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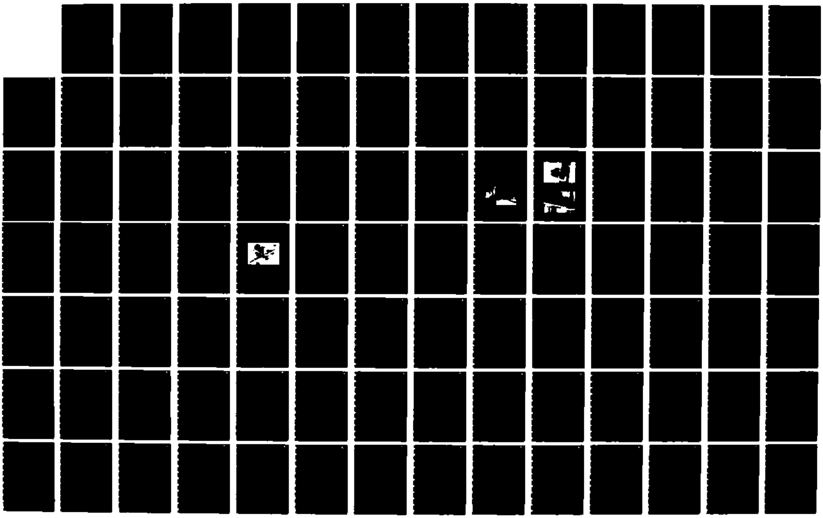

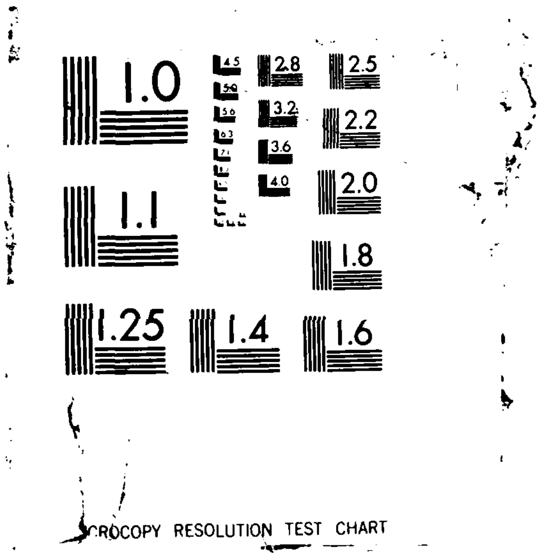
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CR 87.002
October 1986
An Investigation Conducted By
The Danish Hydraulic Institute

NCEL
Contract Report

Sponsored By Naval Facilities
Engineering Command

AD-A175 331

INVESTIGATIONS AND TESTS TO DETERMINE HYDRODYNAMIC FORCES AND MOMENTS ON SHIPS MOORED IN A CURRENT - VOL I FINAL REPORT

ABSTRACT Experiments with 1:50-scale models produced data on the horizontal force and the yawing moment exerted by a steady current on ships moored in shallow water. Data were obtained for one ship with various headings and for two ships arranged side by side in a beam current. The models were restrained by elastic lines simulating real moorings; for a single ship, rigid supports were also used. The experiments included brief investigations of the minimum flume width, turbulence, flow patterns, and flow-induced motions.

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20 ABSTRACT (Continue on reverse side if necessary and identify by block number)

Experiments with 1:50-scale models produced data on the horizontal force and the yawing moment exerted by a steady current on ships moored in shallow water. Data were obtained for one ship with various headings and for two ships arranged side by side in a beam current. The models were restrained by elastic lines simulating real moorings; for a single ship, rigid

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1. INTRODUCTION

This report describes the results of the work carried out by Danish Hydraulic Institute (DHI) for the Naval Civil Engineering Laboratory (NCEL), Department of the Navy, Port Hueneme, California, U.S.A. under contract No. N62474-84-C-3142. The Danish Maritime Institute (DMI) has acted as a consultant and subcontractor to DHI during the project.

The work consisted of an ~~rather~~ extensive series of experiments with ship models that were either fixed or moored in a current in shallow water. The experiments were designed to shed light on apparent contradictions in published data on the hydrodynamic force coefficients and to provide data for two ships moored side by side.

The work was accomplished in two phases. Phase I consisted of 33 experiments with a single model. The objective~~s~~ were to test the effect of the Reynolds number, ~~to~~ define the effect of the width of the flume, and ~~to~~ investigate the potential for ship motions in the shallow water.

Phase II consisted of 116 experiments with one vessel and with two vessels side by side, using both fixed models and models restrained by elastic moorings. The objectives were as follows.

1) To determine the horizontal force components as functions of time and as time averages for one vessel and for two vessels in various positions and flow conditions.

2) To discover and define significant details of the flow around the ship(s) with the intent to further develop the understanding of the hydrodynamics of the actual situation.

3) To investigate limiting conditions, which mark the transitions between negligible vessel motion and instability-type oscillations.

The full report of the work consists of (1) this volume, containing the main narrative and the primary results (engineering data) and findings; (2) a supplementary volume describing the preliminary (Phase I) tests in greater detail; (3) a volume containing raw data and standard statistics of these Phase II data; (4) a volume containing time series and spectra of selected tests; (5) colour slides; and (6) a video recording of special flow situations.

2. SUMMARY

A comprehensive test program has been carried out in order to describe the general behaviour of ship models moored in a current in shallow water. The flow in the vicinity of the model(s) and the movements of the model(s) have been monitored in various conditions. The longitudinal and lateral forces and the yaw have been measured and analysed.

The report contains the basic data and comprises all data, comments, specific tables and plots, black- and white photographs, colour slides of set-up and test runs, and a video recording of special flow situations.

In the present report volume the results of the two phases of the investigation are summarized in Chapter 3. General information on model set-up and testing techniques is given in Chapter 4 and the six individual test series of Phase II are reported in Chapters 5 through 10. For the free mooring system applied to a single vessel in the test series denoted 4000 and 5000 (Chapter 8 and 9), the discussion of the movement recordings is incorporated in Chapter 10 in connection with the movements of the dual vessel case. Finally, some comments are given in Chapter 11 on the flow patterns observed during testing. These comments are supplemented by the enclosed video recordings.

Based on the data analysis it is concluded that very limited movements appear. The critical instability type of movement as indicated by the tests of Phase I did not appear. The forces on the ships in fixed mooring arrangement compare well with data from similar tests reported in literature. The forces for the free mooring system are of the same magnitude although slightly smaller.

Inspection of the flow under the vessel did not give any sign of critical separation. Study of the secondary flows in the leeward wake neither showed movement exciting flows, except for one condition with 2 ships, high Froude Number and relative displacement of the ships where a non-stationary eddy was found and filmed on video. But even in this most adverse situation the forces and movements were very limited.

3. OVERVIEW OF PHASE I AND PHASE II MODEL TESTS

3.1 Phase I

The Phase I model study was carried out by DHI in 1984/1985 and the results of the tests have been reported previously in "Current Forces on Ships Moored in a Beam Current, Draft Report, Part I, Model Tests". An overview of the Phase I study is given below.

3.1.1 Scope of Work

The Phase I had the following objectives:

- Blockage Effect: Find the maximum width at which the lateral force at the transversely mounted vessel is not affected by more than approximately 5% relative to the situation with an infinitely wide flume.

- Determine the influence of the Reynolds Number on the lateral drag force on the hull shaped body in a beam current so that the Phase II measurements can be properly converted to full scale predictions of drag forces and moments.

- Investigate the behaviour of a floating body moored in a beam current and the speed of the current is increased. Special emphasis was given to determine if and when erratic or violent motions take place.

The tests were carried out in the facility described in Section 4.

3.1.2 Blockage Effects

The blockage effects were investigated by inserting walls into the current basin, and by varying the distance between these as sketched in Fig. 3.1 below.

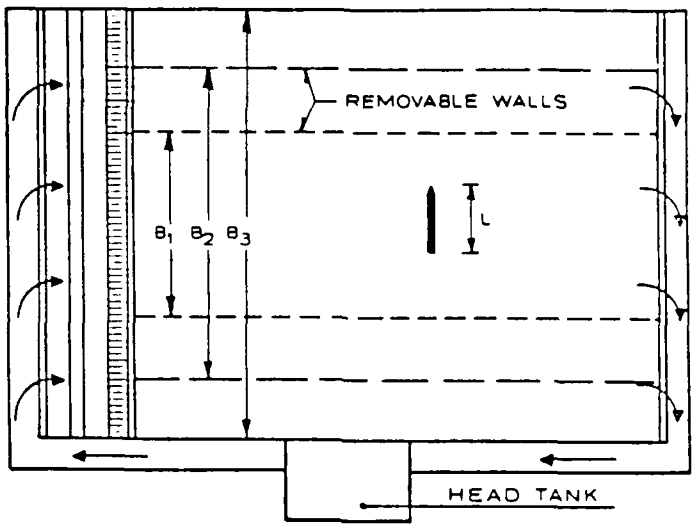


Fig. 3.1 Sketch of the Model Set-up in the Current Basin.

The results of the tests for 3 different Froude numbers are given in Fig. 3.2 below as lateral drag coefficients versus the blockage ratio.

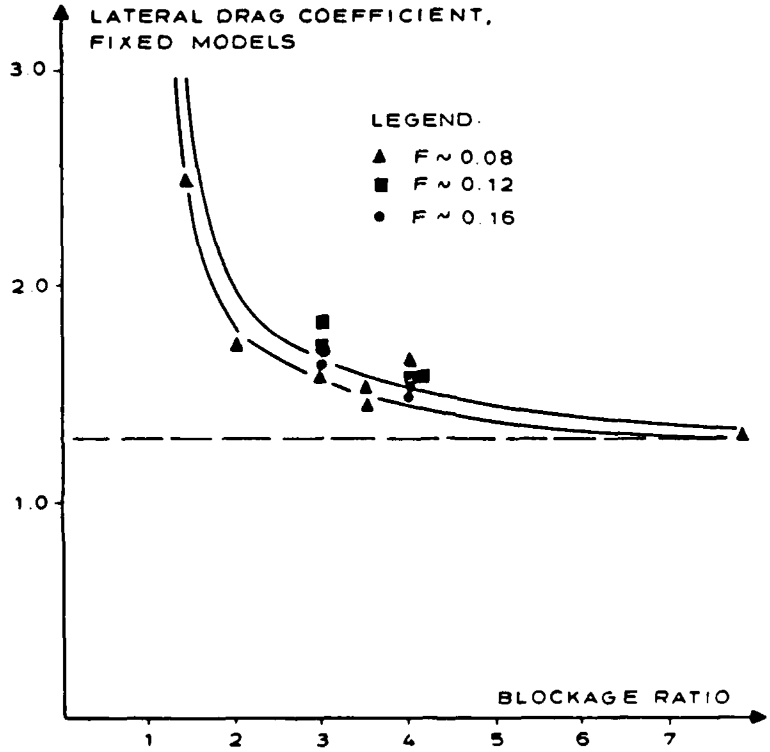


Fig. 3.2 C_D-Values vs. Blockage Ratio, B/L, for 3 F-Values. Depth to draft ratio equals 1.67.

From the tests is was concluded that a flume width of 4 to 5 times the length of the ship will result in drag coefficients that differ less than 5 per cent from the infinite flume case. Furthermore, the value of C_D found in the tests was of the same magnitude as those reported by OCIMF (Ref. /1/) for VLCC's.

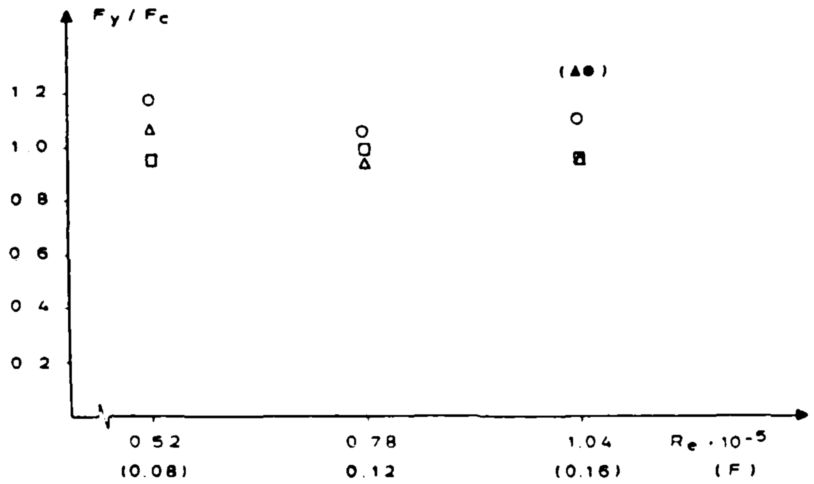
3.1.3 Reynolds Number Effects

The influence of the Reynolds Number on the lateral drag coefficient was studied by using 2 different scale models of the same ship, one being two times larger than the other. In this way all other parameters such as Froude Number and depth to draft ratio would be identical for the two sets of tests, but the Reynolds Number would increase by a factor of $2^{3/2} \sim 2.8$.

In these tests a flume width equal to 2 times Lpp (the length between fore and aft perpendicular) was chosen in order to achieve a reasonable Froude Number for the large model vessel at the maximum flow rate obtainable in the flume.

In addition, the models were tested with and without bilge keel, and the small model vessel was equipped with trip wires outside the bilge keel region.

The results of the study are shown in Fig. 3.3 below, where the relative lateral force, i.e. the force measured on the vessels normalized by the force measured on a circular plate, is plotted versus the Reynolds Number.



LEGEND

HULL CONFIGURATION	SCALE 1 50	SCALE 1 25
BARE HULL	○	●
BILGE KEELS	△	▲
BILGE KEELS & TRIP WIRES	□	

Fig. 3.3 Relative Force Coefficients found in the Model Tests.

The effect of adding trip wires to the bilge keels is insignificant, whereas the application of the bilge keels reduces the lateral force.

For the low Froude Number the increase in Reynolds Number leads to a slight increase in the lateral force. It is believed that this increase is more related to a change in turbulence level (lower for the large Re-number) than to a Reynolds Number effect.

Within the range of Reynolds Numbers tested in this study no evidence has been found for a strong Re-number influence on the lateral force.

3.1.5 Instability Tests

The interaction between a flowing fluid and an elastic, bluff body may create oscillations of the body. The oscillations may be caused by the shedding of vortices with a frequency close to a natural frequency of the elastic system or they may be related to an instability caused by an initial movement of the body.

To see whether or not such oscillations would be possible for the vessel in a beam current, test were conducted with the small model, where the vessel was "moored" using rigid rods preventing surge, sway, and yaw motion, but allowing for heave, roll and pitch.

The instrumentation is shown in Fig. 3.4.

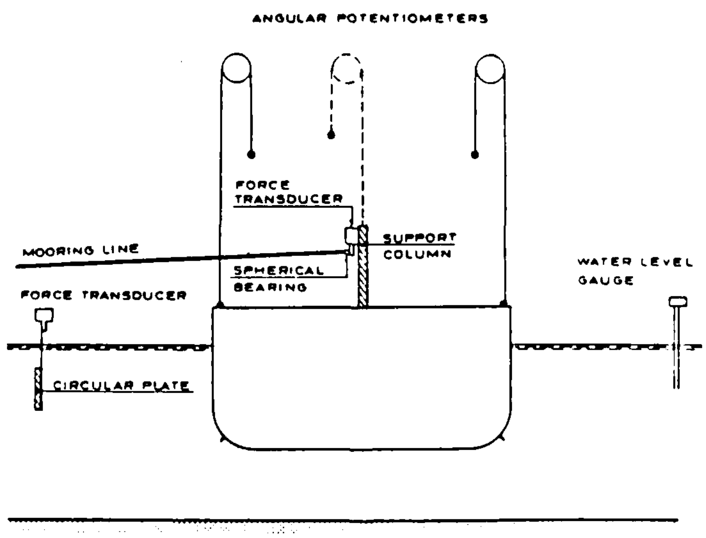


Fig. 3.4 The Measuring System (in principle) applied in the Instability Tests and the Mooring Arrangement.

With this set-up it was quite evident that a mean roll motion appeared with increasing angle for increasing Froude Number. Furthermore an oscillating roll motion also occurred. The heave motion had a similar trend for increased Froude Number, and also oscillating pitch motions appeared.

From the tests it was observed that oscillating motions could occur and that they seemed to be initiated by the roll motion. It is, however, stressed that the test results are indicative, as a correctly reproduced, elastic, mooring system with prototype similitude is required in the set-up to obtain reliable results usable for full scale design.

3.2 Phase II

The Phase II of the present study deals with the forces and ship movements under various flow conditions and for fixed and free mooring cases. Both a single ship and two adjacent ships were studied. The most important results of the six test series are summarized below. A detailed description of all results is given in the following sections.

1000-Series : Basic Flow Pattern Investigation

The 3-dimensional flow around a single vessel placed in a beam current can be divided into three sections:

1) The central wake, rotation about a horizontal axis.

2) The bow wake, rotation about a vertical axis.

3) The stern wake, rotation about a vertical axis.

Small scale vortex shedding occurred at the bow and at the bilge keels beneath the vessel.

In addition to the flow field observations, the force coefficients were determined and found to be within the range of the data reported in literature.

2000 Series : Basic Drag Data- One Single Ship

For one single ship the lateral force coefficient, C_Y, was determined as function of the depth draft ratio, h/T.

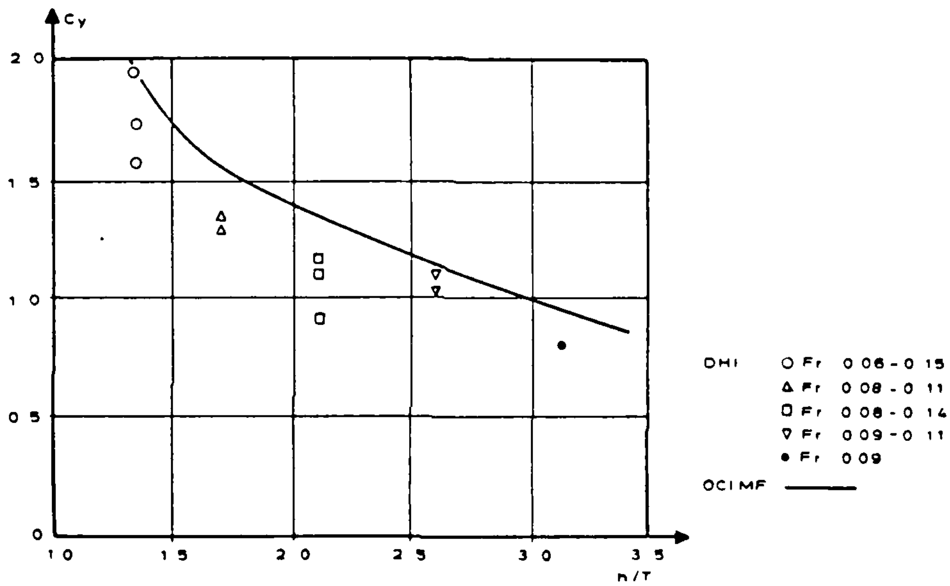


Fig. 3.5 C_Y-h/T Relations, Test 2000, Beam Current.

The results of the tests are presented in Fig. 3.5 and compared with existing data from literature. The agreement between the two sets of data seems to be good. The discrepancy between the two sets of data may be explained by the configurations of the hull of the vessel used in the experiments.

The flow pattern was observed intensively during the series and showed the same characteristics as found in the 1000-series for all flow conditions.

3000-Series : Basic Heading Effect - One Single Ship

The effect of different angles of current impact, i.e. headings, was studied with respect to the force coefficients for the fixed mooring condition. The force coefficients are the transverse force coefficient C_y, the longitudinal force coefficient C_x, and the coefficient of the yawing moment C_{MZ}. The variation with different headings is shown in the following figures.

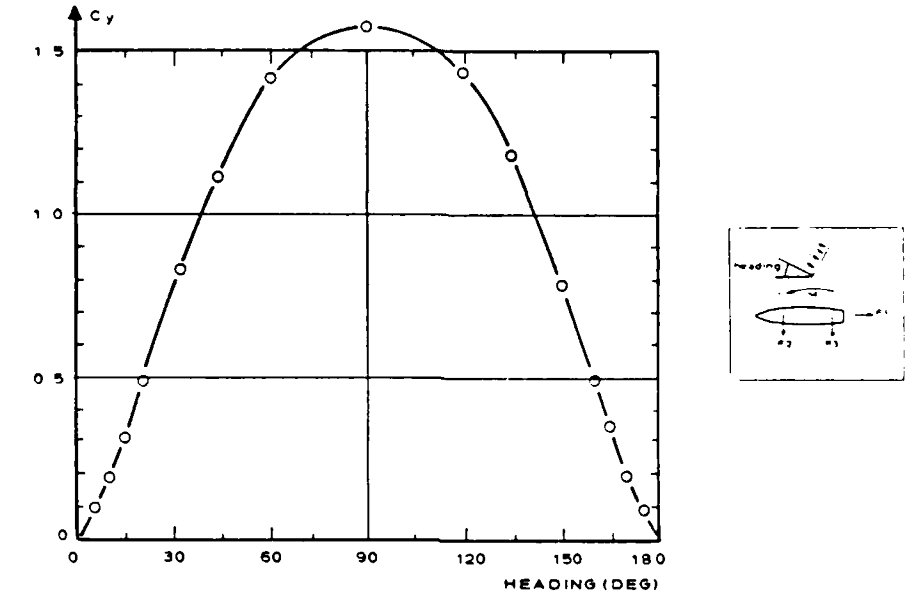


Fig. 3.6 C_Y-Heading Relation
3000-Series, fixed model

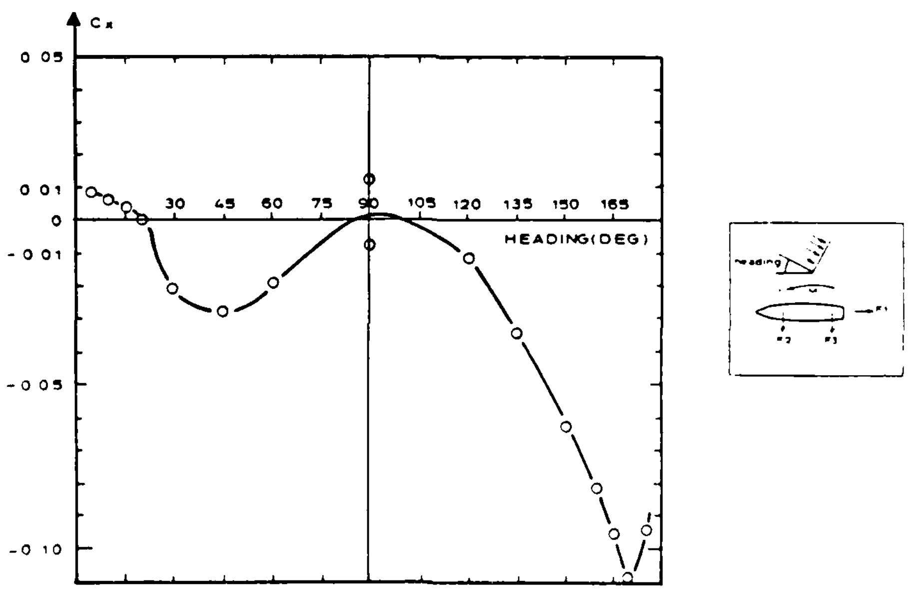


Fig. 3.7 C_X-Heading Relation
3000-Series, Fixed model

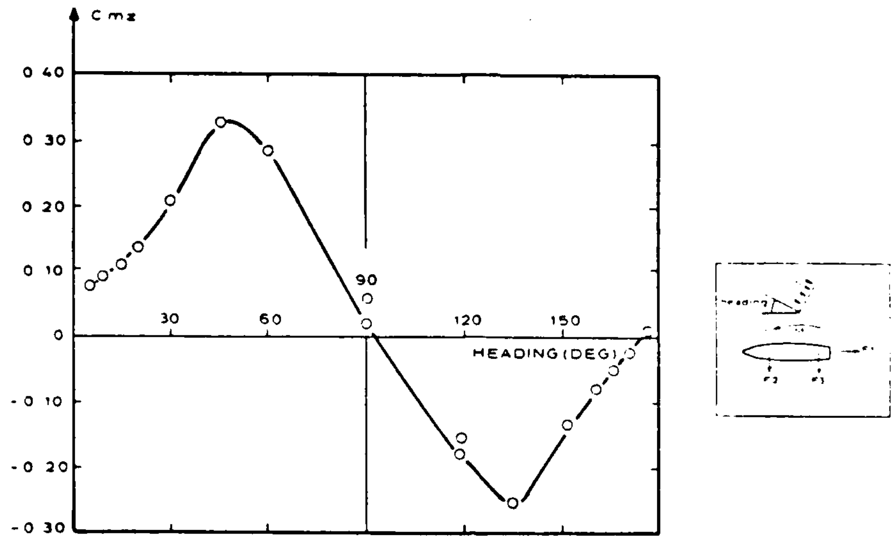


Fig. 3.8 C_{mz}-Heading Relation
3000-Series

4000-Series : Basic Sinkage, Heel, Stability and Mooring Forces, One Single Ship in Free Mooring Condition

In this first free mooring condition basic studies on static and dynamic movement and forces were performed in flow conditions corresponding to the investigations on a fixed ship model. The mooring force components were found to be slightly higher than for the fixed condition.

