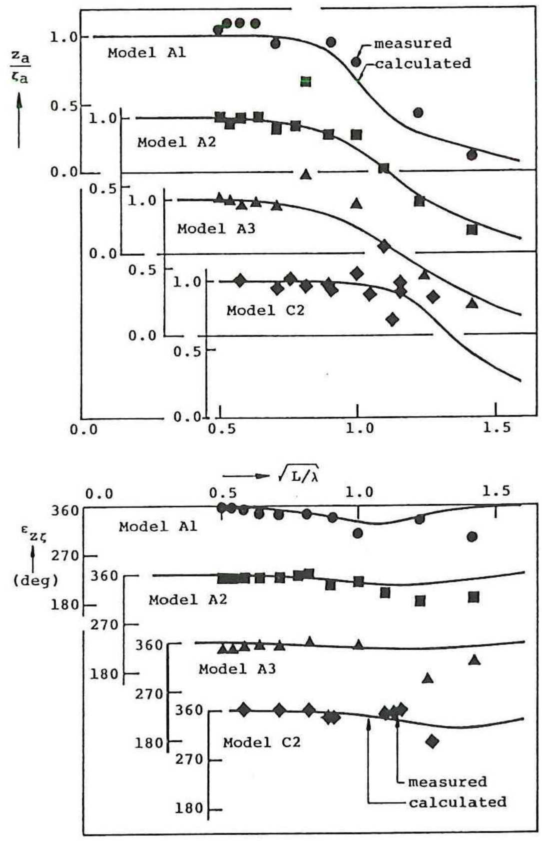


Fig. 2 Measured and Calculated Heave Responses at Zero Forward Speed in Regular Beam Waves

The experimental results at zero forward speed in beam waves of the Models A, B and C with their L/B ratios as 3.0 and 5.0 associated with a range of B/T ratios have been analysed. The heave responses are predicted fairly well by the strip-theory.

Figure 2 shows a comparison of the measured and the calculated heave responses at zero forward speed in beam waves of Models A1, A2, A3 and C2. Extreme peak values appear in the experiments, probably caused by tankwall interference.

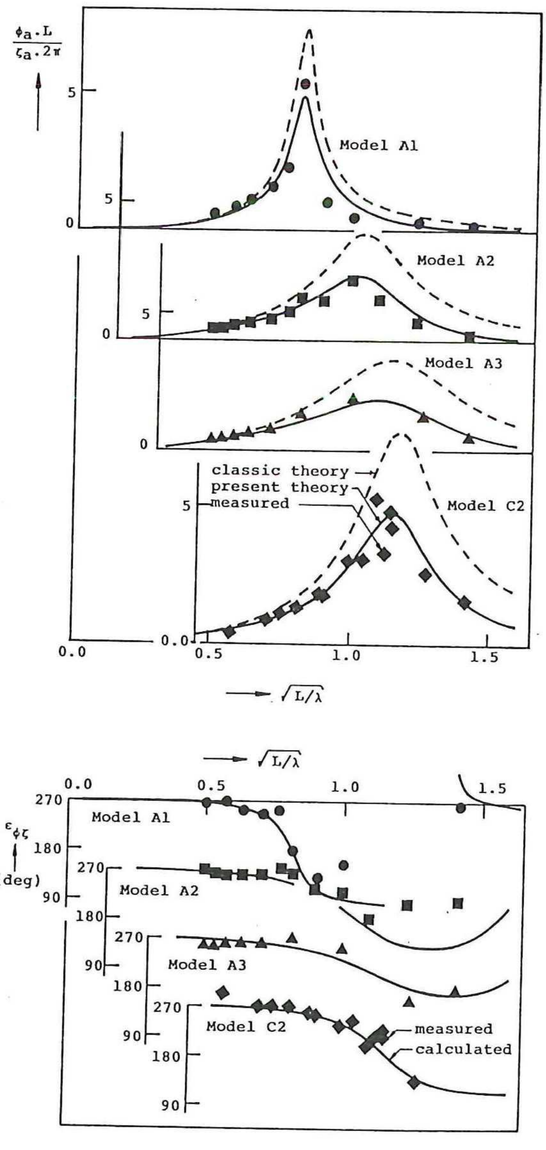


Fig. 3 Measured and Calculated Roll Responses at Zero Forward Speed in Regular Beam Waves

The calculated roll motions obtained by the present approach for the wave loads are much lower than those obtained by the classical approach. This is mainly caused by the inclusion in the present approach of the potential mass and damping coefficients for roll in the diffraction part of the roll wave moment. Because of the B/T ratio, these potential coefficients are much greater for a barge as for a conventional ship. So the inclusion will have a larger consequence here. The effect of different equivalent orbital motions is relatively small.