A maximum Froude Number with a significant change to severe ship motion was not observed. The general ship motions and especially the roll oscillation all showed a continuous increase for increasing Froude Number.

An interesting finding is gained from the comparison of the ship motions measured on a partially restrained model (Phase I) and the ship motions measured on a free moored model (Phase II): The partially restrained model performed critical movements while the free model moved in a much more moderate way. This discrepancy is attributed to the stiff mooring system which was connected to the ship at a higher level.

Flow separation beneath the vessel was observed to occur in accordance with the rolling of the ship.

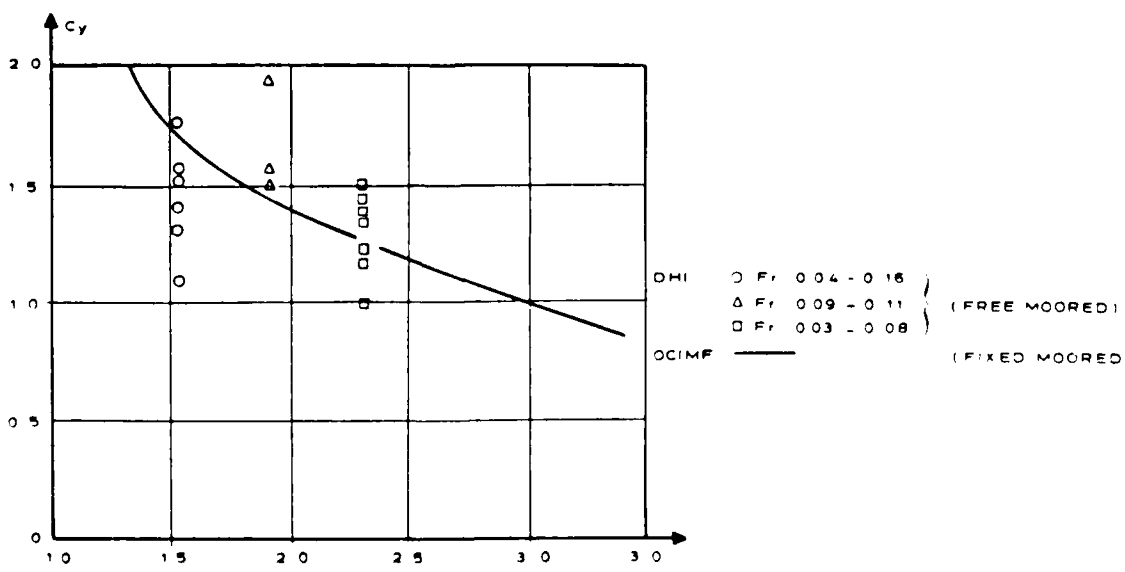
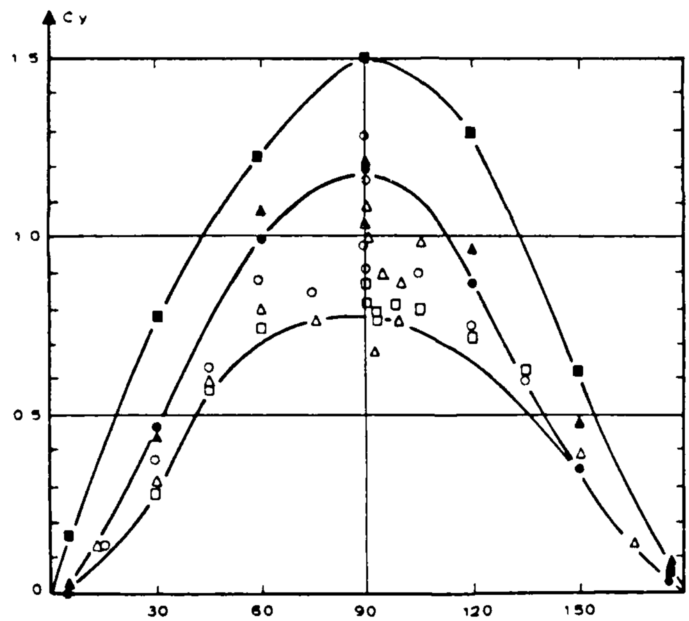


Fig. 3.9 C_Y-h/T Relation
4000-Series, Free ship model

5000-Series: Heading Effect on Sinkage, Heel, Stability and Forces One Single Ship in Free Mooring Condition

Corresponding to the 3000-series tests the heading effect on ship motions and forces was studied for the free mooring condition. An additional free mooring arrangement (Case II) was applied in a few tests.

The results of these heading tests for a free moored vessel show the same variation with heading as the results reported in Ref. /3/.



F_r	CURRENT, FREE DHI 86	TOW. TEST, FIXED OTC 81 REF /3/
0.04	●	○
0.08	▲	△
0.11	■	□

Fig. 3.10 Comparison between Recent Fixed Model Tow Tests and the Free Model Current Tests.

6000-Series : Two Ships, Sinkage, Heel, Stability and Mooring Forces.

Based on the former tests a test series for two ships connected to each other by fenders, breast- and spring lines was finally performed. The forces and motions of the two ships were recorded along with observations of the flow pattern.

Since the leeward ship model is placed more or less in the wake of the upstream vessel, the total mooring force increase is insignificant as compared to the one ship case.

The presence of a leeward ship had a slightly stabilizing effect on the heel motion of the upstream vessel. The relative roll of the two vessels was observed and is illustrated in Section 10.

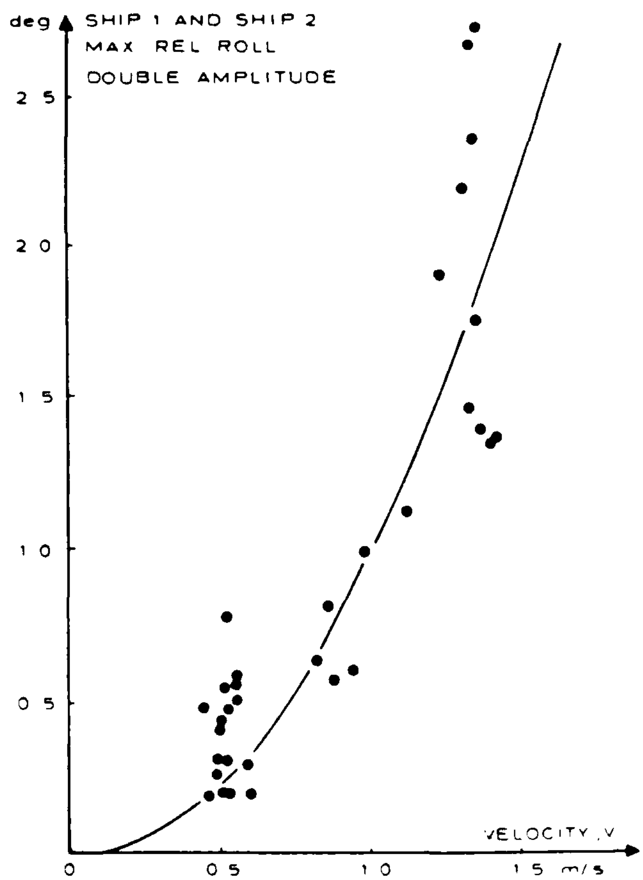


Fig. 3.11 Relative Roll of two Adjacent Vessels related to the Mean Velocity of the Flow.

The flow pattern in this two ship case was almost identical to the single ship case. A special and interesting detail, however, was observed and video taped at the bow of the leeward vessel, where large scale, long term vortex shedding occurred correlated to the surge oscillation of the two vessels.

The present 6000 series is so comprehensive that a complete hydrodynamic analysis of all tests is far beyond the scope of the present study. The complete set of reduced data and a magnetic tape of the raw data are provided for possible further analysis.

July 30th, 1986

DANISH HYDRAULIC INSTITUTE

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Marine Structures
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Project Manager

4. GENERAL SET-UP, INSTRUMENTATION AND TEST PROGRAMME

4.1 Model Basin

The set-up was made in a rectangular basin with the dimensions 20 x 35 m where the inlet and outlet were located along the short sides. The position of the vessel is determined by the support frame as shown on Fig. 4.1.

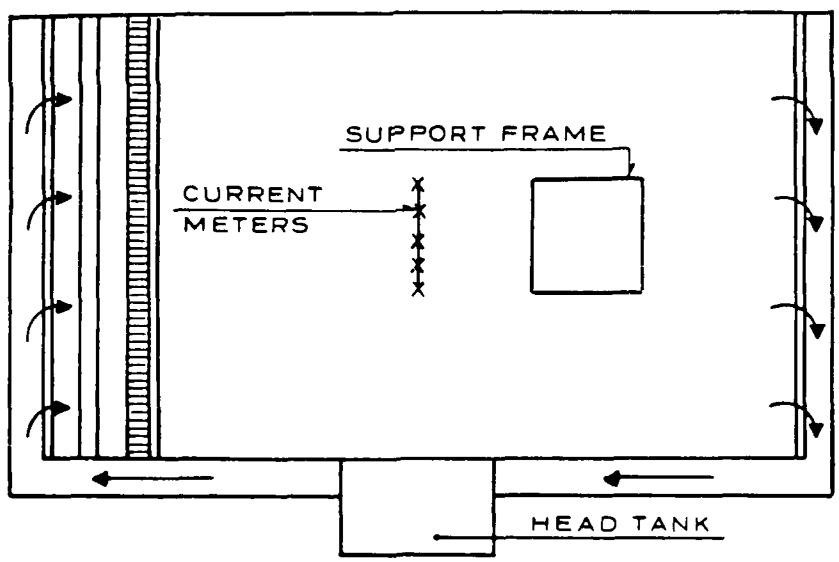


Fig. 4.1 Position of the Support Frame and Current-meter rack.

The flow through the basin was established by use of a pump and head tank system in connection with inlet-outlet flumes around the basin. The principle for the system operation is shown in Fig. 4.2.

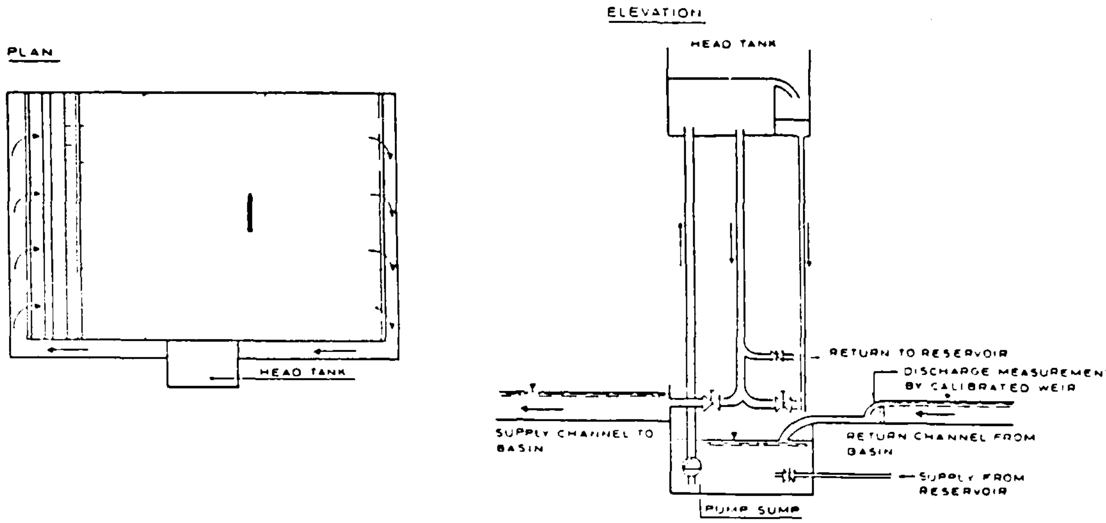


Fig. 4.2 The Principle for Current Generating System.

<u>Inlet</u>: The inlet consists of a double-weir, a sill and a filter arrangement, see Fig. 4.3. This system provided a homogeneous flow over the entire width.

<u>Outlet</u>: The outlet is a simple weir.

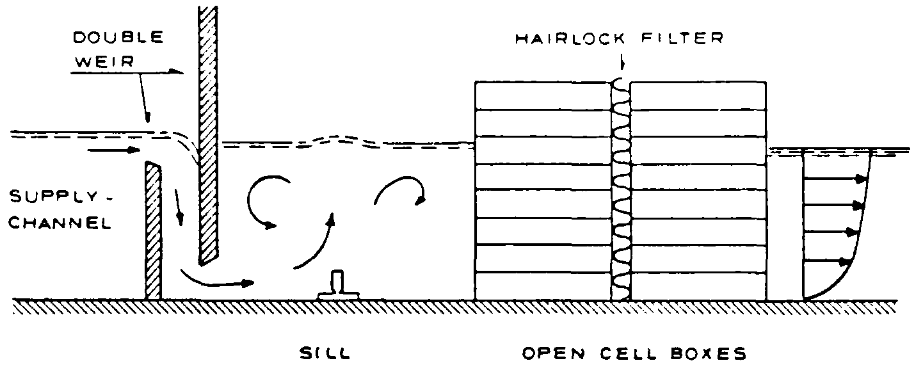


Fig. 4.3 Inlet Arrangement.

4.2 Support Structure

The test set-up used is shown in Fig. 4.4 and consists of:

- Main Frame, a stiff 5x5m frame supported by stream-lined legs.

- "Bridge", a light but stiff "bridge" resting on the main frame. The bridge can be lifted by the overhead crane and moved to any desired position on the main frame.

This support structure is used both for the fixed and for the free mooring system and for tests with either 1 or 2 models involved.

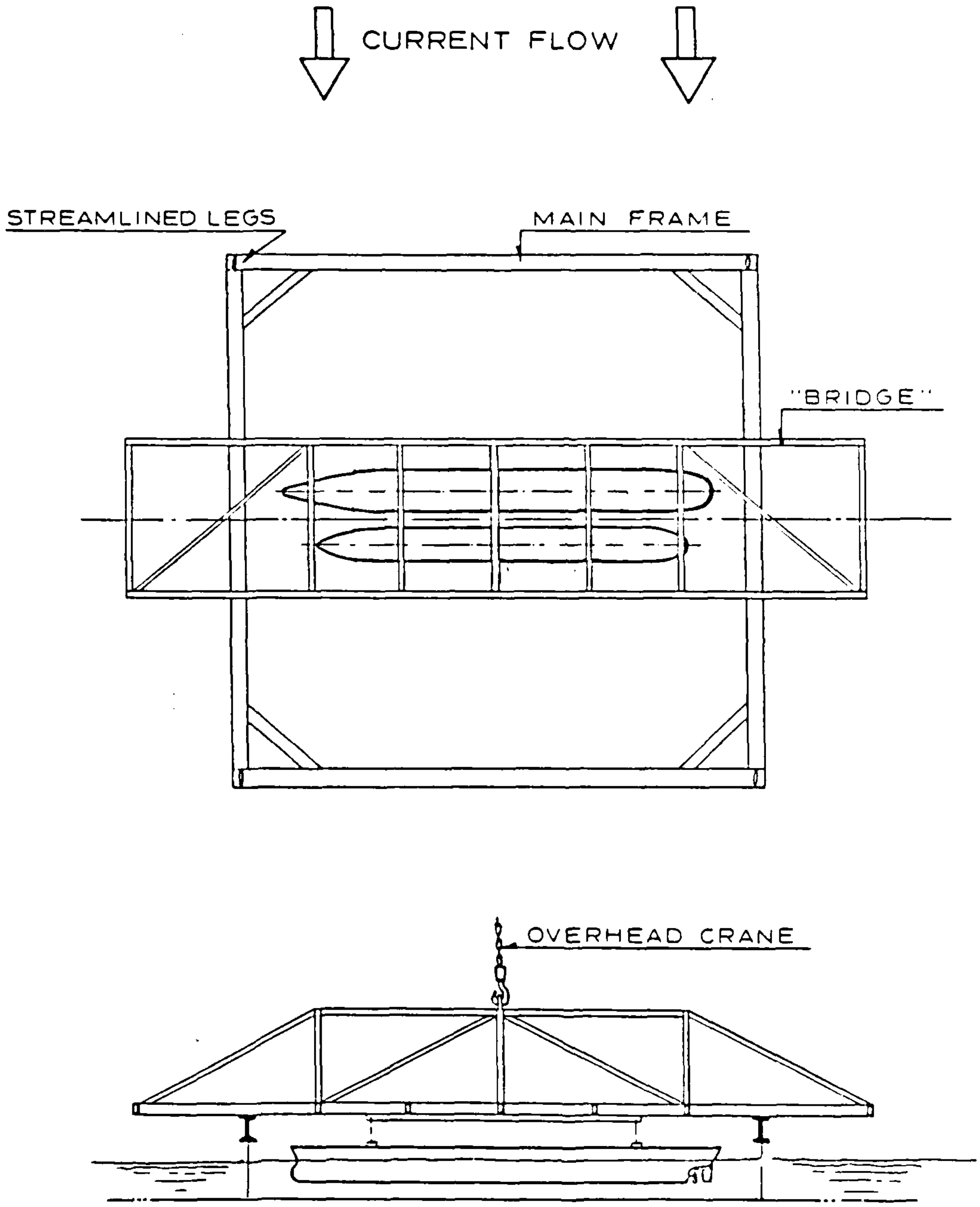


Fig. 4.4 Layout for Support Structure.

4.3 Current Calibration

For each of the specified current situations, the calibration procedure was as described below: The predetermined water level was established. A current meter set-up was mounted in the center of the flume upstream to the vessel position at depths corresponding to the velocity V (averaged over the entire depth), and the velocity U, (averaged over the draft of the ship).

Preliminary investigations gave the empirical vertical velocity distribution, as function of the depth and the flow velocity, see Dwg. Nos. 4.1 and 4.2

Other preliminary studies verified the uniform horizontal velocity distribution. See Fig. 4.5.

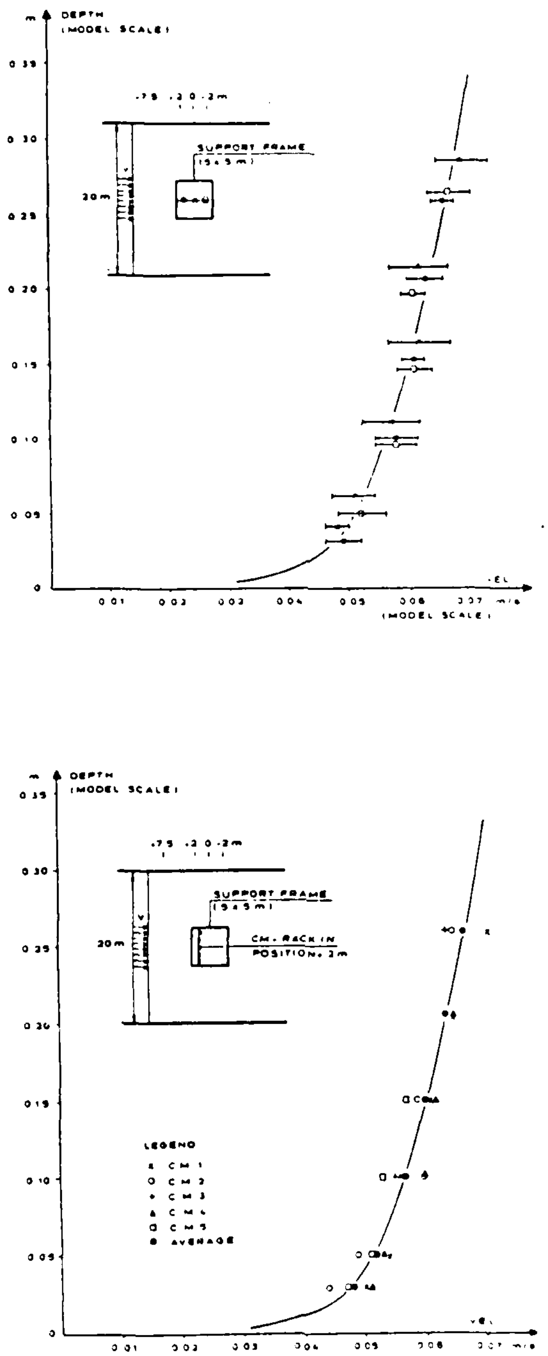


Fig. 4.5 Longitudinal (upper) and Transversal (lower) Velocity Distribution in the Flume.
Longitudinal: 1 instrument, 3 positions
Transverse : 5 instruments, 1 rack position

Minor velocity differences were found at the basin walls. Within the central 5 m, i.e. the actual area of interest, no horizontal velocity differences could be observed.

Table 4.1 below gives the ratio of the velocity averaged over the entire depth V, to the velocity averaged over the draft of the ship, U, for T_1 = 7.92 m.

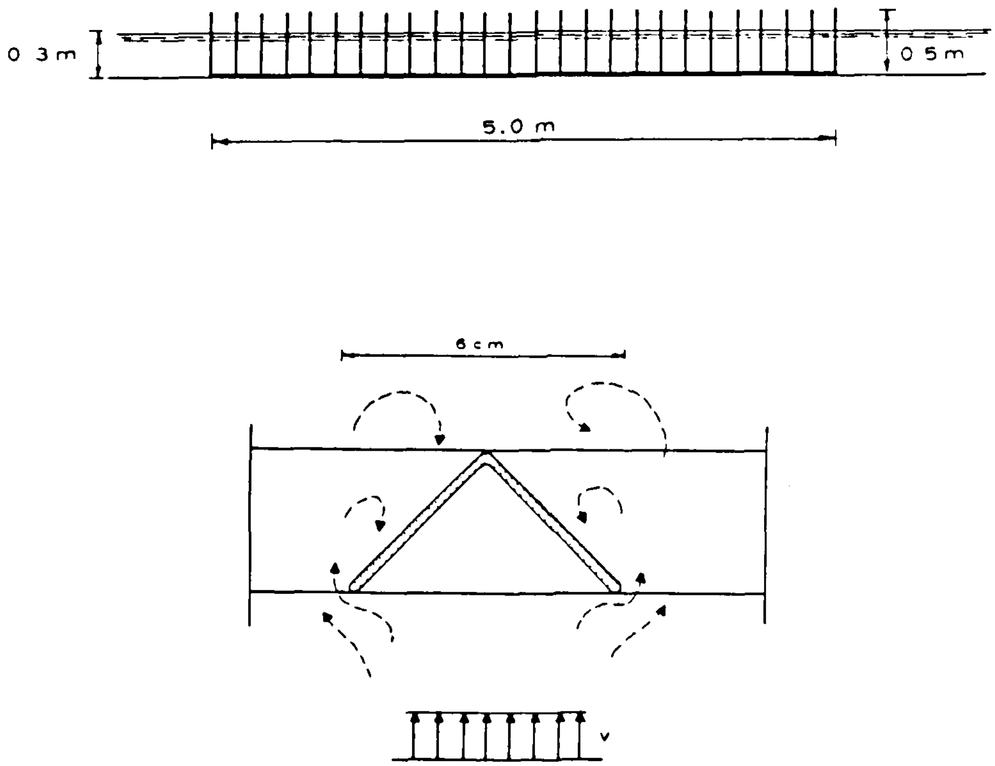
Depth	Froude Number			
(m)	0.04	0.08	0.105	0.145
18.29	0.92	0.90	-	-
15.24	0.91	0.94	0.92	-
12.19	0.90	0.90	0.92	0.92

Table 4.1 Ratio of V/U Empirically Determined by Vertical Velocity Profiles, Ship Models Absent, see Dwg. No. 4.1 and Dwg. No. 4.2.

During testing the current meters were placed in position +7.5 m (see Fig. 4.5a).

4.4 Turbulence Lattice

Tests with an increased level of turbulence in the approach flow were also performed. The increased turbulence was produced by means of a lattice structure, see Fig. 4.6.



Horizontal flow around single section of turbulence lattice.

Fig. 4.6. Turbulence Lattice, General Layout and Detail of Single Section.

4.5 Ship Models

Tests have been performed with a "Mariner" class cargo ship (Phase I only), a modified "Mariner" and an "Export Leader" class container ship.

The ships were equipped with the following appurternances:

- Rudder
- Propellers, locked
- Bilge keels
- Trip wires (in few tests only)

The properties of the ships are listed in Table 4.2 and 4.3.

Test Phase	Ship No.	Identification	Length between Perpendiculars, Lpp (m)	Moulded Breadth, B (m)	Bilge Radius (approx.) (m)	Bilge Keel Width (m)	Bilge Keel Length (m)	Extention from midship ahead (m)	Extention from midship astern (m)
I	M	"Mariner" class cargo ship	160.9	23.0	3.05	0.46	66.0	-	-
II	1	"Mariner" class, modified (middle body lengthened)	192.9	23.2	3.05	0.55	66.0	31,[illegible]5	3[illegible],25
II	2	"Export Leader"	177.3	23.8	3.35	0.80	52.9	21,00	31,[illegible]

Table 4.2 Particulars of the Ships.

Test Phase	Ship No.	Draft (m)	Trim	Displacement (measured) (m^3)	KG (m)	Transverse Metacentric Height (m)	Elevation of Point of Attachment of Anti-Sway Rod (Phase I) or Mooring Lines (Phase II) (m above base line) At Side	At Bow	At Stern
I	M	9.[illegible]	zero	18.54×10^3	?	2.13	15.20 aft 16.[illegible]5 fwd	-	-
II	1	7.92	zero	$23.9[illegible] \times 10^3$	7.47	2.[illegible]3	13.07	13.07	13.07
II	2	5.85	zero	$1[illegible].14 \times 10^3$	6.61	[illegible]	17.[illegible]5	17.25	17.[illegible]5
II	2	9.08	zero	25.19×10^3	9.14	0.[illegible]5	17.25	17.25	17.25

Table 4.3 Further Particulars of the Ships, as tested.
Values of KG are not measured.

4.6 Tripwire

In some tests so-called "tripwires" were applied on Ship 1 in order to investigate the effect of an artificial turbulent boundary layer around the ship. The tripwires are made of wire, coated with coloured plastic. The diameter is 2.7 mm and the distance from the hull is 10 mm. The arrangement is shown on slides 8,9, and 10.

The vertical tripwires at bow and stern increase the turbulence in the horizontal boundary flow while the horizontal tripwires extending from the bilge keel increase the vertical boundary flow.

Photographs of the tripwire arrangement are shown below:

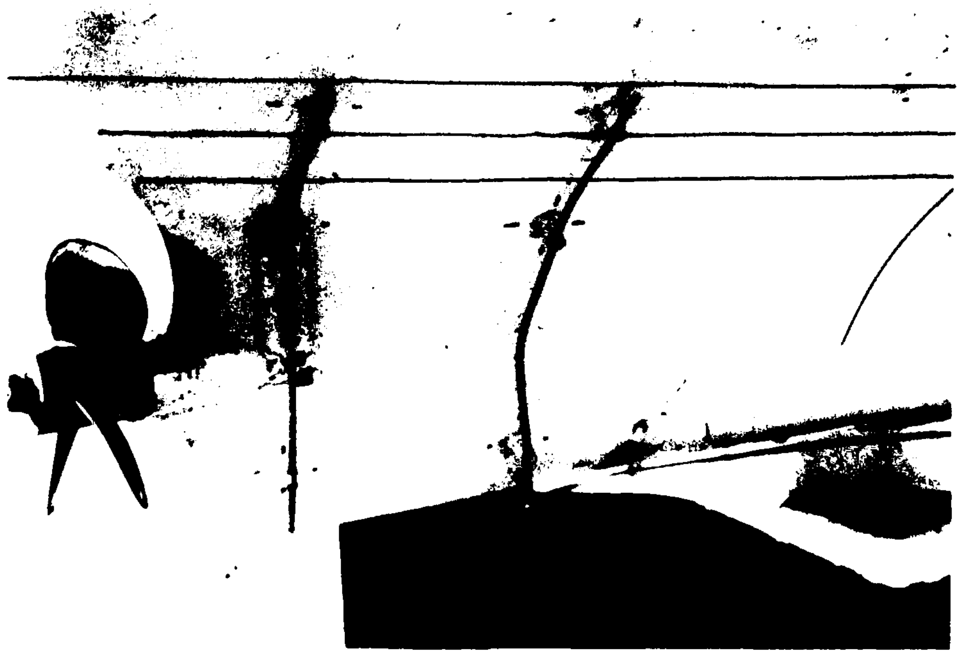


Photo 4.1 Tripwires, stern.

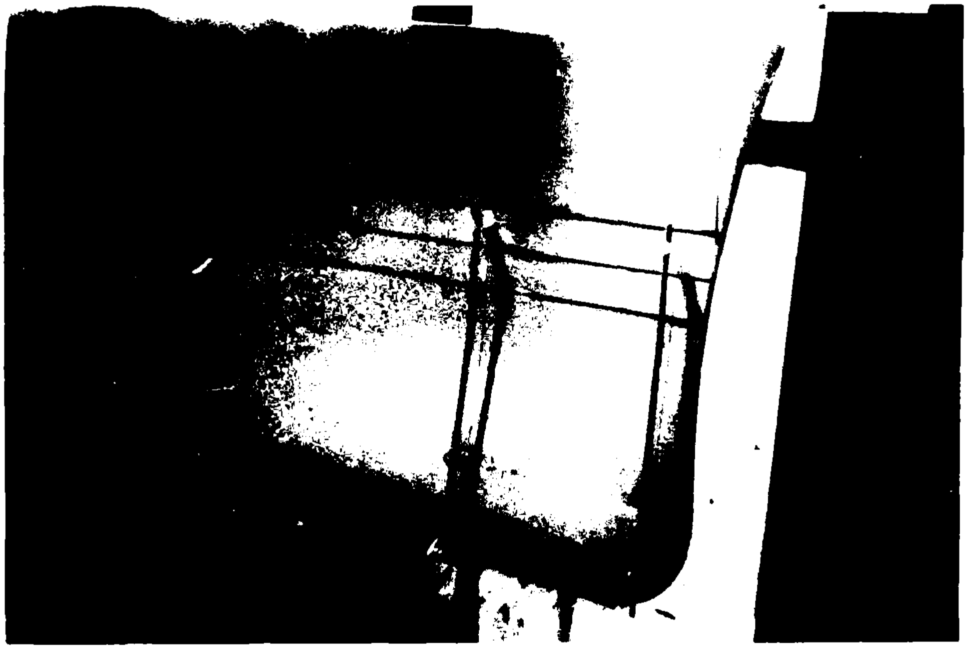


Photo 4.2, Tripwire, Bow.

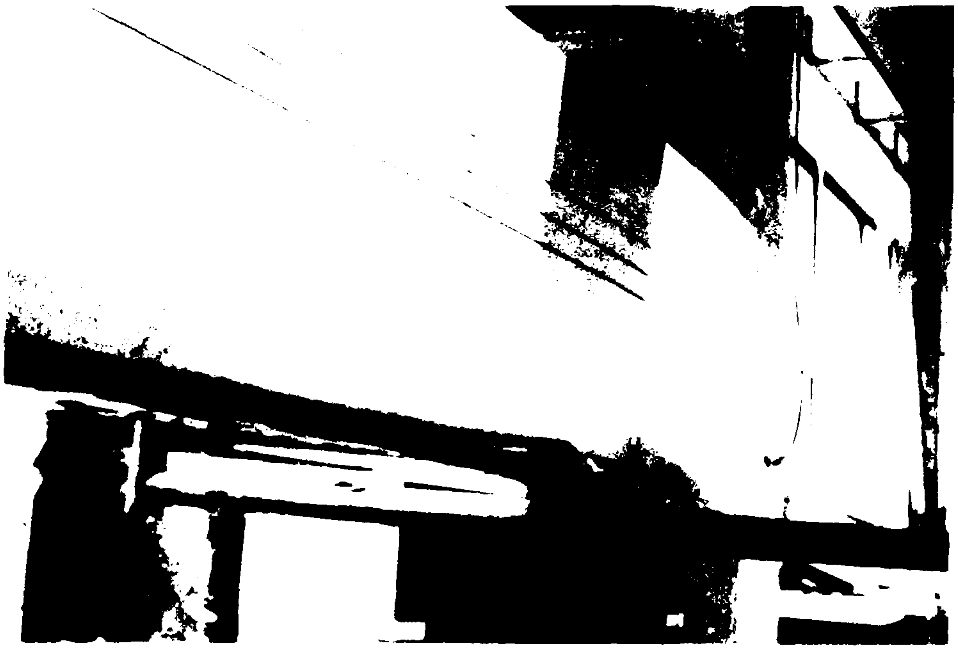


Photo 4.3, Tripwire.

The introduction of trip wires resulted in no visible changes in the flow pattern nor in the vortex shedding frequency.

The effect on the mooring forces was found to be negligible, probably due to the turbulent flow in the flume. Therefore, no further tests were performed with the trip wires mounted on the hull.

4.7 Moorings

Two mooring systems were applied:

- The fixed mooring system
- The free mooring system.

In the fixed system, the ship model was fixed to the support frame. No significant movements were allowed and only the forces (1 longitudinal, 2 transverse) and the moment about a vertical axis were measured.

In the free system, where the model(s) are floating, the vessel(s) were supplied with simulated mooring lines with the following linear spring characteristics.

Mooring	Length (m)	Individual Elasticity (t/m)	Height above WL (m)
Mooring lines (abeam)	121.92	41.8	Ship 1: 5.15
			Anchor: 1.52
Head line (ahead/astern)	91.44	15.0	Ship 1: 5.15
			Anchor: 1.52
Tension springs	3.65	209	4.10
Compression springs	3.65	151	1.05
Spring lines	approx. 75	stiff	4.10 (above tension spring)
Mooring lines (abeam)	121.92	41.8	Ship 2: 11.40
			Ship 2: 8.17

For different mooring conditions (due to different draft and relative position) different mooring points for the tension springs were used on ship 2. On ship 1, the same points were used throughout the tests.

Tension and compression springs were placed approximately in the same distance from centerline of ship 1.

The elasticity of the mooring lines, the head line and the tension springs were modelled by different steel springs.

The compression springs are shown on Fig. 4.9. The small hull separation did not allow the presence of spring and force gauges between the models. Therefore, the force gauge was placed on the deck of ship 1, measuring the forces induced by the deflection of the vertical steel rods.

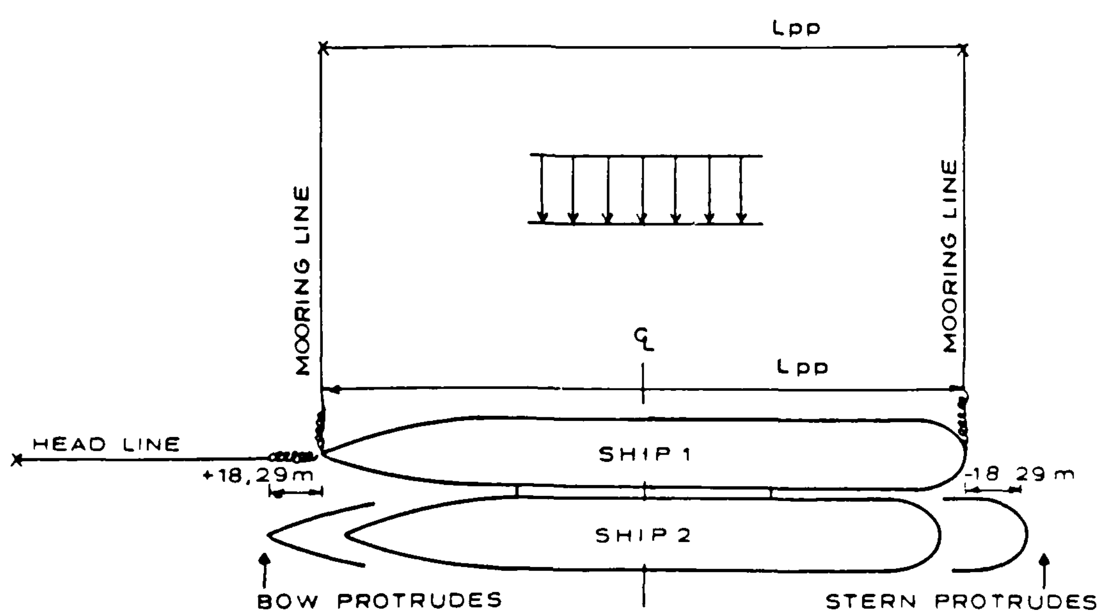


Fig. 4.7 General Mooring Arrangement (Case I).

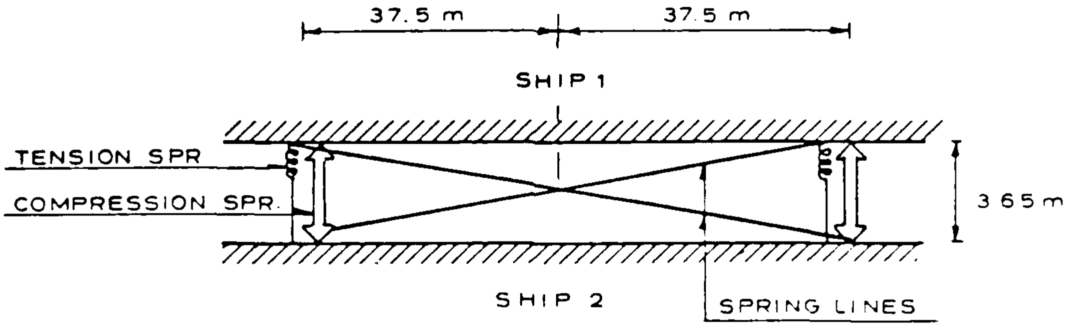


Fig. 4.8 Detail of Moorings Between Ship 1 and Ship 2.

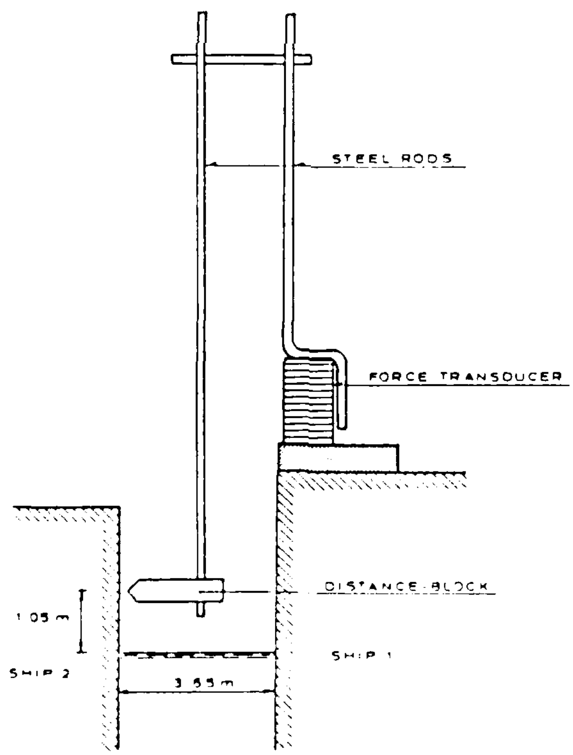


Fig. 4.9 Compression Spring Arrangement (Fenders).

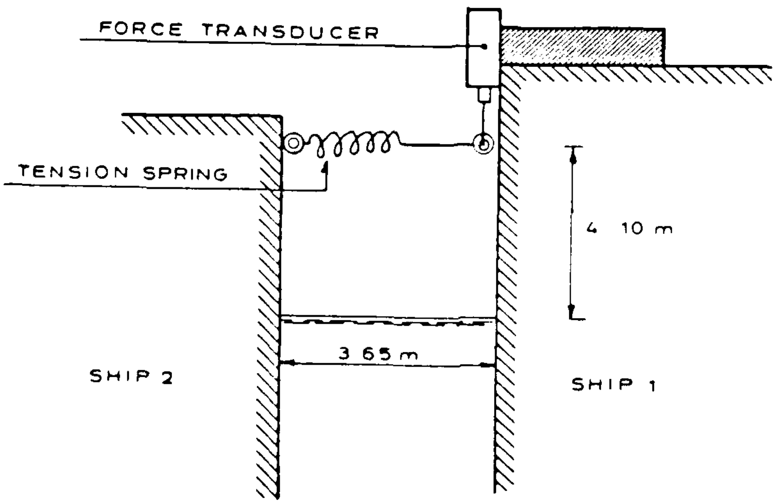


Fig. 4.10 Tension Spring Arrangement.

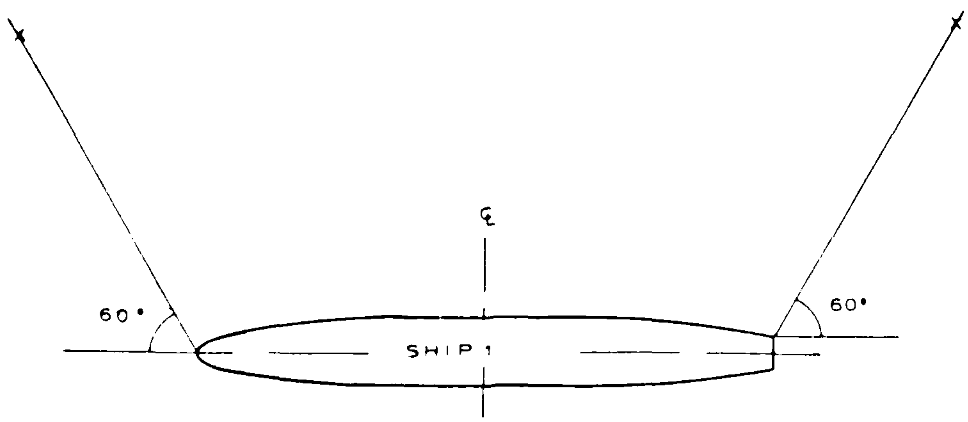


Fig. 4.11 Mooring Arrangement, Case II.

The alternative mooring arrangement, Case II, is shown on Fig. 4.11.

Mooring Points

In the free mooring system, transverse mooring points were placed perpendicular to the ship axis in a distance of 100 m (300 ft) upstream. The longitudinal mooring point was placed on the longitudinal ship axis either fore or aft, depending on the actual ship heading. These fixed mooring points were located on the main frame of the support structure at points 1.5 m (5 ft) above the surface of the water.

For beam currents, the mooring-line layout was as shown in Fig. 4.7 which also shows the horizontal locations of the mooring attachment points on the ships. The elevations of the attachment points are given in Table 4.2.

In one test in the 5000-series (heading angle of 60 deg.), the mooring line layout was as shown in Fig. 4.11.

4.8 Measuring Techniques

For recording of the signals of forces and motions, the applied instruments were scanned by the computer and the signals were stored for further analysis. The scanning frequency was 10 Hz during all tests. Some parameters (like water level) were measured by various instruments, and not all were logged on the computer. Visual control observations have been performed and documented on special test sheets.

The following instrumentation has been applied:

Water Level

a) A sharp, vertical rod, pointing on the water surface and pre-set to the right level. A simple, but very useful device for visual control of the general water level. Accuracy: ± 1 mm.

b) Standard resistance type wave gauge, consisting of two parallel rods, used to determine the short term water level variation in the flume. Accuracy: ± 0.5 mm.

c) Water Level Difference Gauge (WLD), an instrument to detect very small water level differences upstream and downstream of the model. Small displacements are measured by a differential amplifier. Accuracy: ± 0.1 mm.

Current Velocities

a) Ultra Sonic Current Meters (USCM) were used in this project, See Fig. 4.13. Tests were made with up to five instruments simultaneously at five different positions in the flume.

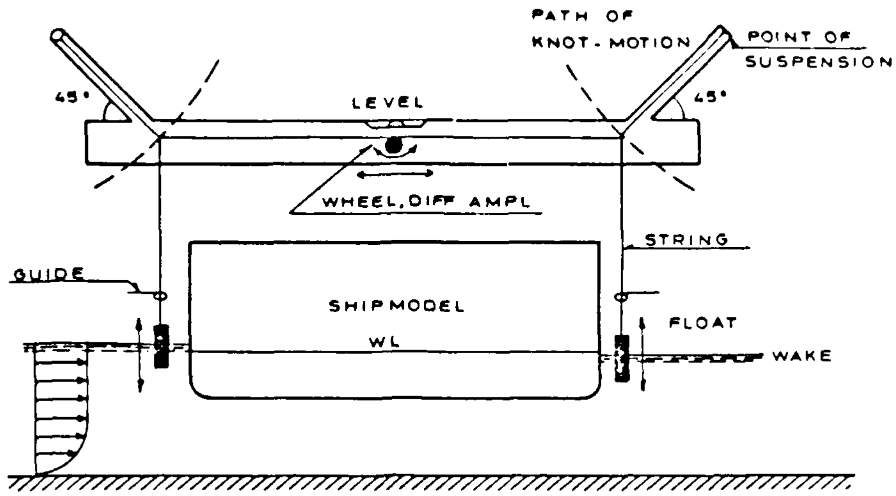


Fig. 4.12 Principle of water level difference measurements. The measured quantity is half the difference between the upstream and the downstream water level.