The strip-theory with the classic approach fails when calculating roll motions of these barges. The predicted roll motions are much too high. The present approach predicts the roll responses much better. Phase lags are predicted fairly well by both approaches.

Figure 3 shows a comparison of measured and calculated roll responses at zero forward speed in beam waves of Models A1, A2, A3 and C2.

CONCLUSIONS

Based on this study, it has been concluded here for rectangular barges with a length-breadth ratio of 3.0 or higher:

1. The relatively simple ordinary strip-theory method can be used safely for a first estimation of the motions of rectangular barges with a length-breadth ratio of 3.0 or higher.

2. The heave and pitch responses in head waves can be predicted fairly well by the ordinary strip-theory method.
When using the present and the classic approach for the wave loads, no significant differences will be found between the calculated responses.

3. Only at zero forward speed, the integrated pressure method predicts the added resistance in head waves fairly well. So only drift forces at zero forward speed can be predicted by this method.
The radiated energy method fails.

4. When using the present approach for the wave loads and results of free rolling tests are available, the roll responses at zero forward speed in beam waves can be predicted fairly well by the strip-theory method.
The classic approach delivers much too high predicted values for the roll amplitudes in the whole frequency range, mainly caused by omitting the potential roll coefficients in the diffraction part of the exciting wave moment.

However, a "fair agreement" or "fairly well" means here that in the whole frequency range, deviations up to about ten per cent of the maximum value are still possible.

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APPENDIX I:

Orbital Motions and Pressure Distributions

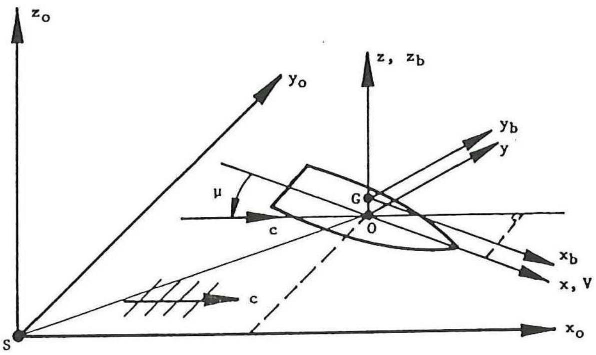

Fig. 4 Coordinate Systems

A right-handed coordinate system $S-(x_o,y_o,z_o)$ is fixed in space. The (x_o,y_o)-plane lies in the still water surface, x_o is directed as the wave propagation and z_o is directed upwards.

A second right-handed coordinate system O-(x,y,z) is moving forward with a constant ship speed V. The directions of the axes are: x in the direction of the forward speed V, y in the lateral port side direction and z in the upward direction. The ship is supposed to carry out oscillations around this moving O-(x,y,z) coordinate system. The origin O lies above or under the time-averaged position of the centre of gravity G. The (x,y)-plane lies in the still water surface.

A third right-handed coordinate system $G-(x_b,y_b,z_b)$ is connected to the ship with G at the ship's centre of gravity. The directions of the axes are: x_b in the longitudinal forward direction, y_b in the lateral port side direction and z_b upwards. In still water the (x_b,y_b)-plane is parallel to the still water surface.

The first order wave potential for an arbitrary waterdepth is given by:

$$\Phi_w = -g/\omega \cdot \frac{\cosh k(h+z_b)}{\cosh kh} \cdot \zeta_a \cdot \sin(\omega_e t - kx_b \cdot \cos\mu - ky_b \cdot \sin\mu)$$

The local relative orbital velocities of the waterparticles in a certain direction follow from the derivative of the wave potential in that direction.
From these velocities the local directional components of the orbital accelerations of the waterparticles are obtained by:

$$\ddot{\zeta}_{wi}' = \frac{D}{Dt}\left[\dot{\zeta}_{wi}'\right] \qquad \text{for } i = 1, 2, 3, 4$$

with:

$$\frac{D}{Dt} = \left[\frac{\partial}{\partial t} - V \cdot \frac{\partial}{\partial x_b}\right]$$

These relative velocities and accelerations are defined here for the four modes of motions.