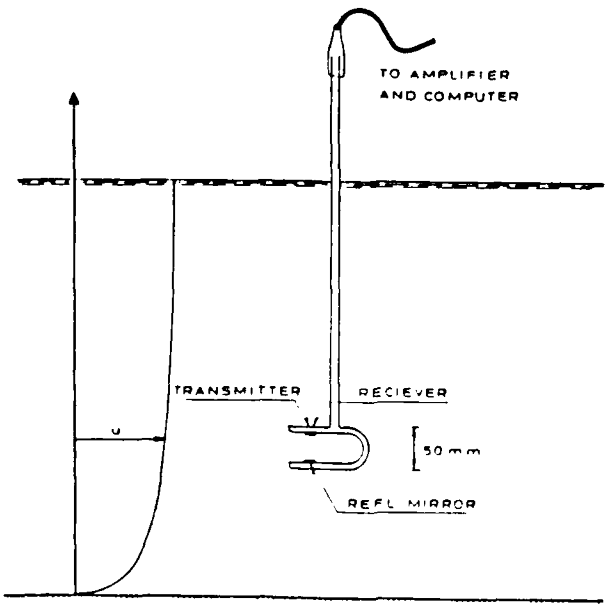


Fig. 4.13 Ultra Sonic Current Meter.

The USCM current meters measure the time of an ultrasonic signal travelling a constant and wellknown distance. The travel time depends on the current velocity.

By supplementing USCM-measurements with velocities determined by the high precision velocity profile, previously measured with a single USCM, a reliable and consistent determination of the mean velocity was made.

Mooring Forces

a) In the fixed mooring system the forces were measured by means of two-directional shear force transducers. Instrument accuracy: ± 10 g.

M1: Longitudinal force
M2: Transverse force, fore
M3: Transverse force, aft.

The force gauge arrangement for M1 and M2 is shown on Fig. 4.14.

b) In the free mooring system the mooring forces were measured by means of one-directional force gauges. Instrument accuracy: ± 10 g.

In tests with 2 ships, the internal moorings were:

M4: Breast line, fore
M5: Breast line, aft

c) Fender forces (free systems only) were measured by force transducers with an accuracy similar to the ones above. Fenders were placed close to the breast lines. F1 is the fore fender force, F2

Ship Movements

All ship movements were measured by potentiometers. As for the force measurements the measurements of the ship movements are based on well known and well proven technology. Accuracy: ± 1 mm.

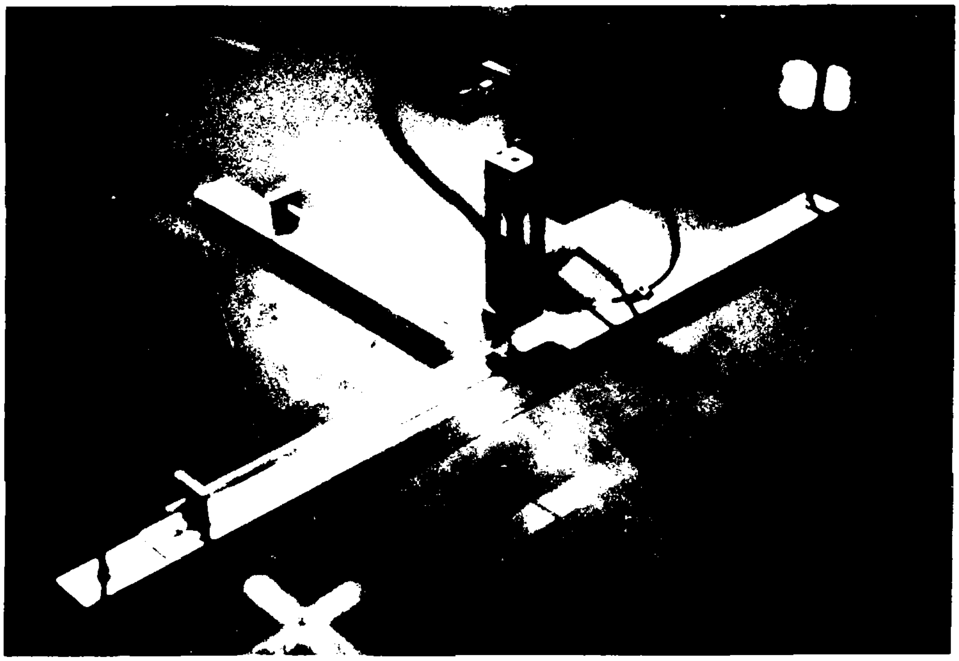


Fig.4.14 Force gauge arrangement
Fixed conditions
The 2-directional force transducer is visible in the middle of the photo, and measures two forces (M1 and M2).
The ship model is absent on this photo.

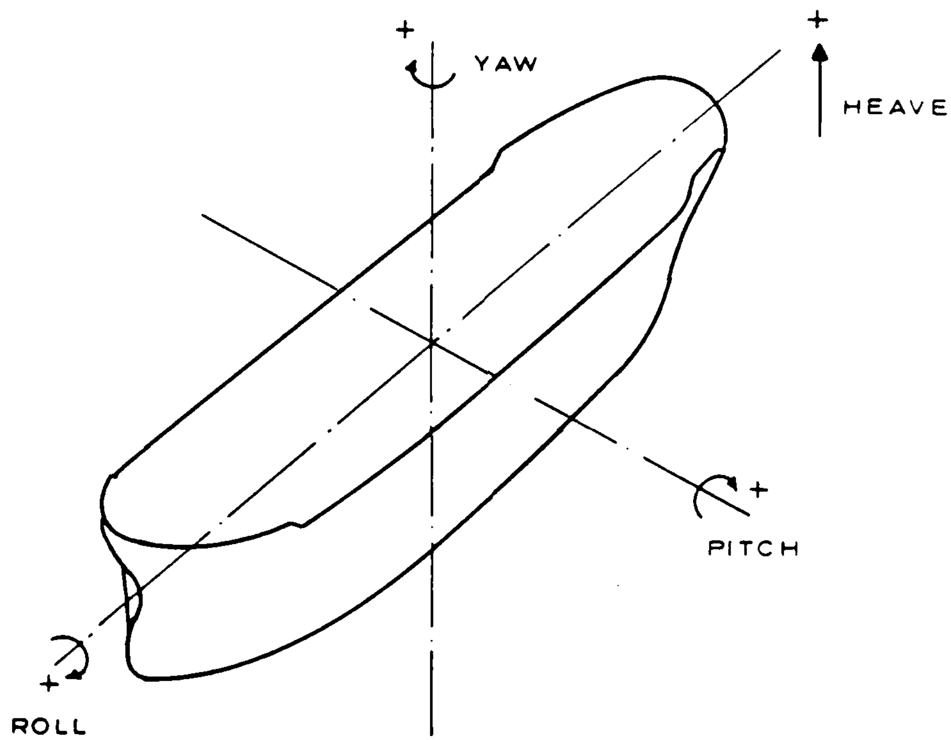


Fig.4.15 Sign-convention for movements. Valid for Ship 1 and Ship 2.
The relative roll for two ships are defined as
Relative Roll = Roll 2 - Roll 1.

4.9 Data Analysis

The datalogging system can be split up in three groups:

1. Calibration
2. Zero-scan (O-scan)
3. Logging and Analysis

1. Calibration: The calibration constant of each channel is stored in a separate calibration file. Each time a test is performed, the logging program calls the actual calibration file.

2. Zero-scan: Before a test condition is established, the signal on each channel is logged at the reference conditions (e.g. no current implies no forces and no movements). The signal at this so-called "O-stage" is automatically subtracted from the signal during the tests. Therefore it is not necessary to zero-set each single amplifier.

3. Analysis: The analysis consists of three parts:

- 3.1) Standard statistics and parameters
- 3.2) Spectrum-analysis
- 3.3) Time series

3.1 Standard statistics and parameters: The calibrated and zero-corrected signal of each channel is analysed with respect to:

MIN:	Minimum value
MAX:	Maximum value
MEAN:	Mean value
RMS:	Root of the Mean Squared value (corrected for mean value).
Tz:	Mean Period, based on autocorrelation-coefficient, lag 1 (RHO):

The above analyses are applied on measured and computed channels. The special parameters (Fr, Re, Cy, Cx etc.) that are based on mean values of measured quantities are listed at the end of each table of statistics. (See Volume 3).

3.2 Spectrum Analysis: is performed on selected channels. The analysis is based on FFT-analysis.

3.3 Time Series: Standard prints of selected time series are produced for each test. Selected time series are enclosed in Volume 4.

All data, including the calibration files and the O-scan files, were stored on magnetic tape.

The arrangement of force transducers and potentiometers is shown in the following figures:

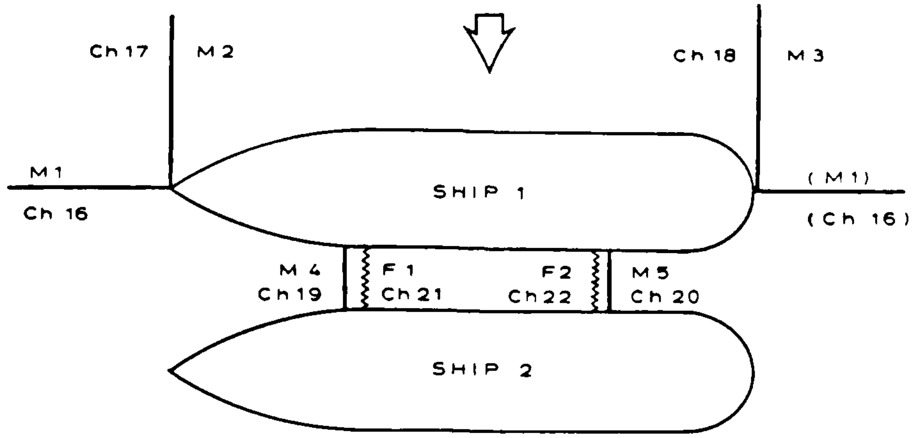


Fig.4.16 Force transducer arrangement. The channel numbers correspond to the analysis outlined below (they do <u>not</u> correspond to the processed channels presented in the result tables, Vol. 3).

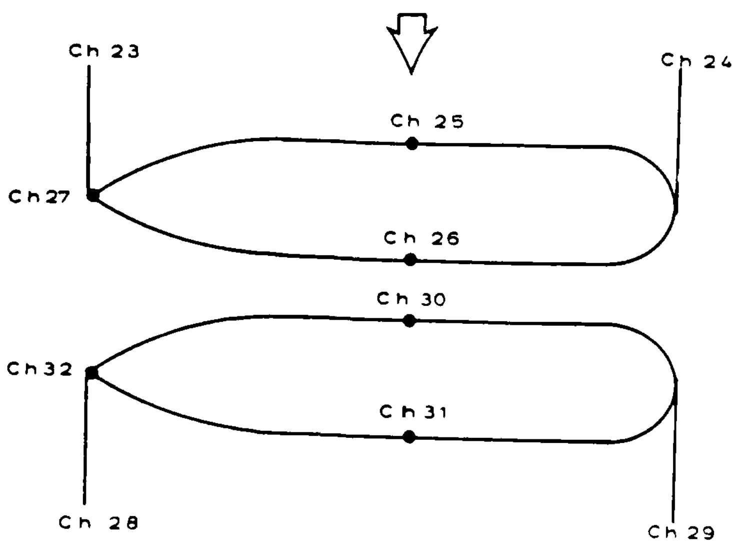


Fig. 4.17 Definition Sketch of Potentiometer Arrangement, Measuring the Movements.

The calculations for the items listed in the result tables, Vol. 3, are as follows:

(The Nos. relate to the figures above.)

<u>Wave Gauge</u>
Shows the general water level difference in the flume between the 0-scan and the actual test.

<u>Water Level Difference</u>
Shows the water level difference upstream and downstream of the vessel. The instruments were used in series 1000 and 2000.

<u>Ultrasonic</u>
Flow velocity measured by ultrasonic current meters.

<u>M1, Fx, Ship 1(kN)</u>
Longitudinal mooring force.

M1 = ch 16

<u>M2 (kN)</u>
Transverse mooring force, fore

M2 = ch 17

<u>M3 (kN)</u>
Transverse mooring force, aft

M3 = ch 18

<u>M4 (kN)</u>
Tension spring force / breast line force, fore

M4 = ch 19

M5 (kn)

Tension spring force / breast line force, aft

M5 = ch 20

Fy Ship 1

Total transverse mooring force

Fy = ch 17 + ch 18

Note: Heading = 90 deg. Fy acts on ship 1.
Heading = 270 deg. Fy acts on ship 2.

Moment Ship 1

Moment induced by mooring forces.

Moment = L1 x (ch17-ch18)

L1: distance between mooring forces

fixed mooring: 70 m

free mooring : 192.94 m

Note: Heading = 90 deg. moment acts on ship 1
Heading = 270 deg. moment acts on ship 2

Fy, Ship 2

Total transverse force between Ship 1 and 2

Fy = ch19 + ch20

Moment Ship 2

Moment induced by tension springs/breast lines between the two vessels:

Moment = L2x (ch19-ch20)

L2 = 177.33 m

<u>F1 (kN)</u>

Compression spring/Fender force, fore

F1 = ch 21

<u>F2 (kN)</u>

Compression spring/fender force aft.

F2 = ch 22

<u>F1+F2 (kN)</u>

Total compression force/Fender force:

F1+F2 = ch21 + ch22

<u>Roll Ship 1</u>

[illegible] = mean [illegible]

$$\text{Roll} = \frac{1}{B1} \times (ch25-ch26) \times 360/2\pi$$

B_1 = 23.16 m

<u>Pitch Ship 1</u>

$$\text{Pitch} = \frac{2}{L1} (ch27-(ch25+ch26)) \times 360/2\pi$$

L1 = 192.94 m

<u>Heave Ship 1</u>

$$\text{Heave} = \frac{1}{2} (ch25+ch26)$$

<u>Yaw Ship 1</u>

$$\text{Yaw} = \frac{1}{L1} (ch23-ch24) \times 360/2\pi$$

L1 = 192.94 m

Roll Ship 2

$$\text{Roll} = \frac{1}{B2}\ (\text{ch30}-\text{ch31})\ \times\ 360/2\pi$$

B2 = 23.77 m

Pitch Ship 2

$$\text{Pitch} = \frac{2}{L2}\ (\text{ch32}-(\text{ch30}+\text{ch31}))\ \times\ 360/2\pi$$

L2 = 177.33 m

Heave Ship 2

$$\text{Heave} = \frac{1}{2}\ (\text{ch30}+\text{ch31})$$

Yaw Ship 2

$$\text{Yaw} = \frac{1}{L2}\ (\text{ch28}-\text{ch29})\times 360/2\pi$$

L2 = 177.33 m

Rel. Roll

Rel. Roll = Roll Ship 2-Roll Ship 1

The calculations outlined above were performed on the time series, i.e. once per 0.1 sec. The derived time series were processed with reference to standard statistics, spectra and coefficients.

Force Coefficients Definitions

$$C_x = 2F_x/(LT\rho U^2)$$
$$C_y = 2F_y/(LT\rho U^2)$$
$$C_{mz} = 2M_z/(L^2T\rho U^2)$$
$$C_{pw} = 2g(1/2(\overline{h_1-h_2}))/U^2$$

Comments to applied terms and force coefficients:

ad h)
h is the actual, measured difference between the preset water depth at still water and the depth at flowing water. h is measured at a point approximately 5 m downstream of the model and approx. 1.5 m off the centerline. At still water this location was found to give exactly the same water depth as the location of the ship model.

ad T)
T is the draft of the actual ship. The draft is valid for still water.

ad F_r)
All Froude Numbers are based on the mean velocity averaged over the flow depth and on the preset depth.

ad C)
The force coefficients are always based on the velocity U and the still water draft of the ship, except for the C_{pw}.

ad C_{pw})
The "wake under pressure coefficient" (C_{pw}) was initially defined as:

$$C_{pw} = 2g(h-\bar{h}_2)/U^2, \text{ where}$$

g gravity
h depth of flowing water at location of ship model, with model absent
$\bar{h}_2$ mean depth adjacent to hull on the downstream (wake) side
U mean velocity above keel depth

With the present set-up it was not practical to determine the depth of the flowing water before the model was mounted.

The zero scan of the force gauges requires the model mounted in still water. After the current had been established the water level was not the same. Accepting this physical fact, another definition was elaborated:

$$C_{pw} = 2g \left(\frac{\overline{h_1 - h_2}}{2} \right) / \bar{U}^2, \text{ where}$$

h_1: Depth adjacent to hull on the upstream side

— : Sign for time average

The principle of this definition is shown in Fig. 4.12.

In order to reach a coefficient as close to the specified coefficient as possible, the difference $(h-\bar{h}_2)$ is substituted by the difference $(1/2(\overline{h_1-h_2}))$.

Sinkage: The vertical movement of the ship is logged on the computer as the traditional heave motion. This is the reason for the name "heave" on the computer prints. The static part of this motion is found as the time averaged MEAN-value and denoted sinkage.

4.10 Test Programme, Phase II Tests

A complete list of the Phase II tests is given below.

The main test conditions are given along with special notes for each test. The remaining parameters for describing the test conditions are provided in the respective chapters.

Each test was performed in accordance with the specifications given by NCEL. A total number of 116 tests has been performed in Phase II.

The model scale is 1:50, and Froude's model law is applied. The presented data are given in prototype values, unless otherwise specified.

Test No.	Depth (m)	Froude Number	Draft Ship 2 (m)	Heading (deg.)	Notes
1110	18.29			90	
1101	15.24	0.105		90	
1102	15.24	0.08		90	
1103	12.19	0.145		90	
1105	12.19	0.145		90	
1113	12.19	0.145		90	Incr. Turb.
1114	12.19	0.145		90	Incr. Turb.
1115	12.19	0.145		90	Incr. Turb.
1123	12.19	0.145		90	Tripwire Identical
1124	12.19	0.145		90	Tripwire Testcond.
1125	12.19	x		90	Tripwire

Table 4.5 Basic Flow Pattern Tests.

Test No.	Depth (m)	Froude Number	Draft Ship 2 (m)	Heading (deg.)	Notes
2200	12.19	0.08	5.85	90	
2201	12.19	0.105	5.85	90	
2202	12.19	0.145	5.85	90	
2204	12.19	0.145	9.08	90	
2205	12.19	0.105	9.08	90	
2206	12.19	0.08	9.08	90	
2207	15.24	0.08	9.08	90	
2208	15.24	0.105	9.08	90	
2209	15.24	0.105	5.85	90	
2210	15.24	0.08	5.85	90	
2211	18.29	0.08	5.85	90	
2216	12.19	0.08	9.08	90	IDENTICAL TO 2206

Table 4.6 Basic Drag Tests.

Test No.	Depth (m)	Froude Number	Heading (deg.)	Notes
3201	15.24	0.105	90	
3202	15.24	0.105	5	
3203	15.24	0.105	10	
3204	15.24	0.105	15	
3205	15.24	0.105	20	
3206	15.24	0.105	30	
3207	15.24	0.105	45	
3208	15.24	0.105	60	
3209	15.24	0.105	120	
3210	15.24	0.105	135	
3211	15.24	0.105	150	
3212	15.24	0.105	160	
3213	15.24	0.105	165	
3214	15.24	0.105	170	
3215	15.24	0.105	175	
3216	15.24	0.105	90	

Table 4.7 Basic Heading Effect Tests.

Test No.	Depth (m)	Froude Number	Heading (deg.) (m)	Notes
4100	18.29	0.04	90	
4101	18.29	x	90	
4102	18.29	x	90	
4103	18.29	0.08	90	
4104	18.29	x	90	Incr. Turbulence
4200	18.29	0.04	90	
4201	18.29	x	90	
4202	18.29	x	90	
4203	18.29	0.08	90	
4300	15.24	0.04	90	
4301	15.24	0.08	90	
4302	15.24	0.105	90	
4303	15.24	0.105	90	
4304	15.24	0.105	90	
4304	15.24	0.105	90	
4305	15.24	0.105	90	
4400	12.19	0.04	90	
4401	12.19	0.08	90	
4402	12.19	0.105	90	
4403	12.19	0.145	90	
4404	12.19	0.145	90	
4405	12.19	0.145	90	

Table 4.8 Basic Movement and Forces Tests.

Test No.	Depth (m)	Froude Number	Heading (deg.) (m)	Notes
5100	15.24	0.04	5	
5101	15.24	0.04	30	
5102	15.24	0.04	60	
5103	15.24	0.04	120	
5104	15.24	0.04	150	
5105	15.24	0.04	175	
5200	15.24	0.08	5	
5201	15.24	0.08	30	
5202	15.24	0.08	60	
5203	15.24	0.08	120	
5204	15.24	0.08	150	
5205	15.24	0.08	175	
5206	15.24	0.08	175	
5300	15.24	0.105	5	
5301	15.24	0.105	30	
5302	15.24	0.105	60	
5303	15.24	0.105	120	
5304	15.24	0.105	150	
5305	15.24	0.105	175	
5399	15.24	0.105	5	Identical to 5300
5400	15.24	0.105	60	Transverse mooring lines: Direction changed $\pm$30 deg. to original direct.

Table 4.9 Heading Effect on Movement and Forces Tests.

Test No.	Depth (m)	Froude Number	Draft Ship 2	Heading (deg.)	Ship 2 Relative Pos. (m)	Notes
6100	18.29	0.04	9.08	90	0	
6101	18.29	0.04	5.85	90	0	
6104	18.29	0.04	9.08	270	0	
6105	18.29	0.04	5.85	270	+18.29	Bow of ship 2 protrudes
6106	18.29	0.04	5.85	270	+18.29	identical conditions
6107	18.29	0.04	9.08	270	+18.29	
6108	18.29	0.04	9.08	270	+18.29	
6109	18.29	0.04	9.08	90	+18.29	
6110	18.29	0.04	5.85	90	+18.29	
6111	18.29	0.04	5.85	90	+18.29	Incr. turbulence,
6112	18.29	0.04	5.85	90	-18.29	Stern of ship 2 protrudes
6113	18.29	0.04	9.08	90	-16.29	
6114	18.29	0.04	9.08	270	-18.29	
6115	18.29	0.04	5.85	270	-18.29	
6116	18.29	0.08	5.85	270	-18.29	
6117	18.29	0.08	9.08	270	-18.29	
6118	18.29	0.08	9.08	270	0	

Table 4.10 Tests on Two Ships, Movements and Forces.

5. BASIC FLOW PATTERN TESTS

1000-Series

Test conditions:

Ship:	1
Condition:	Fixed
Heading:	90 deg.
Draft:	7,92 m
Trim:	Zero
Variables:	Depth, h
	Froude Number, Fr
	Special: Increased turbulence
	Trip wires

This first test series was performed in order to gain a fundamental description and understanding of the flow pattern, including the effects of increased turbulence in the approach flow. The drag coefficient is a parameter of major interest in this series and its correlation with various other quantities was investigated. The drag coefficient is presented in this Chapter, whereas the flow description is included in Chapter 11.

5.1 Determination of Resonance Frequencies

The fixed mooring system did not allow any significant movements, but, since the force measurements are based on strain gauges, very small displacements are necessary to measure the forces. In this connection it is of interest to know the different resonance frequencies of the system, i.e. the ship mounted in the force transducers.

The resonance frequencies for the fixed mooring system were empirically determined to:

SHIP 1, Mariner ($1Hz = \frac{1}{1sec}$)

Longitudinal ship motion	0.38 Hz	(Prototype)
Longitudinal frame	0.74 Hz	(")
Transverse ship motion	0.42 Hz	(")

SHIP 2, C5-S-73b Class

Loading Condition A (light):

Longitudinal ship motion	0.44 Hz	(Prototype)
Longitudinal frame	0.76 Hz	(")
Transverse ship motion	0.56 Hz	(")

Loading Condition B (loaded):

Longitudinal ship motion	0.35 Hz	(Prototype)
Longitudinal frame	0.81 Hz	(approx.)
Transverse ship motions	0.43 Hz	(")

5.2 Test Results

The velocities used to calculate the different coefficients are based on surface velocities, transformed to the mean velocity over the full depth, V, or the mean velocity down to keel depth, U, by use of the actually measured velocity profiles. The results are given in Table 5.1 and visualized in Dwg. No. 5.1.

The measurements are compared with values given in Ref/1/, OCIMF.

Test	Depth,h (m)	Froude Number, Fr	h/T	L/T	Cy	Cpw	Notes
1110	18.29	0.065	2.31	24.4	1.45	0.081	
1101	15.24	0.090	1.92	24.4	1.50	0.064	
1102	15.24	0.077	1.92	24.4	1.42	0.053	
1103	12.19	0.114	1.54	24.4	1.78	0.127	
1105	12.19	0.083	1.54	24.4	1.88	0.150	
1113	12.19	0.099	1.54	24.4	1.49	0.096	
1114	12.19	0.091	1.54	24.4	1.59	0.141	Turbulence
1115	12.19	0.068	1.54	24.4	1.56	0.137	Turbulence
1123	12.19	0.140	1.54	24.4	1.71	0.28	Tripwire
1124	12.19	0.138	1.54	24.4	1.62	0.32	Tripwire 1125 12,1
1125	12.19	0.091	1.54	24.4	1.67	0.14	Tripwire

Table 5.1 Test Results. Series 1000.
Heading 90°.
Test duration: 103,1 s (Model scale).

5.3 Test for Increased Level of Turbulence

The level of turbulence is in the following defined as the Root Mean Squared value (RMS) of the longitudinal velocity fluctuations divided by the Mean-value of the velocity. Since the USCM-signal is proportional to the velocity, the analysis can directly be made on the calibrated signal. Turbulence-profiles are produced for different Froude Numbers and for increased level of turbulence, see Fig. 5.1. For normal flow conditions, a turbulence-peak can be observed rather close to the bottom. The level decreases upwards through the flow and ends up with a vertical tangent at the water surface. For increasing flow velocity the turbulence gradient decreases.

When a so-called turbulence lattice (see Fig. 4.6) is mounted in the approach flow (actually at the upstream side of the main frame) in order to increase the general level of turbulence, the gradient is almost vertical in the upper part of the flow, see Fig. 5.1.

By introducing the lattice, the turbulence is obviously more evenly distributed over the flow depth, i.e. the upper flow contains more turbulence, but the total turbulence integrated over the entire depth seems not affected by the presence of the lattice.

The "turbulence-lattice" consists of vertical, wedge-shaped steel rods of approx. 6 cm width and internal spacing of approx. 15 cm. Total length: 5 m. The lattice configuration is shown in Fig. 4.6.

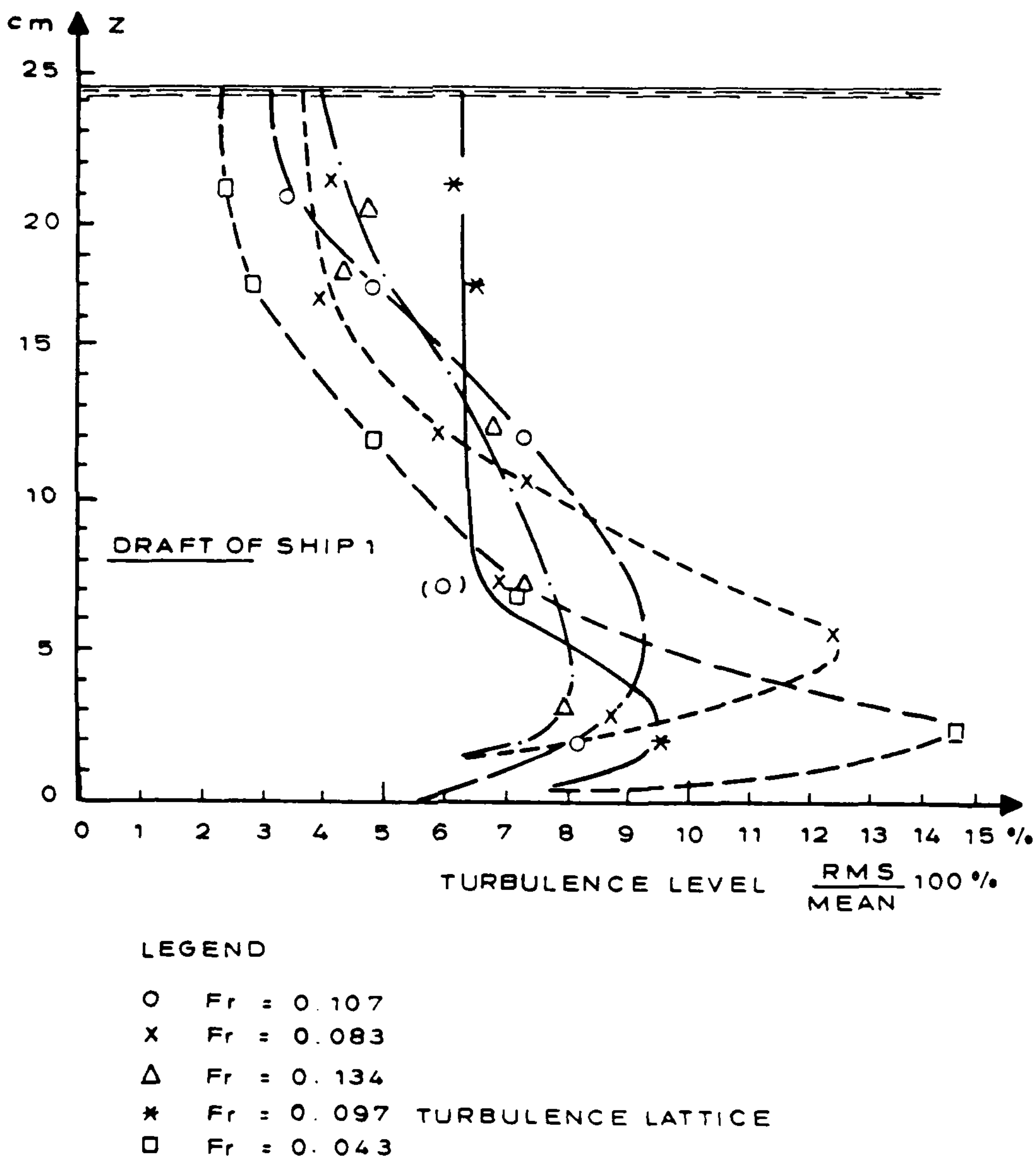


Fig. 5.1 Profile of turbulence level measured in the center of main frame with the ship model absent. Special test series.

6. BASIC DRAG DATA TESTS

2000-Series

Test conditions:

Ship No:	2
Conditions:	Fixed
Heading:	90 deg.
Trim:	Zero
Turbulence:	Normal
Tripwire:	None
Variables:	Draft, T
	Depth, h
	Froude, Fr

In the 2000-series an advanced and more thorough investigation on the basic data was conducted. Special attention was paid to the depth-draft ratio and the hull form. The flow pattern was monitored in order to detect significant changes.

6.1 Resonance Frequencies

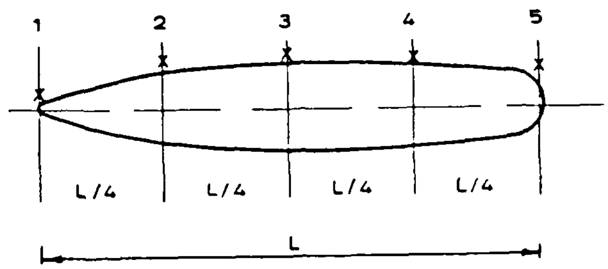
Resonance frequencies for the fixed ship 2 for different loading conditions are given in chapter 5.

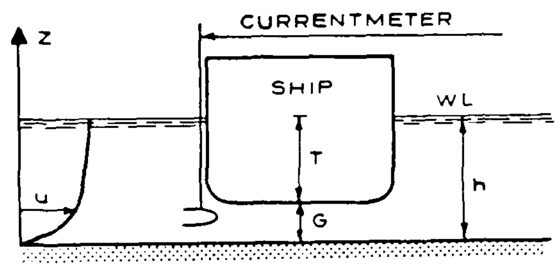
6.2 Test Results

As for the 1000-series, the 2000-series data analysis is based on computed velocities, using the vertical velocity profiles. The results of this test series is given in Table 6.1 and the C_Y-variation is visualized in Dwg. No. 6.1.

Test	Depth, h (m)	Froude Number, Fr	h/T	L/T	C_Y	C_{pw}	Notes
2200	12.19	0.077	2.08	30.3	1.10	0.24	
2201	12.19	0.092	2.08	30.3	1.17	0.26	
2202	12.19	0.136	2.08	30.2	0.91	0.20	
2204	12.19	0.150	1.34	19.5	1.70	0.41	
2205	12.19	0.099	1.34	19.5	1.92	0.39	
2206	12.19	0.064	1.34	19.5	2.47	0.14	Failed
2207	15.24	0.080	1.68	14.5	1.30	0.28	
2208	15.24	0.114	1.68	19.5	1.32	0.24	
2209	15.24	0.108	2.61	30.3	1.02	0.16	
2210	15.24	0.074	2.61	30.3	1.06	0.15	
2211	18.29	0.086	3.13	30.3	0.79	0.13	Conditions as for 2206
2216	12.19	0.082	1.34	1.34	1.56	0.35	

Table 6.1 Test results,
Ship 2, Basic Drag Data
Test duration: 102,1 sec (Model scale)





u: Velocity
h: Water depth
z: Vertical coordinate
G: Gap between sea floor and ship
T: Draft of ship
L: L_{pp} of ship

Fig. 6.1 Flow under Vessel. Current Meter Array and Definition Sketch.

6.3 Velocity Distribution beneath the Vessel

Surface of separation beneath the vessel

In the 2000-series, the description of the flow beneath ship model 2 was an important and difficult objective.

A USCM was placed close to the upstream side of the model, measuring the flow velocity in the gap between model and basin floor at a distance z_u from the floor. The velocity is measured at 5 positions along the model, see Fig. 6.1.

The results of the underflow tests are shown in Table 6.2 together with the value of the mean approach velocity from the corresponding force tests.

From the velocity measurements carried out during the 2000-series it was found that the mean approach velocity midship is relatively constant over the width of the gap between hull and bottom. Furthermore, it was found that this midship velocity is approximately equal to the mean velocity of the approach flow (see Table 6.2).

This second finding illustrates the significant difference between a pure two-dimensional test (as often found in literature) and the three-dimensional model tests.

The measurements mentioned above are for a fixed ship. The limited movements in the later free ship situation indicate a very similar flow under and around the vessel. More detailed discussion of the flow separation and flow pattern is given in Chapter 11. Fig. 6.2 below illustrates the flow observed underneath the fixed ship.

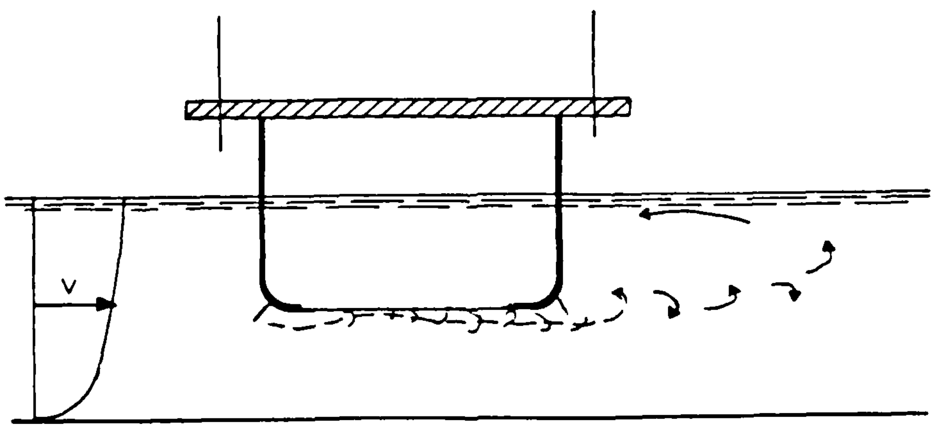


Fig. 6.2 Flow Beneath the Vessel.

Test	Pos.	Depth (cm)	Draft (cm)	Gap (cm)	Fr	Z_u (cm)	V (cm/s)	u (cm/s)
2200		24.4	11.7	12.7	0.08		12.0	
168	3			12.7	0.08	10.1		12.8
2201		"	"	"	0.105		14.3	
169	1	"	"	"	"	6.9		14.2
170	2	"	"	"	"	"		
171	3	"	"	"	"	"		14.1
172	4	"	"	"	"	"		
173	5	"	"	"	"	"		
2202		"	"	"	0.145	"	21.1	
191	1	"	"	"	"	6.4		21.0
192	2	"	"	"	"	"		21.5
193	3	"	"	"	"	"		23.7
194	4	"	"	"	"	"		18.9
195	5	"	"	"	"	"		15.7
2204		"	18.2	6.2	0.105		23.2	
198	3	"	"	"	"	9.8		22.4
2205		"	"	"	0.145		15.4	
197	3	"	"	"	"	9.8		15.3
2206		"	"	"	0.08		9.9	
199	3	"	"	"	"	10.1		8.7
2207		30.5	"	12.3	0.08		13.8	
200	3	"	"	"	"	3.7		13.8
2208		"	"	12.3	0.105		19.7	
201	3	"	"	"	"	9.4		20.3

Table 6.2 Velocity Distribution under Vessel (Model scale).

7. BASIC HEADING EFFECT

3000-Series

Test Conditions

Ship	:	1
Draft, T	:	7.92 m
Trim	:	Zero
Turbulence	:	Normal
Tripwires	:	None
Depth, h	:	15.24 m
Fr	:	0.105
Condition	:	Fixed
L_{pp}	:	192.94 m
Variables	:	Heading

From velocity profiles: $U/V_s = 0.99$
$V/V_s = 0.914$

The determination of the dependence of force coefficients on different headings and a detailed force analysis were the major objectives of the 3000 test series.

7.1 Result and Tables:

Velocity: The velocity was based on surface float measurements. All tests in this test series 3000 were carried out under very constant flow conditions: They were finished within one working day and all pumps, valves and weirs remained untouched. The measured surface velocities V_s show a limited scatter (see Table 7.1). The table also shows a good agreement between the first few USCM measurements and the velocities based on the measured surface velocity, V_s. The measured V_s is transformed to the actual velocities V and U (depending on the corresponding depth) relative to the measured velocity profiles for the same flow conditions.

The average value for all measurements (i.e. the total test series 3000) is used in the analysis.

USCM No	Test	Model V_s (cm/s)	Profile U (cm/s)	Measured U (cm/s)	Fr	Heading (deg)	C_xx100	C_y	C_{mz}x100
104	3201	19.7	19.5	19.8	0.104	90	1.3	1.58	2.5
104	3202	18.9	18.7	19.1	0.100	5	0.8	0.104	7.1
106	3203	17.7	17.5	18.7	0.093	10	0.6	0.198	9.2
106	3204	18.8	18.6	17.1	0.100	15	1.4	0.314	10.5
	3205	17.6	17.4		0.093	20	0.0	0.486	13.5
104	3206	20.0	19.8	21.2	0.106	30	-2.2	0.827	20.2
	3207	10.7	18.5		0.099	45	2.8	1.11	32.6
	3208	16.9	16.7		0.090	60	-2.0	1.42	28.3
	3209	19.5	19.3		0.103	120	-1.2	1.45	-15.2
	3210	20.4	20.2		0.108	135	-3.4	1.23	-23.8
	3211	20.7	20.5		0.110	150	-6.4	0.880	-10.3
	3212	18.5	18.3		0.098	160	-8.2	0.619	-5.4
	3213	18.2	18.0		0.096	165	-9.5	0.496	-2.2
	3214	18.9	18.7		0.100	170	-10.9	0.348	+1.5
	3215	19.2	19.0		0.102	175	-9.4	0.256	+5.0
	3216	18.8	18.6		0.100	90	-0.8	1.73	+6.1
Average			18.7		0.100				

Tab. 7.1 Results, Basic Heading Effect.
Test duration: 102,1 sec (Model scale)
(Note: All velocities are in model scale)

C_x-Heading

Dwg. No. 7.1:

The picture of the C_x-Heading relation is quite complicated and a detailed study is required to achieve a complete description and understanding of the hydrodynamic phenomenon.

C_y-Heading

Dwg. No. 7.2:

From Table 7.1 it is noted that the C_y-values for 90 degree heading has changed from 1.58 to 1.73 between the first and the last test. The same difference appears for the 5 and the 175 degree tests. This difference is due to electrical drift in the transducer amplifier system and the data shown in Dwg. No. 7.2 have been corrected for this drift. The variation of the C_y-values with heading angle is in general as expected.

C_{mz}-Heading

Dwg. No. 7.3:

Also the C_{mz}-values of Table 7.1 have been corrected in Dwg. No. 7.3.

8. BASIC MOVEMENTS AND FORCES

4000-Series

Test conditions

Ship No: 1
Condition: Free
Heading: 90 deg.
Draft: 7.92 m
Trim: Zero
Tripwire: None
Variables: Depth, h
Froude Number, Fr
Turbulence level

For different flow parameters and a free mooring condition, the mooring forces, ship motions and flow pattern were studied.

This Chapter deals mainly with the forces. The movement analysis and discussion is included in Chapter 10 and the flow pattern description in Chapter 11.

The vessel was ballasted as shown in Table 4.3 and moored as shown in Fig. 4.7 (one ship only). The correct moments of inertia and roll-periods were modelled and verified by control measurements.

dhi

Test	Froude No	h/T	Fy (kN)	Mz (kNm)	U (m/s)	C_y	C_{mz}	Notes
4100	0.033	2,31	249	7811	0.47	1.48	0.240	
4101	0.045	2.31	402	7995	0.67	1.17	0.121	
4102	0.058	2.31	680	7626	0.86	1.20	0.069	
4103	0.075	2.31	1263	7833	1.11	1.341	0.044	
4104	0.054	2.31	696	6135	0.80	1.42	0.066	Turbulence
4200	0.04	2.31	250	7116	0.58	0.97	0.143	
4201	0.05	2.31	471	7146	0.66	1.42	0.110	
4202	0.07	2.31	792	3580	0.91	1.25	0.030	
4203	0.08	2.31	1279	967	1.11	1.36	0.006	
4300	"0.04"	1.92	262	493	0.54	1.19	0.012	
4301	"0.08"	1.92	995	-2108	1.07	1.14	0.013	
4302	0.107	1.92	2321	-9332	1.41	1.53	- 0.033	
4303	0.113	1.92	-28	3080	1.53	-0.02	0.011	
4304	0.094	1.92	2249	-7855	1.24	1.91	0.036	
4305	0.106	1.92	2267	-11096	1.40	1.51	0.039	
4400	0.043	1.54	220	2604	0.52	1.06	0.066	
4401	0.083	1.54	983	8218	1.00	1.29	0.055	
4402	0.107	1.54	1924	11730	1.27	1.56	0.050	
4403	0.143	1.54	3074	14819	1.70	1.39	0.036	
4404	0.134	1.54	3371	15034	1.59	1.75	0.041	
4405	0.155	1.54	3857	13313	1.85	1.47	- 0.028	

Table 8.1 Basic results, 4000 Series
Test duration: 205.1 Sec (Model scale)

8.1 Velocity Measurements

The velocity measurements for the 4100 et seq. series are based on USCM-measurements. The following test results (i.e. 4200 to 4405) are based on surface velocities.

8.2 Lateral Force Coefficient

The C_y-coefficients are shown in Dwg. 8.1.

8.3 Surge Movements

The free mooring condition allows surge-oscillations. This movement was not measured directly, but the forces in the bow and stern line were recorded. The effect of this secondary movement on the ship movements and forces can be observed by inspection of the time-series, Volume 4. The appearance of this secondary oscillation is an interesting finding of the test series.

9. HEADING EFFECT ON SINKAGE, HEEL, STABILITY AND FORCES

5000-Series

Test Conditions

Ship	:	1
Condition	:	Free
h/T	:	1.92
Trim	:	Zero
Turbulence	:	Normal
Tripwire	:	None
Depth	:	15.24 m
Froude, Fr	:	0.04-0.08-0.105
Headings	:	5°-30°-60°-120°-150°-175°
Add. Headings	:	90° (from 4000 series)

The effect of different headings at different Froude Nos. was studied with respect to forces and movements. Special attention was paid to a possible critical Froude Number which initiates significant ship motion.

This Chapter deals only with the forces. The movement analysis and discussion is included in Chapter 10.

Froude	Mooring system	Heading (deg) 5	30	60	90	120	150	175
0.04	Case I	5100	5101	5102	4300	5103	5104	5105
0.08	Case I	5200	5201	5202	4301	5203	5204	5205
0.105	Case I	5300	5301	5302	4302	5303	5304	5305
0.105	Case I	5399			4305			
0.105	Case II			5400				

Table 9.1 Conducted Test Matrix for 5000-Series.
Including selected 4000-tests for 90 deg. heading.
Case I : Parallel Mooring Lines
Case II: Mooring Lines on Angle

Froude No.	Test No.	F_y (kN)	F_x (kN)	M_z (kNm)	U $=0.91V_s$ (m/s)	C_y	C_x	C_{mz}	Heading (deg)
0.04	5100	-29.6	22.8	471	0.59	-0.112	0.087	0.009	5
	5101	88.4	19.1	14965	0.51	0.39	0.084	0.389	30
	5102	182	42.8	18316	0.52	0.89	0.21	0.458	60
	5103	173	4.8	-18777	0.60	0.63	0.017	-0.353	120
	5104	61.8	-86.0	-16809	0.56	(0.25)	(-0.36)	-0.362	150
	5105	-12.0	24.2	-3704	0.57	-0.05		-0.077	175
0.08	5200	10.9	-16.1	15111	1.05	0.013	0.792	0.092	5
	5201	482	-183	62324	1.05	0.576	0.219	0.382	30
	5202	875	-208	82016	1.05	1.05	0.249	0.503	60
	5203	864	48.7	-82413	1.05	1.02	0.574	-0.505	120
	5204	945	18.2	-73097	1.08	0.498	0.0204	-0.424	150
	5205	-12.7	15.4	-10820	1.07	-0.014	0.0174	-0.064	175
	5206	-7.1	20.6	-8122	1.01	0.009	0.0264	-0.054	175
0,105	5300	28.7	5.7	12118	1.27	0.023	0.0046	0.051	5
	5301	964	-13.7	101002	1.28	0.77	-0.011	0.417	30
	5302	1687	-23.2	145903	1.35	1.21	-0.017	0.541	60
	5303	1719	38	-161458	1.33	1.27	0.028	-0.617	120
	5304	870	55.4	-145296	1.36	0.61	0.055	-0.531	150
	5305	92	77.8	- 7565	1.35	0.066	0.056	-0.028	175
	5399	43.3	1.4	11385	1.25	0.026	00012	0.049	5
Case II Mooring	5400	1440	0	34706	1.10	1.57			60

Table 9.3 Coefficients, Series 5000, Velocities Calculated from Surface Velocity V_s. Test duration: 205,1 sec (Model scale).
Note: Case II Mooring System for 5400.