Surge:

$$\dot{\zeta}_{w1}' = +k \cdot g/\omega \cdot \cos\mu \cdot \frac{\cosh k(h+z_b)}{\cosh kh} \cdot \zeta_a \cdot \cos(\omega_e t - kx_b \cdot \cos\mu - ky_b \cdot \sin\mu)$$

$$\ddot{\zeta}_{w1}' = -k \cdot g \cdot \cos\mu \cdot \frac{\cosh k(h+z_b)}{\cosh kh} \cdot \zeta_a \cdot \sin(\omega_e t - kx_b \cdot \cos\mu - ky_b \cdot \sin\mu)$$

Sway:

$$\dot{\zeta}_{w2}' = +k \cdot g/\omega \cdot \sin\mu \cdot \frac{\cosh k(h+z_b)}{\cosh kh} \cdot \zeta_a \cdot \cos(\omega_e t - kx_b \cdot \cos\mu - ky_b \cdot \sin\mu)$$

$$\ddot{\zeta}_{w2}' = -k \cdot g \cdot \sin\mu \cdot \frac{\cosh k(h+z_b)}{\cosh kh} \cdot \zeta_a \cdot \sin(\omega_e t - kx_b \cdot \cos\mu - ky_b \cdot \sin\mu)$$

Heave:

$$\dot{\zeta}_{w3}' = -k \cdot g/\omega \cdot \frac{\sinh k(h+z_b)}{\cosh kh} \cdot \zeta_a \cdot \sin(\omega_e t - kx_b \cdot \cos\mu - ky_b \cdot \sin\mu)$$

$$\ddot{\zeta}_{w3}' = -k \cdot g \cdot \frac{\sinh k(h+z_b)}{\cosh kh} \cdot$$
$$\cdot \zeta_a \cdot \cos(\omega_e t - kx_b \cdot \cos\mu - ky_b \cdot \sin\mu)$$

Roll:

$$\dot{\zeta}_{w4}' = +k^2 \cdot g/\omega \cdot \sin\mu \cdot \frac{\sinh k(h+z_b)}{\cosh kh} \cdot$$
$$\cdot \zeta_a \cdot \cos(\omega_e t - kx_b \cdot \cos\mu - ky_b \cdot \sin\mu)$$

$$\ddot{\zeta}_{w4}' = -k^2 \cdot g \cdot \sin\mu \cdot \frac{\sinh k(h+z_b)}{\cosh kh} \cdot$$
$$\cdot \zeta_a \cdot \sin(\omega_e t - kx_b \cdot \cos\mu - ky_b \cdot \sin\mu)$$

The pressure follows from the linearised equation of Bernouilli:

$$p = -\rho \cdot g \cdot z_b + \rho \cdot g \cdot \frac{\cosh k(h+z_b)}{\cosh kh} \cdot$$
$$\cdot \zeta_a \cdot \cos(\omega_e t - kx_b \cdot \cos\mu - ky_b \cdot \sin\mu)$$

Also, it can be written:

$$p = p_o + \frac{\partial p}{\partial x_b} \cdot dx_b + \frac{\partial p}{\partial y_b} \cdot dy_b + \frac{\partial p}{\partial z_b} \cdot dz_b$$

with the following expressions for the pressure gradients:

$$\frac{\partial p}{\partial x_b} = +\rho \cdot k \cdot g \cdot \cos\mu \cdot \frac{\cosh k(h+z_b)}{\cosh kh} \cdot$$
$$\cdot \zeta_a \cdot \sin(\omega_e t - kx_b \cdot \cos\mu - ky_b \cdot \sin\mu)$$

$$\frac{\partial p}{\partial y_b} = +\rho \cdot k \cdot g \cdot \sin\mu \cdot \frac{\cosh k(h+z_b)}{\cosh kh} \cdot$$
$$\cdot \zeta_a \cdot \sin(\omega_e t - kx_b \cdot \cos\mu - ky_b \cdot \sin\mu)$$

$$\frac{\partial p}{\partial z_b} = -\rho \cdot g + \rho \cdot k \cdot g \cdot \frac{\sinh k(h+z_b)}{\cosh kh} \cdot$$
$$\cdot \zeta_a \cdot \cos(\omega_e t - kx_b \cdot \cos\mu - ky_b \cdot \sin\mu)$$

This can be expressed in the orbital accelerations too:

$$\frac{\partial p}{\partial x_b} = -\rho \cdot \ddot{\zeta}_{w1}'$$

$$\frac{\partial p}{\partial y_b} = -\rho \cdot \ddot{\zeta}_{w2}' = -\rho \cdot \frac{\ddot{\zeta}_{w4}'}{k \cdot \tanh k(h+z_b)}$$

$$\frac{\partial p}{\partial z_b} = -\rho \cdot (g + \ddot{\zeta}_{w3}')$$