Test	Fr	F_y (kN)	M_z (kNm)	U (m/s)	C_y	C_{mz}
4300	0.04	262	493	0.54	1.19	-0.012
4301	0.08	995	-2108	1.07	1.14	-0.013
4302	0.107	2321	-9331	1.43	1.49	-0.031
4305	0.106	2267	-11096	1.40	1.51	-0.038

Table 9.4 Force Coefficients, 4000-Series, Velocities Calculated from Surface Velocity V_s. Heading: 90 deg.

9.2 F_x-Measurements

The longitudinal force measurements are neglected for Fr = 0.04 and Fr = 0.08 since the magnitude of the force is very small and of the same order as the measuring accuracy.

The results for Fr = 0.105 are shown in Dwg. No. 9.1. These results can be compared with the results from the fixed vessel on Dwg. No. 7.1. The same order of magnitude and similar characteristics are found for the two mooring systems.

9.3 Force Coefficients

A comprehensive analysis of the force coefficients has been carried out for this test series. The coefficients are defined in Section 4. The list below gives an overview of the Drawing Nos. 9.1 to 9.7, showing the variations of the different coefficients with different parameters:

Dwg No.	Item	Variable	Fixed parameters
9.1	C_x, C_y	Heading	Fr = 0.105 , Free
9.2	C_{mz}	Heading	Fr = 0.105 , Free
9.3	C_y	Heading	Fr = 0.105 , Free
9.4	C_{mz}	Heading	Fr = 0.08 , Free
9.5	C_y	Heading	Fr = 0.08 , Free
9.6	C_{mz}	Heading	Fr = 0.04 , Free
9.7	C_y	Heading	Fr = 0.04 , Fixed + Free
			= 0.08 , Fixed + Free
			= 0.11 , Fixed + Free

9.4 Results

A good impression of the general results is gained from the comparison with data from literature as shown in Dwg. No. 9.7.

In general the values for C_Y are significiantly higher in the free mooring condition than in the fixed.

Furthermore it shows an increasing coefficient for increasing Froude Number. In the free condition this increase appears more pronounced than in the fixed condition, especially for 90 deg. heading.

However, it has to be kept in mind that the fixed condition results in Ref. 3 were found for a towed model, where there is no velocity gradiant in the approach flow, which may affect the forces.

10. TWO SHIPS, FORCES AND MOVEMENTS

6000-Series

Test conditions:

Number of ship:	2
Mooring Condition:	Free
Draft: Ship 1:	7,92m
Ship 2:	9,08m
	5,85m
Trim:	Zero
Turbulence:	Normal, except one test
Tripwire:	None
Froude Number:	Variable
Depth:	18.29 m, 15.24 m
Heading:	90 deg., 270 deg.
Relative Position of Vessel No. 2 to Vessel No. 1. (irrespective of heading angle) Positive sign. indicates Bow of Ship No. 2 Protrudes.	+ 18.29m, 0 m or -18.29 m

In the 6000 test series two ships were studied in free mooring conditions. For various flow-, heading- and relative longitudinal positions of the ships, the forces and motions were investigated. For the sake of completeness the measurements from the 4000- and 5000-series are included in the analysis and subsequent discussions of the test results.

10.1 Set-up and Test Procedure

Mooring points: The mooring points are fixed on the main frame. Their distance from each other is equal to the Lpp of the actual upstream vessel. Their height corresponds to 5 ft. over the actual water surface.

The longitudinal mooring points are mounted on beams extending from the lattice-bridge, in the forward and backward directions.

A sketch of the set-up is shown in Figs. 4.7 and 4.8.

The positions of force transducers and movement gauges are shown on Figs. 4.16 and 4.17.

Note: In all computer results special attention should be paid to the transverse mooring forces in this series. Since the coupled ships change position for changing heading, ship 1 will be in the upstream place for 90 deg. heading, but in the downstream position for 270 deg. heading. This means that ship 2 is moored to the anchor points and the mooring forces M2 and M3 do now (270 deg) act on ship 2 and not ship 1 as written on the computer prints. All other items remain unchanged.

Movements: are measured by potentiometers mounted on the lattice-bridge. Their position is adjusted to the actual positions of the ships, i.e. to different headings and relative positions.

Forces: are measured as in the foregoing tests by strain gauges. This series includes measurements of fender forces.

Velocities: measured by six (6) USCM's, arranged in the traditional array in the approach flow. The USCM No's 102, 103, 105 are measuring V and the USCM No's 104, 106 and 107 are measuring U.

Water level: measured as usual by a resistance type wave gauge placed in the upstream vicinity of the main frame.

A comprehensive test run procedure was elaborated to ensure an efficient performance of this test series, which included many changes of set-up and test conditions.

The data analysis is based on the same programs, input and output as for the foregoing tests.

Surface Velocity Measurements

The surface velocity measurements for test series 6000 appear in Table 10.1.

Test	h (m)	Fr	Vs (m/s)	V (m/s)
6100	18.29	0.04	0.62	0.56
6101			0.59	0.53
6104			0.51	0.46
6105			0.59	0.53
6106			0.57	0.52
6107			0.62	0.56
6108			0.62	0.56
6109			-	-
6110			0.56	0.50
6111			0.67	0.60
6112			0.57	0.51
6113			0.57	0.51
6114			0.5	0.53
6115			0.57	0.51
6116		0.08	0.95	0.86
6117			0.98	0.88
6118			1.06	0.95
6200	15.24	0.04	-	-
6201			0.53	0.47
6202			0.54	0.49
6203			0.58	0.52
6204		0.105	1.52	1.38
6205			1.46	1.33
6206			1.47	1.34
6207			1.48	1.35
6208			1.55	1.41
6209			1.57	1.43
6210			1.50	1.36
6211			1.36	1.24
6112			1.48	1.34
6213			1.44	1.31
6300	15.24	0.048	0.65	0.59
6301		0.067	0.90	0.82
6302		0.080	1.08	0.98
6303		0.092	1.23	1.12

Table 10.1 Velocity Measurements by Surface Floats (prototype scale).

Special remarks on the test - Test Series 6000

Test No.

6109: The string for the potentiometer on Ch 28 fell off the instrument after O-scan. Offset is expected.

6114: Offset on Ch 24 expected.

6200: Unstable flow condition
Test results rejected - test was repeated

6202: Visual heel observations: (cfr. slides)

Ship 1: 0.25 $\pm$ 0.25 deg.
Ship 2: 0 $\pm$ 0.25 deg.

6303: Offset on Ch 23 expected.

6209: Turbulence lattice applied

6213: Offset on Ch 28 expected

6108: Visual heel observations: (cfr. slides)

Ship 1: 0.4 deg. $\pm$ 0.25 deg.
Ship 2: 0.1 - 0.4 deg.

10.2 Results and Tables.

The numerical test results are given in tables enclosed in Volume 3. Test duration in all 6000-tests: 205.1 s (Model scale).

Diagrams confirming the consistency of the results and giving the main results are presented in the following.

Test No.	Heading (deg)	h/T_1	Fr	Rel. Position	h/T_2
6100	90	2.31	).04	0	2.01
6101		h=18.29 m			3.13
6110				+18	3.13
6111					
6109					2.01
6113				-18	2.01
6112					3.13
6212		1.92	0.105	0	2.61
6213		h=15.24			1.68
6200				-18	1.68
6104	270	2.31	0.04	0	2.01
6107		h=18.29		+18	2.01
6108					
6105					1.13
6106					
6115				-18	3.13
6114					2.01
6118			0.08	0	2.01
6117				-18	2.01
6116					3.13
6200		1.92	0.04	0	1.68
6201					
6203		h=15.24		-18	1.68
6202					2.61
6211			0.105	0	2.61
6210					1.68
6209				18	
6207				-18	1.68
6204					
6205					2.61
6206					
6300	270	1.92	0.045	-18	1.68
6301			0.061		
6302			0.071		
6303			0.074		

Table 10.2a 6000-series : Tests arranged after Test Conditions.

h/T	T_1 = 7.92 m	T_2 = 5.85	T_2 = 9.08
h = 18.29 m	2.31	3.13	2.01
h = 15.24 m	1.92	2.61	1.68

Table 10.2b Draft Ratios for Various Combinations of Water Depths, h, and Draft Values, T.

10.3 Transverse mooring force, F_y

The effect on F_y of varying Froude Number is shown in Table 10.3 and in Fig. 10.1 for a fixed combination of vessel conditions:

Normal turbulence
Draft, Ship 2: 5.85 m
Heading: 270 deg.
Rel. position: -18.29 m (Stern protrudes)

Test No.	Fr	h/T_1	F_{y1} (Ship 2) (kN)	F_{y2} (Ship 1) (kN)	$\overline{\text{Roll}}_1$ (deg.)	$\overline{\text{Roll}}_2$ (deg.)	Rel. Roll (deg.)
6202	0.040	1.92	221	144	-0.133	0.233	0.365
6206	0.110	1.92	2023	523	-1.86	0.123	1.98
6300	0.048	1.92	558	133	0.07	0.336	0.261
6301	0.067	1.92	1194	246	0.114	0.721	0.607
6302	0.080	1.92	1652	379	0.142	0.998	0.856
6303	0.092	1.92	2035	411	0.177	1.23	1.05
6115	0.042	2.31	224	105	0.180	0.255	0.075
6116	0.070	2.31	937	469	0.488	1.02	0.535

Table 10.3 Selection of Test Results, Series 6000, compare Fig. 10.1.
(Note: Mean of Roll = $\overline{\text{Roll}}$ = Heel)

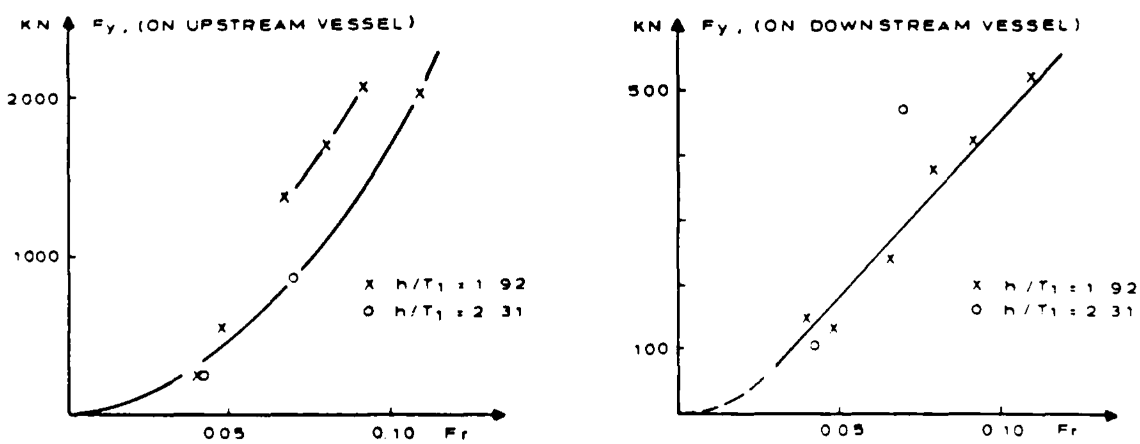


Fig. 10.1 Transverse Force F_y on Upstream Vessel (ship 2) and Downstream Vessel (ship 1).

10.4 Flow Induced Oscillations in Series 4000, 5000, and 6000

A special analysis of the flow induced oscillations for the free mooring conditions is based on the spectrum analysis of the movements.

The roll-movement (including the static heel) seems to be the most critical movement in the present investigation and will be analysed in greater detail. Similar analysis can be carried out for other movements based on the data given in Vol. 4.

The roll-analysis is divided into:

- Frequency-velocity relations
- Heel-velocity relations
- Amplitude-velocity relations

All 6000 tests are included in the study of these relations. This means that the influence of different test conditions such as the draft of ship 2 (T2) or the relative position of the ships or the depth h is neglected in the following diagrams. The finding that the velocity under the ship is approx. equal to the mean velocity of the approach flow is used in the diagrams. All quantities are reported in prototype scale.

Fig. 10.2 Frequency-velocity relation

The frequency is found as T_z^{-1}, where T_z is the mean zero crossing period given in the result tables in Vol. 3.

- The mean roll frequency tends to decrease for increasing flow velocity, i.e. higher flow velocity gives slower roll movements. As mentioned before, the small scale eddies formed in the turbulent shear layer under the vessel give the high frequent contribution to the movements at low velocity. At increasing flow the movement will "lock in" on the resonance frequency.

- The frequency generally appears to be independant of depth/ draft ratio, turbulence level and the different mooring conditions in the 6000-series.

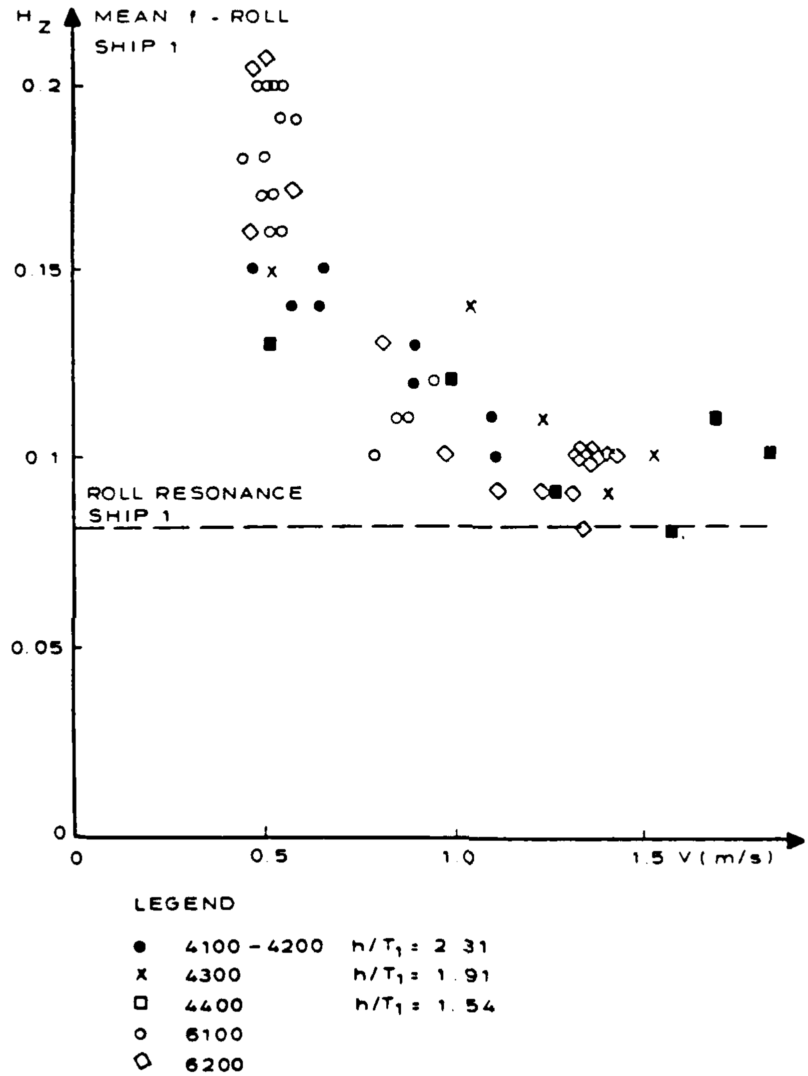


Fig. 10.2 Frequency - Velocity Relation

Fig. 10.3 Heel-Velocity Relation

The heel is determined as the mean value of the roll movement, see Vol. 3.

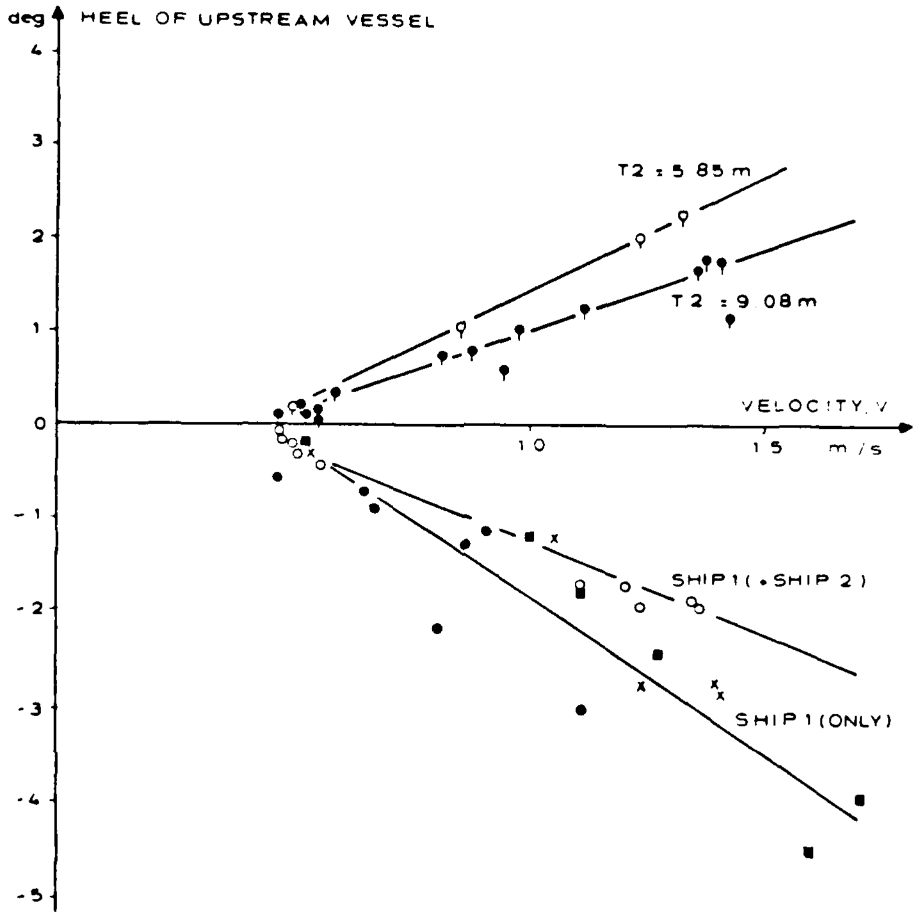
The present diagram shows the heel of the upstream vessel only. Due to the different headings the sign changes.

- For the 4000-series, which includes one vessel only, the heel seems to be a function of V only, i.e. it is mainly unaffected by changing h/T-ratio and turbulence level, within the actual parameter range.

- For the 6000-series, including two vessels, the heel of the upstream vessel seems to be independant to which vessel is upstream, neither does the mooring between the vessels seem to have any significance. The draft of the upstream vessel plays an important role, since the turning moment of the drag force and the mooring force increases. The measurements of the Ship 2 in "light" condition are all higher.

- Within the actual range of measurements the heel angles are approximately linear with the velocity V.

- Contrary to the 6000-series, the 4000-series (1 ship only) shows a significant scatter in the test results, probably due to the different ship arrangement. In general, the combination of two ships tends to decrease the upstream heel.

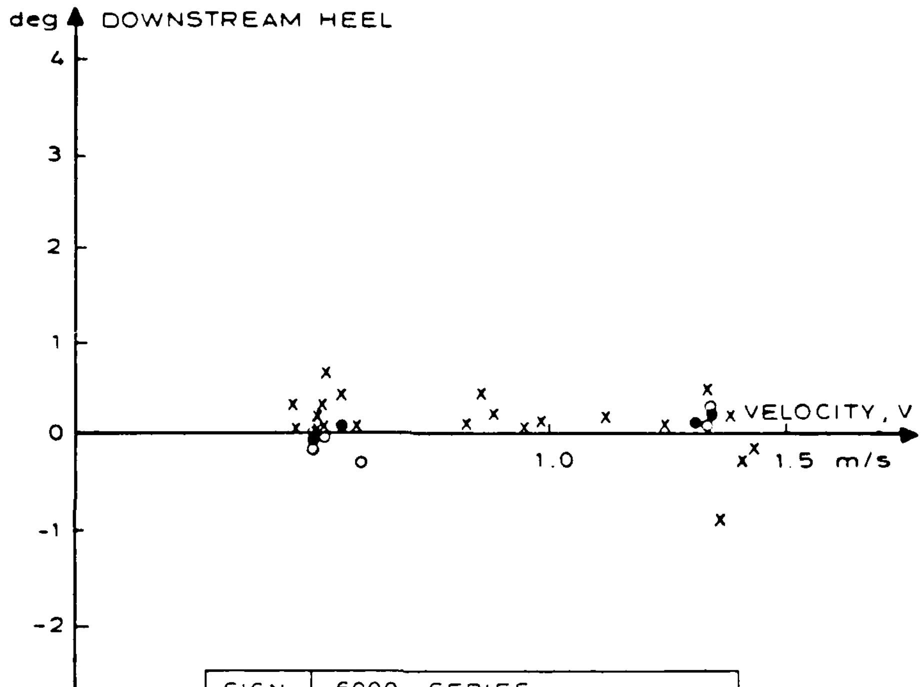


SIGN	SHIP 1	TEST
●	h/T1 = 2.31	4100 - 4200
x	h/T1 = 1.92	4300
■	h/T1 = 1.54	4400

SIGN	6000 - SERIES
o	90 deg SHIP1 (+SHIP 2)
♀	270 deg SHIP 2, T = 5.85 m
♀ (filled)	270 deg SHIP 2, T = 9.08 m

Fig. 10.3 Upstream Heel - Velocity Relation.
Data given with o include three draft ratios for ship 2, 1.68, 2.01, and 3.13.

- The heel of the downstream vessel is between +1 and -1 degree, see Fig. 10.4



SIGN	6000 - SERIES
x	270deg, SHIP 1 (+ SHIP 2)
o	90deg, SHIP 2, T: 5 85 m
•	90deg, SHIP 2, T: 9 08 m

Fig. 10.4 Downstream Heel - Velocity Relation.

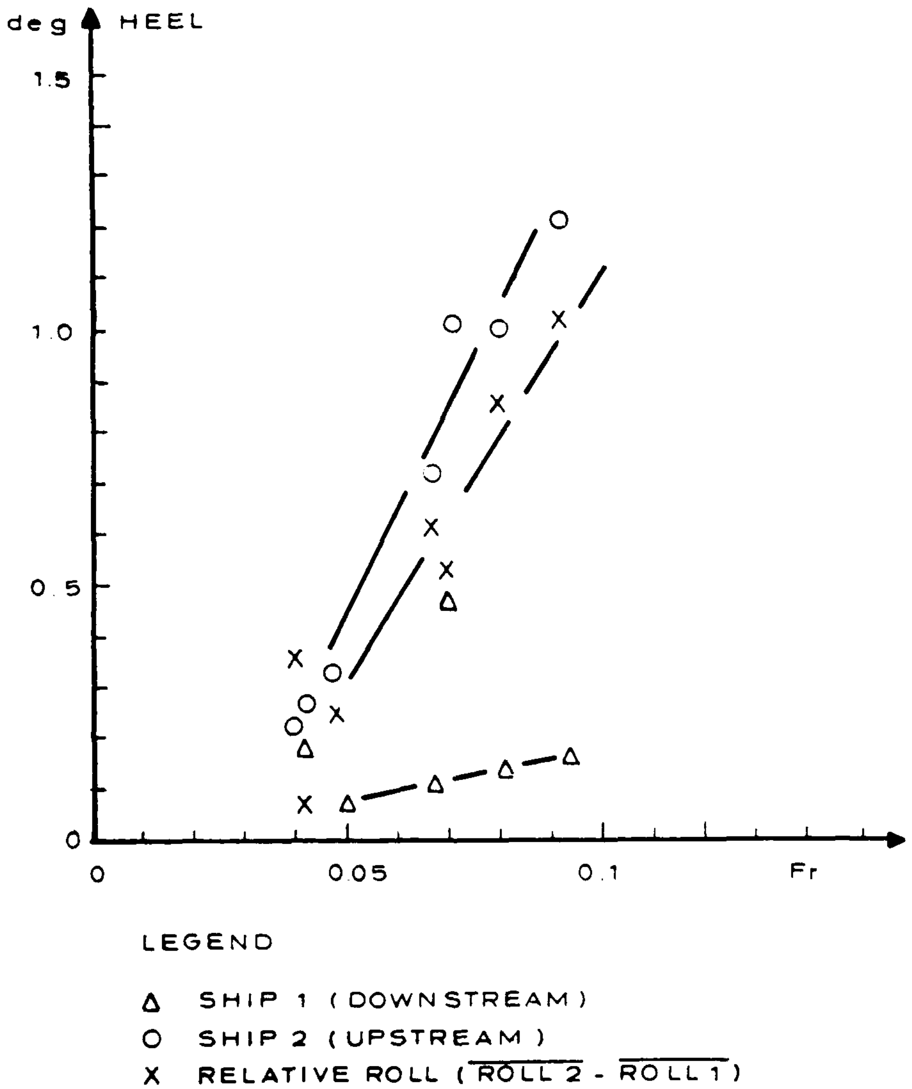


Fig. 10.5 Heel for each Vessel and relative Heel as a Function of Froude No. Selected 6000 tests.

Note : $\overline{\text{Roll}}$ = Heel

Fig. 10.5 summarizes the 6000-series tests for the upstream vessels. Furthermore the dimensionless Froude Number is used instead of the velocity V.

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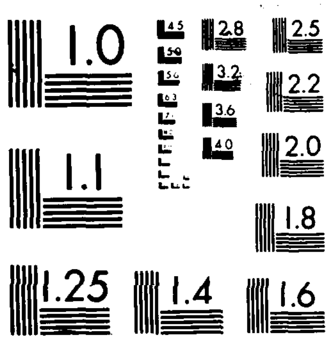


ROCOPY RESOLUTION TEST CHART

Fig. 10.6-10.8 Amplitude-Velocity Relation

Another interesting item is the amplitude of the roll movement. The diagrams show the maximum dobble amplitude for three cases:

1) Ship 1 alone (4000-series) : Fig. 10.6
2) Ship 1 (6000-series) : Fig. 10.7
3) Ship 2 (6000-series) : Fig. 10.8

- The maximum movement of ship 1 alone obviously depends on the actual depth to dra... ratio as the movements seem to escalate easier for increasing velocities at deep water. This escalation which most probably is due to resonance effect is one of the reasons for the scatter of the heel measurements, see above.

- The roll of ship 1 and ship 2 gives an almost identical curve, showing the major results:

  1) The max. roll movement is almost equal for the two (similar) ship models.

  2) The max. roll movement does not change with upstream or downstream position, contrary to the heel-findings.

  3) The turbulence level of the flow does not seem to have any significance.

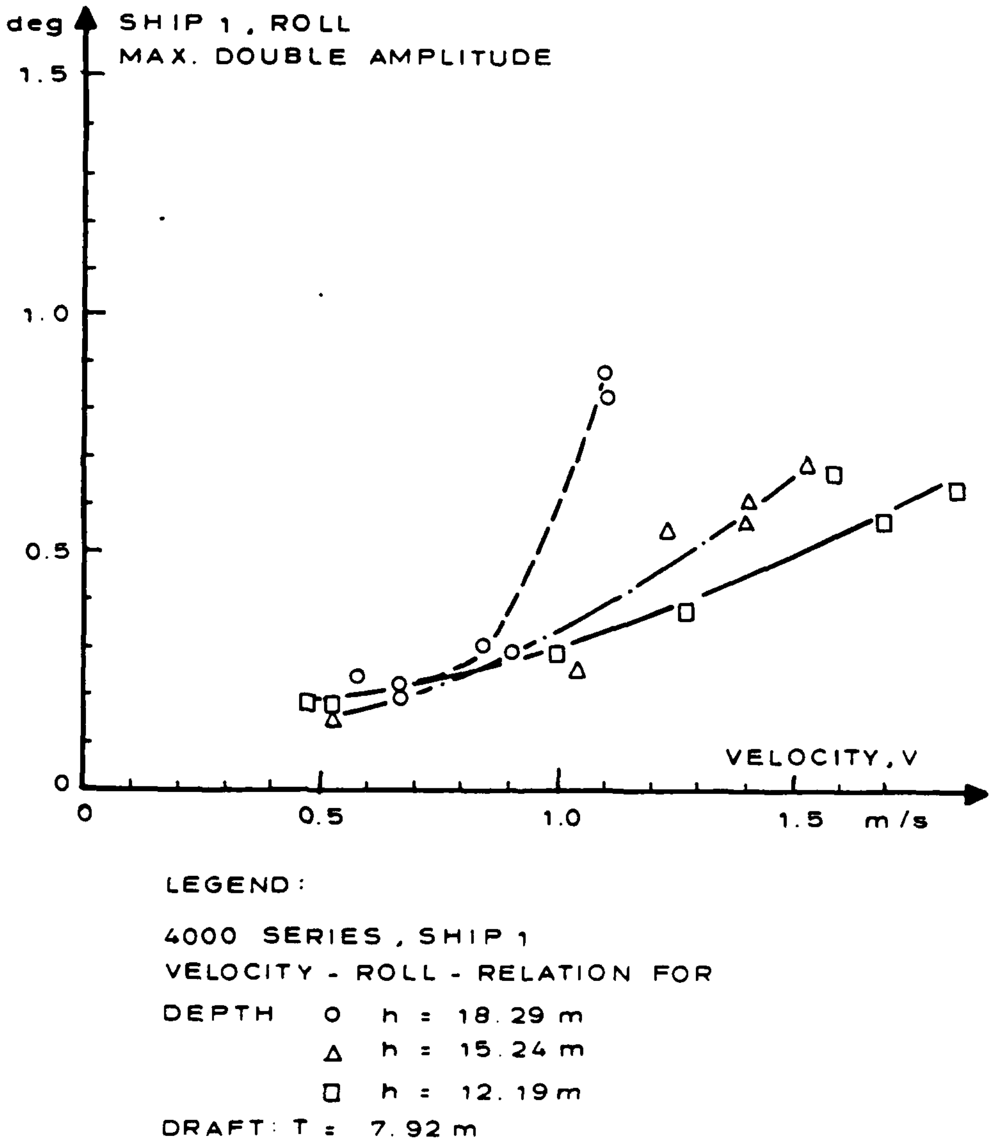


Fig. 10.6 Roll Amplitude-Velocity Relation Ship 1 alone, 4000-Series.

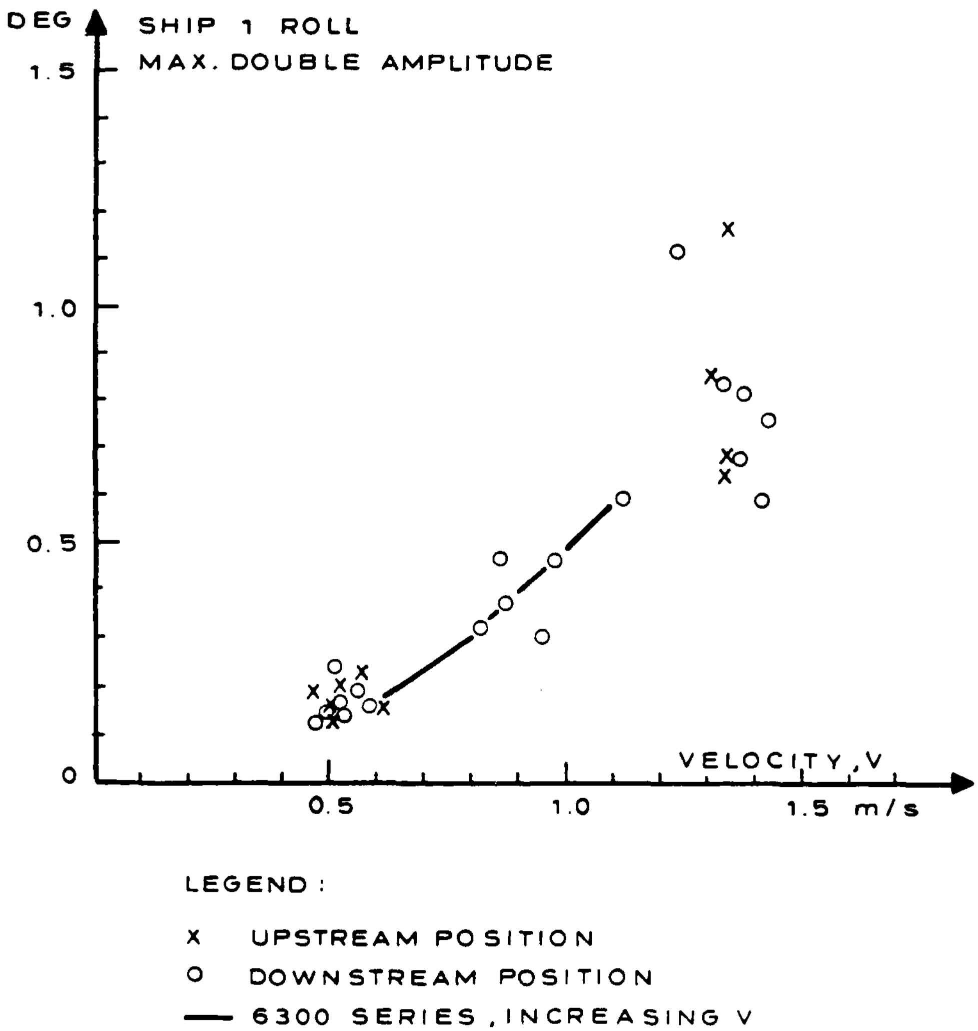


Fig. 10.7 Roll Amplitude-Velocity Relation for Ship 1 (connected to Ship 2), 6000-Series.

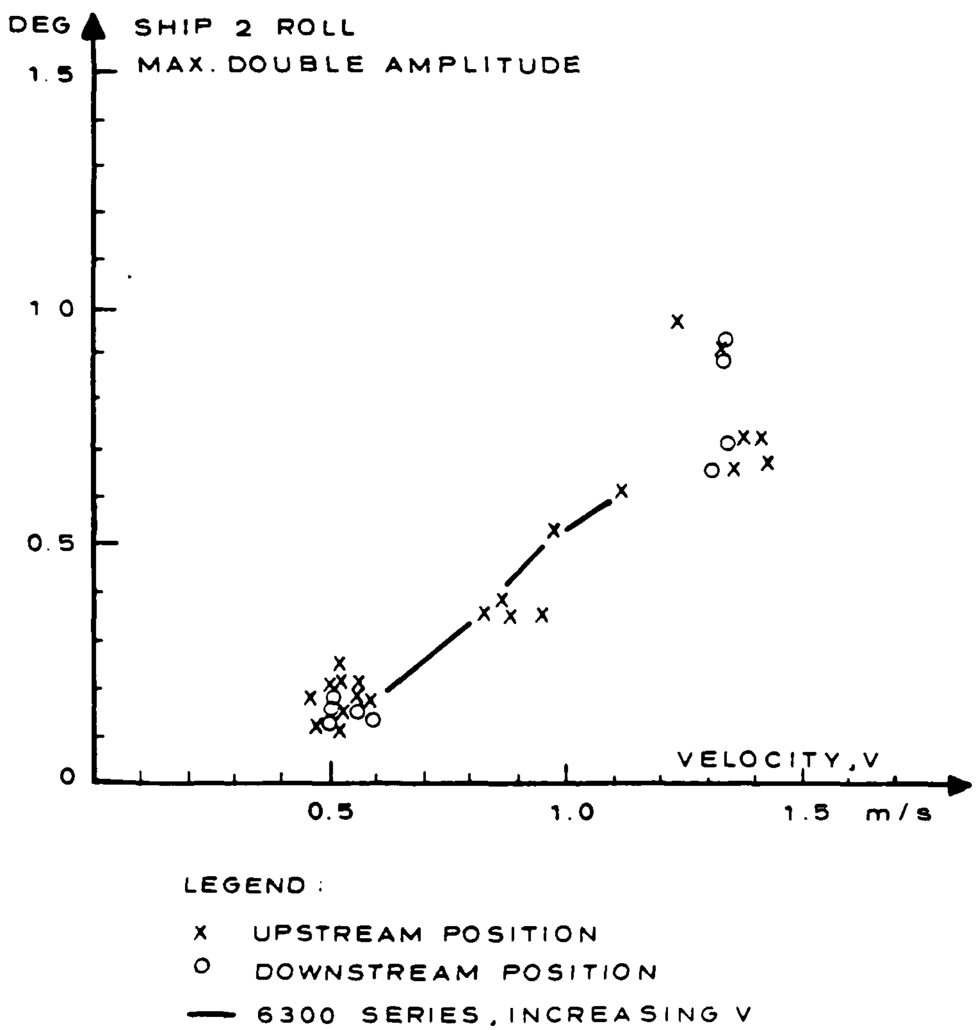


Fig. 10.8 Roll Amplitude - Velocity Relation for Ship 2 (connected to Ship 1), 6000-Series.

Fig 10.9 : Relative Roll

The maximum relative roll movement appears like a superposition of the individual max. movements with a clear quadratic variation with V. The scatter of the values is expected since the relative roll is composed by two almost independant movements.

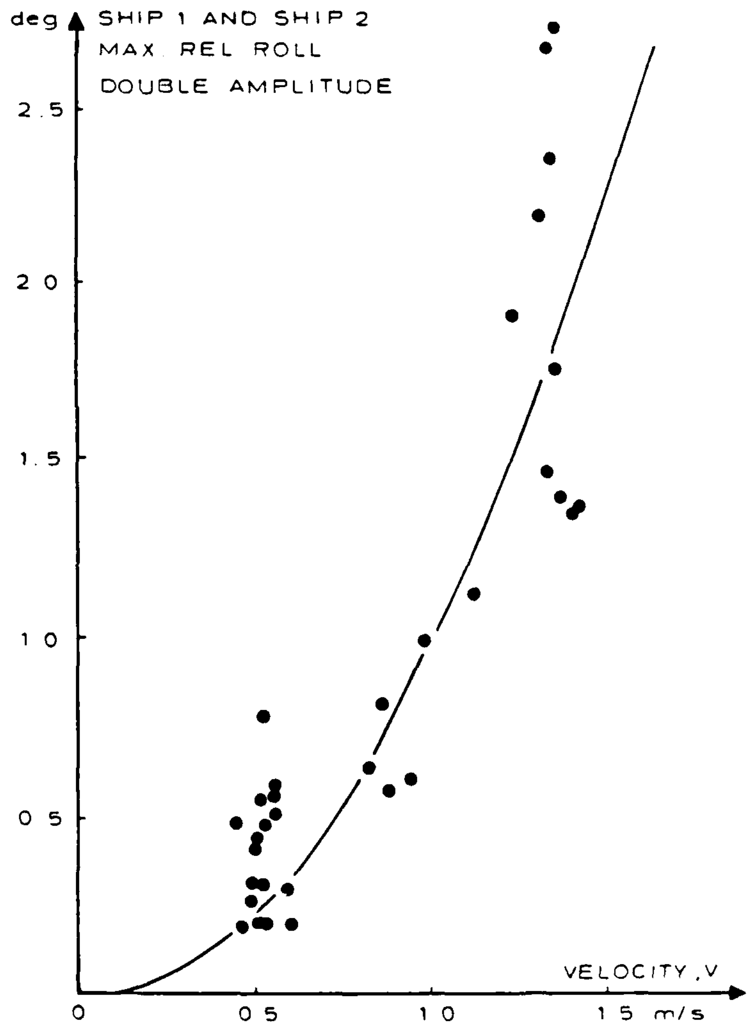


Fig. 10.9 Relative Roll Amplitude-Velocity Relation for Ship 1 and Ship 2, 6000-Series.

Sinkage

The heave measurements do not show the same accuracy as the other movements. Heave measurements have to be corrected by the secondary change of water level measured by the wave gauge 1. Even after this correction there still seems to remain an offset problem for the mean heave motion. A comparison between Phase I and Phase II results is shown in Fig 10.10. The Phase II results are corrected with a general offset of 0.25 m. The sinkage-Froude relation, however, seems to be very similar for the two test series.

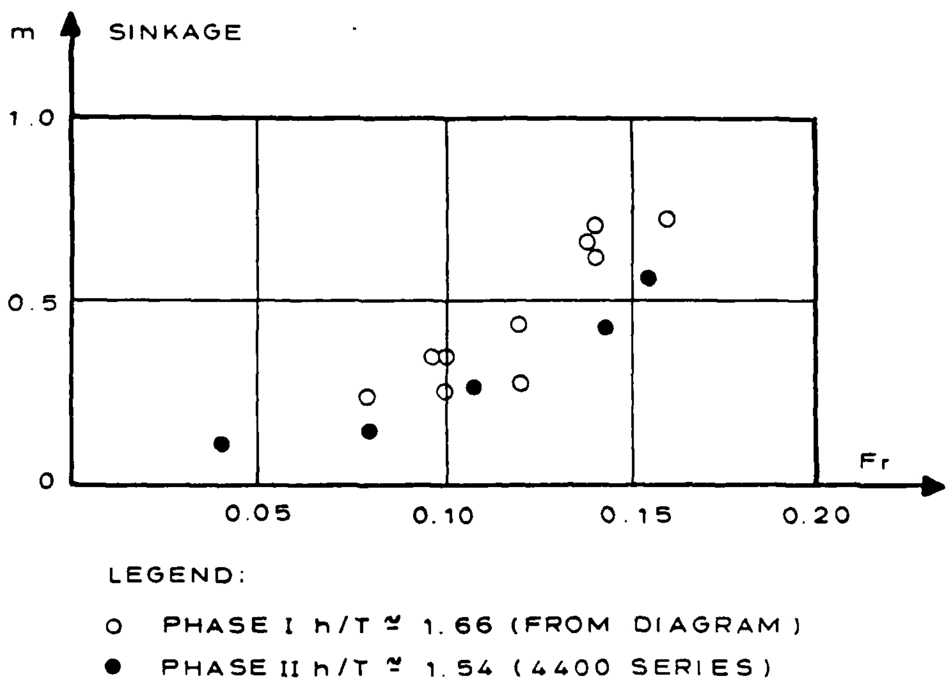


Fig. 10.10 Sinkage for the Different Mooring Arrangements of Phase I and Phase II.

In view of the outlined uncertainties the measurements are in good agreement.

Another study has been performed on the relative heave, i.e. the measured difference between the heave of ship 1 and ship 2 (6000-series).

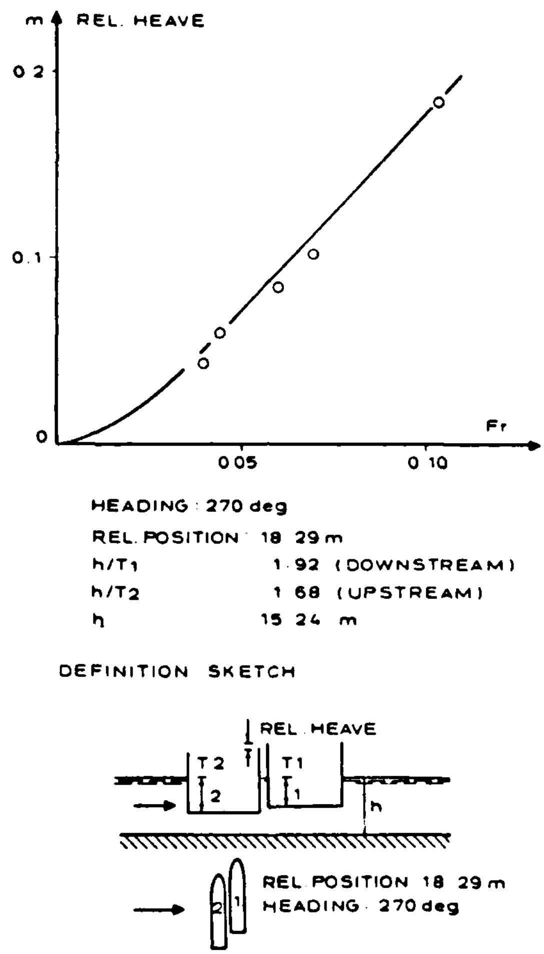


Fig. 10.11 Relative Heave
Froude Number Relation.

The relative heave does not seem to be significantly influenced by the different depth to draft ratios or the relative positions of the vessels.

11. FLOW OBSERVATIONS

Comments on the observed flow characteristics around and at the vessels are given in this Chapter. The written comments are illustrated and supplemented by the video recordings produced during the course of the project.

11.1 Separation and Vortex Formation along Hull Section

A detailed visualization of the flow and especially the separation under the vessel was carried out at high Froude Numbers. In order not to distort the flow or to restrict the vessel movements, the visual observations were made through a "window" inserted in the bottom of the mid section of ship 1, see Fig. 11.1. The observations are illustrated on the enclosed video tape.

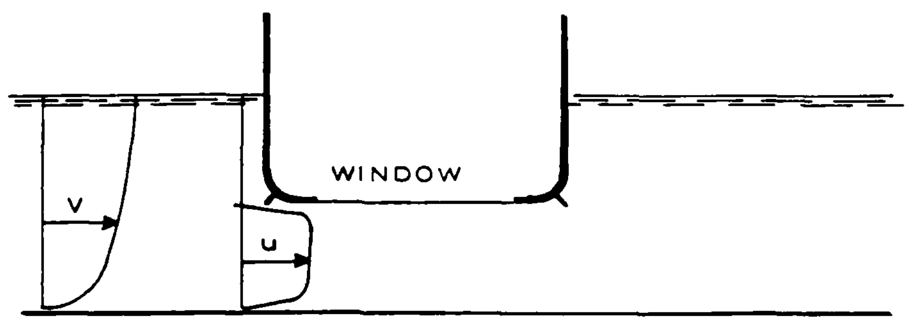


Fig. 11.1 Modification of Ship 1 for Flow Observations Showing Observation "window".

FIXED SHIP

The results of the observations are shown on Fig. 11.2. The area of turbulent return-flow extends from the upstream bilge keel to an attachment point on the vessel bottom. The point of attachment varies with Fr, h/T, heel and with roll-oscillations. No dramatic vortex shedding comparable to the dimensions of the ship or the gap was observed.

In the first case (Fig. 11.2) the vortices are formed in the unstable shear layer. These small-scale vortices are apparently determined by the flow velocity and the geometry of the bilge keels.

The empirical relation between the flow velocity and the vortex shedding frequency in the model was found to be

$$f_y = 8.5 \cdot V$$

where $f_y = 1/T_z$, T_z being the zero-upcrossing period of the total transverse force, and V is mean flow velocity. As mentioned previously the flow velocity beneath the ship is almost identical to V.

A Strouhal Number based on the bilge keel height H_b is then found to

$$S = \frac{f_y \cdot H_b}{V} = \frac{8.5 \cdot V \cdot H_b}{V} = 0.09$$

The order of magnitude of the Strouhal Number agrees reasonably well with values reported in literature for one-sided vortex shedding from bluff bodies.

A figure illustrating this vortex situation is shown below in Fig. 11.2.

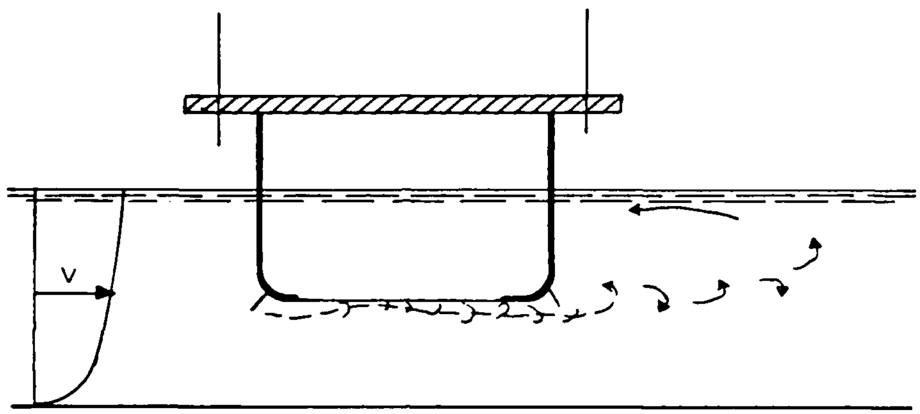


Fig. 11.2 Surface of Separation. General Effect in Fixed Mooring Conditions.

FREE SHIP

In the free condition case the vortices are correllated with the roll-movement. The perturbations by the vortices are believed to "trig" and enhance the natural roll movement (resonance), see Fig. 11.3. For very low velocities (e.g. V = 0.5 m/s) a broad range of roll frequencies is measured, corresponding to a non-critical stage. For higher velocities , however, all movements seem to "lock-in" on the natural resonance period. The oscillation amplitude and the dimensions of the vortices increase with increasing velocity (compare Roll in Vol. 4.).

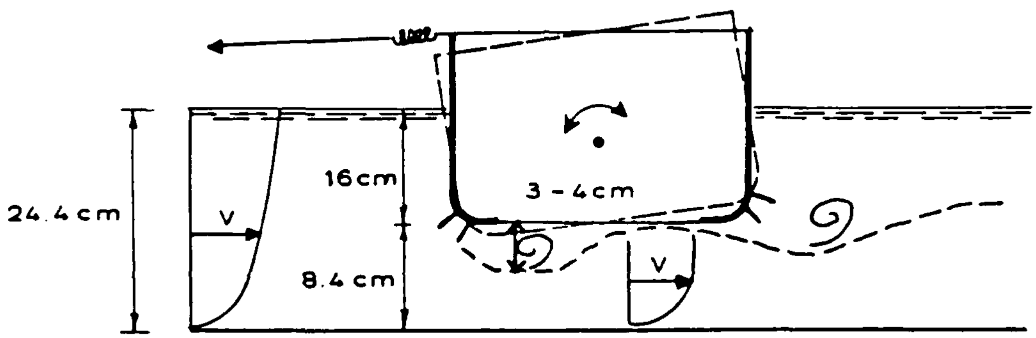


Fig. 11.3 Surface of Separation. General Effect in Free Mooring Conditions.

11.2 Flow Pattern

The flow pattern around the ship(s) was observed throughout the tests. The flow is described by photos and video recordings. In order to summarize the findings and to correlate them with the observations, the following figures are elaborated. The general flow pattern described here was observed under all conditions and did not change significantly for the different test situations.

Two Figures show the horizontal flow: one for the upper flow (11.4) and one for the flow at the basin floor (11.5). The three-dimensional effect on the flow is illustrated by the clear difference of the two flow patterns. The figures show the approximate dimensions.

It is important to underline the generality of these flow patterns. They were observed even in the series with two ships.

The surface flow pattern is dominated by three areas of rotation:

Two vortex bodies (bow and stern) rotate about a vertical axis and one (amidship) rotates about a horizontal axis. This clearly demonstrates the 3-dimensional character of the flow. The interaction between the vortices obviously gives rise to the velocity distribution indicated in the surface flow pattern. The three vortex bodies are highly turbulent.

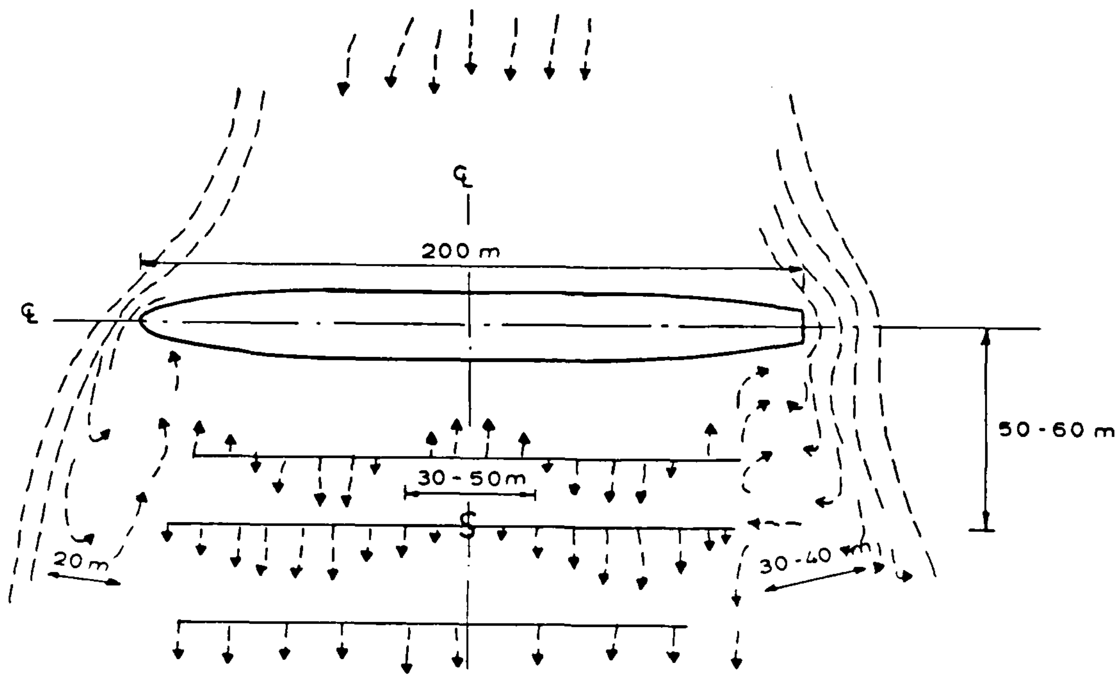


Fig. 11.4 General Horizontal Surface Flow.

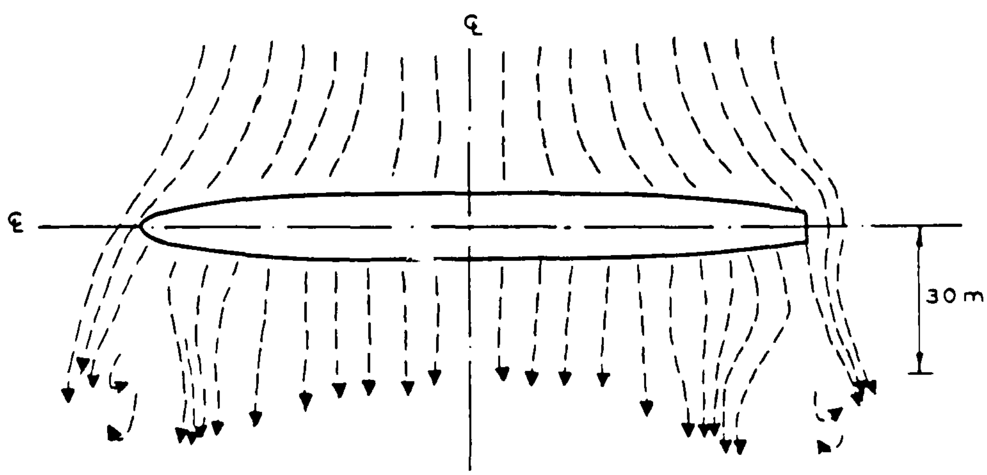


Fig. 11.5 General Horizontal Bottom Flow.

11.3 Vortex Shedding

The possible vortex shedding under different conditions was observed. The vortices created along the hull and at the bilge keels were found to be very small in all conditions.

The vertical vortex (horizontal axis) in the leeward wake of the ship is a highly turbulent wake. The slow net-rotation cannot be characterized as a vortex in terms of shedding frequency or diameter. The leeward extension of the wake is not significantly influenced by the different flow conditions. The dimensions of the wake at the center of the ship is shown in Fig. 11.6.

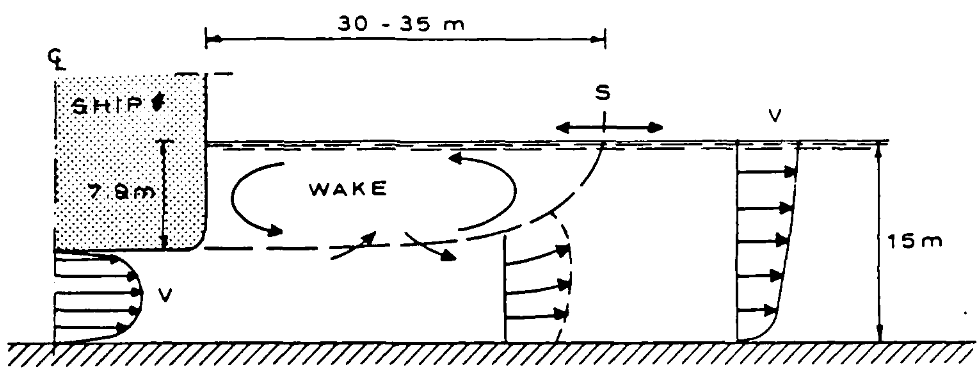


Fig. 11.6 Observed Net-Flow in Midship Wake. S:Separation Point of Surface Velocity.

The horizontal vortices at the bow and the stern (vertical axis) are observed in all flow conditions. Both "vortex-streets" are influenced by the turbulent flow in the wake. The shedding frequency is therefore somewhat irregular and cannot be determined with satisfactory accuracy from visual observations. A much better information is provided by the standard analysis of the force signals and by the selected spectra and time series.

The stern vortex street was in general very vague, i.e. no clear vortex dimension or shedding frequency could be detected. This is probably due to the presence of the propeller and the rudder.

The characteristics of the bow vortex street is mainly determined by the flow velocity and the mooring arrangement. One unusual situation was found in the 6000-series (free models, leeward bow protrudes), where a large scale vortex (OD~10m) was formed between the two bows and ejected 20-30 m out into the flow. The two ships were performing combined surge and yaw movements of the same frequency. Reference is made to the video recording.

12. LIST OF SYMBOLS

AP	= aft perpendicular
B	= beam of ship
C_{MZ}	= yawing moment coefficient based on U
	= $2M_Z/L^2T\rho U^2$
C_{pw}	= wake underpressure coefficient
	= $2g(\frac{1}{2}(\overline{h_1 - h_2})/U^2$
C_X	= longitudinal force coefficient based on U
	= $2F_X/LT\rho U^2$
C_Y	= lateral (or transverse) force coefficient based on U
	= $2F_Y/LT\rho U^2$
F	= Froude Number based on V and depth of flowing water
	= $V/\sqrt{gh}$
F_X	= longitudinal component of the resultant hydrodynamic force (horizontal component in the direction of the ship's heading).
F_Y	= lateral (or transverse component of the resultant hydrodynamic force (horizontal component normal to the ship's heading)
FP	= forward perpendicular
GM_t	= vertical distance between center of gravity and transverse metacenter of a ship
GM_l	= vertical distance between center of gravity and longitudinal metacenter of a ship
h	= depth of flowing water at location of ship-model, with model absent
$\bar{h}_1$	= mean depth adjacent to hull on the upstream side
$\bar{h}_2$	= mean depth adjacent to hull on the downstream (wake) side
KG	= vertical distance from keel to center of gravity of ship
L	= length of ship between perpendiculars
M_Z	= yawing moment (moment of the resultant of F_X and F_Y about a vertical axis lying in the ship's center plane midway between the AP and the FP)
n	= frequency of detachment of vortices (number per unit of time)
Q	= flow rate in flume
R	= Reynolds Number based on V and beam of ship
	= VB/ν
S	= Strouhal Number based on L and U
	= nL/U
T	= mean draft of ship in still water
T_1	= mean draft of ship 1 in still water
T_2	= mean draft of ship 2 in still water
t	= time
$u(z,t)$	= longitudinal horzontal component of velocity at a distance z above the floor of the flume, at time t
$\bar{u}(z)$	= time-average of $u(z,t)$ in turbulent flow = $\int_0^{\Delta t} u(z,t)dt/\Delta t$
$\bar{u}_1$	= $\bar{u}(z_1)$
$\overline{u^2(z)}$	= time-average of $(u(z,t))^2$ in turbulent flow = $\int_0^{\Delta t} u(z,t)dt/\Delta t$
U	= mean velocity above keel depth = $\int \bar{u}(z)dz/T$ (limits, h-T and h)
V	= mean velocity in the water column = $\int \bar{u}(z)dz/h$ (limits, 0 and h)
z	= distance above floor of flume
z_1	= distance above floor of flume to the point where the local time-average velocity, $\bar{u}$, equals U

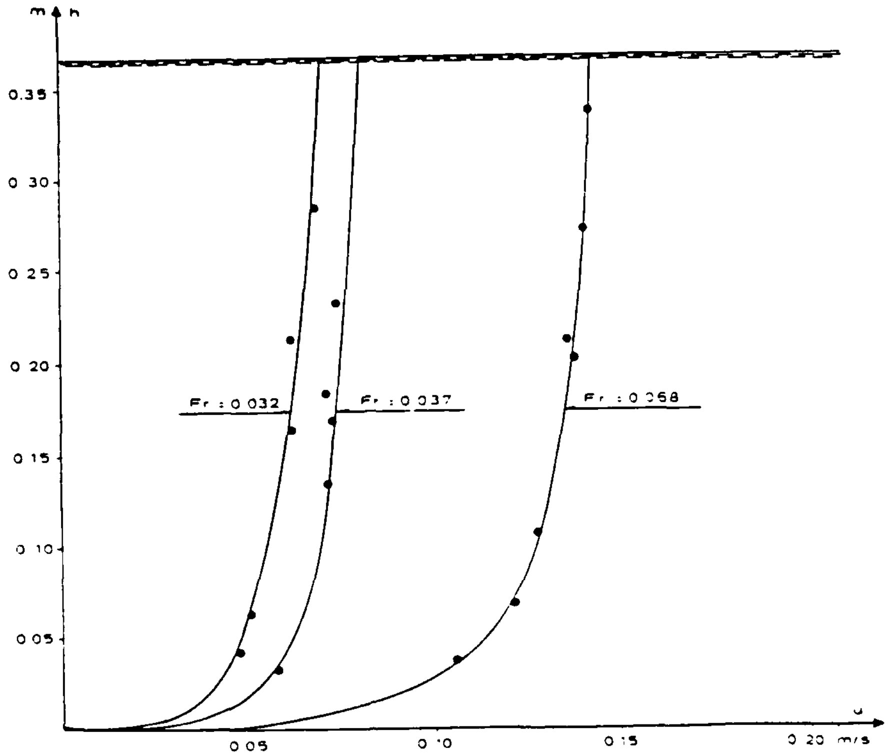
13. REFERENCES

Ref/1/ Oil Companies International Marine Forum. "Predictions of Wind and Current Loads on VLCC's", 1977 Witherby and Co. Ltd., London E.C.

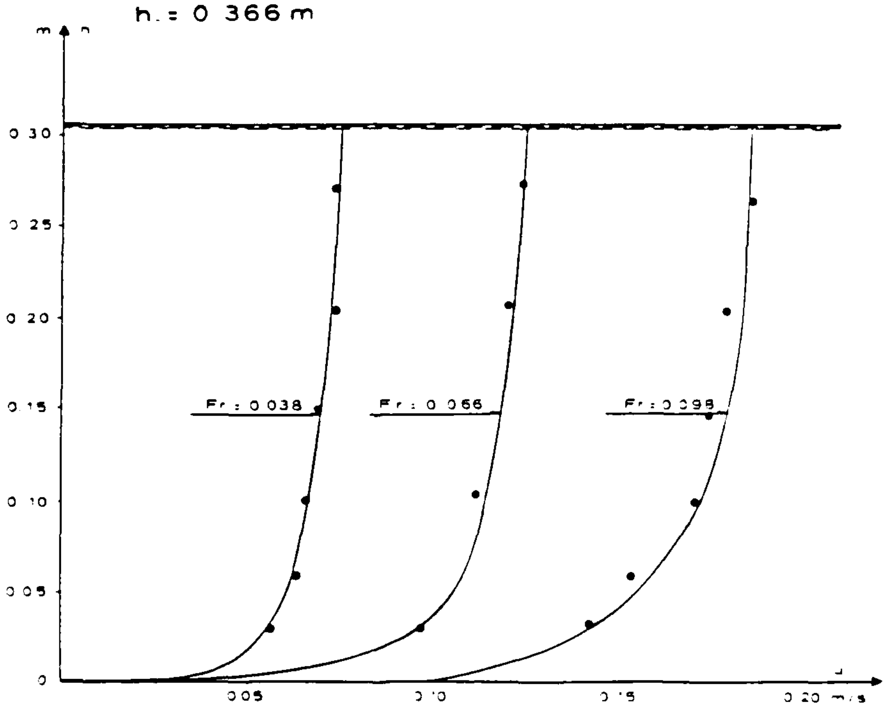
Ref/2/ Danish Hydraulic Institute: "Proposal on Investigations and Tests to determine Hydrodynamic Forces and Moments on Ships moored in a Current", August 1985.

Ref/3/ Edwards, R.Y, "Hydrodynamic Forces on Vessels Stationed in a Current." Paper OTC 5032, 17th Annual OTC, Houston 1985.

D R A W I N G S

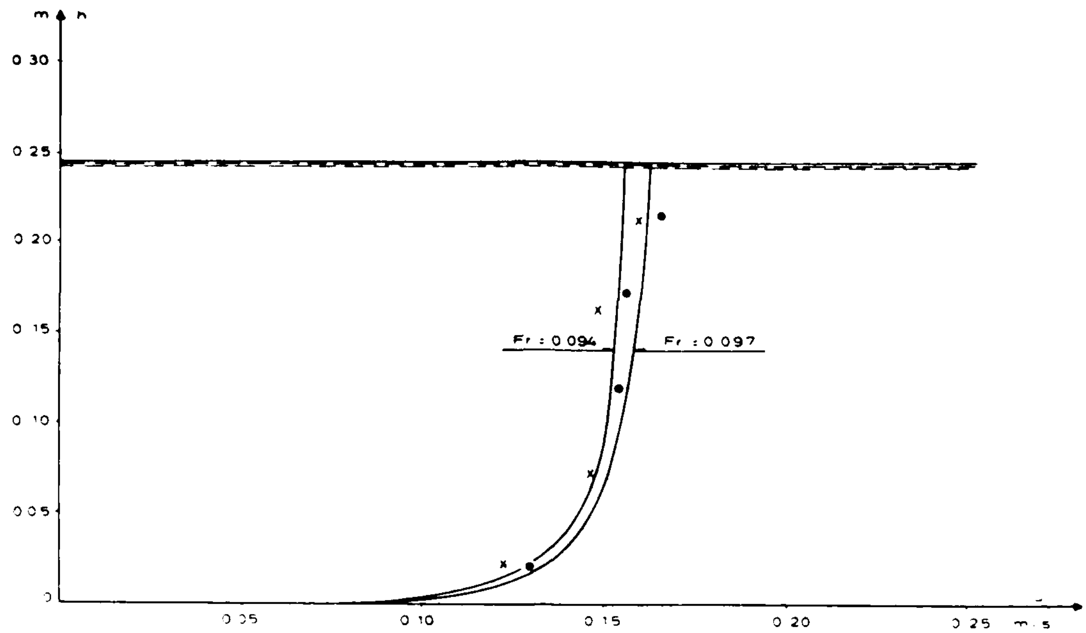


h. = 0.366 m

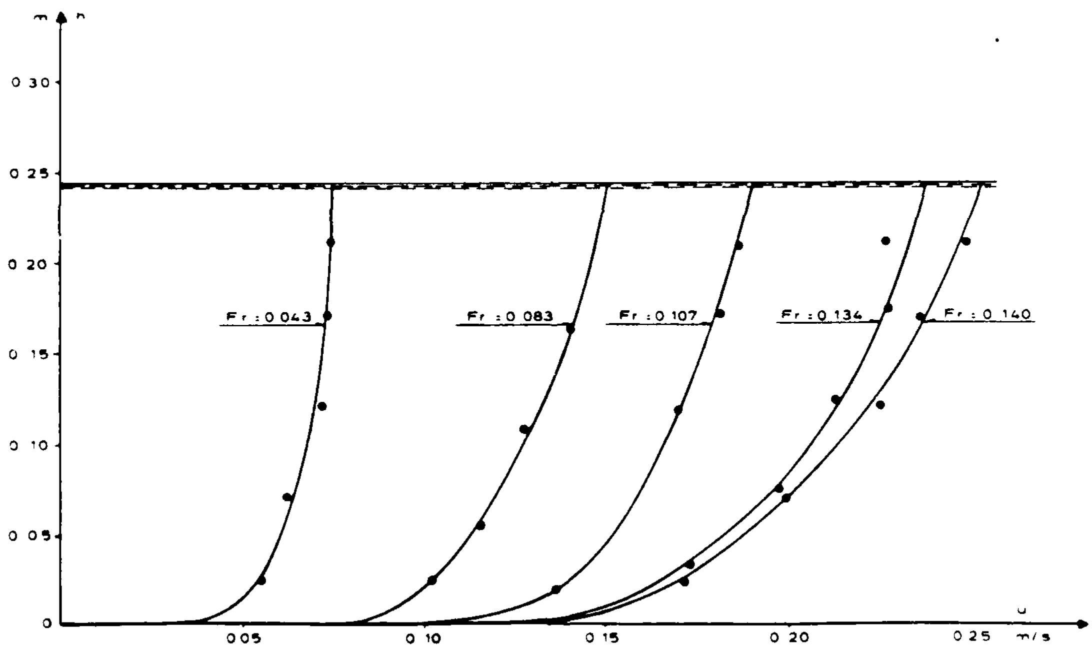


h = 0.305 m

danish hydraulic institute		NAVAL CIVIL ENGINEERING LABORATORY SHIPS MOORED IN A CURRENT	
file 5525	date 2.5.86	VELOCITY PROFILES AT h = 0.366 m AND h = 0.305 m (MODEL SCALE)	dwg no 4.1
scale	init CAJ/GJ		

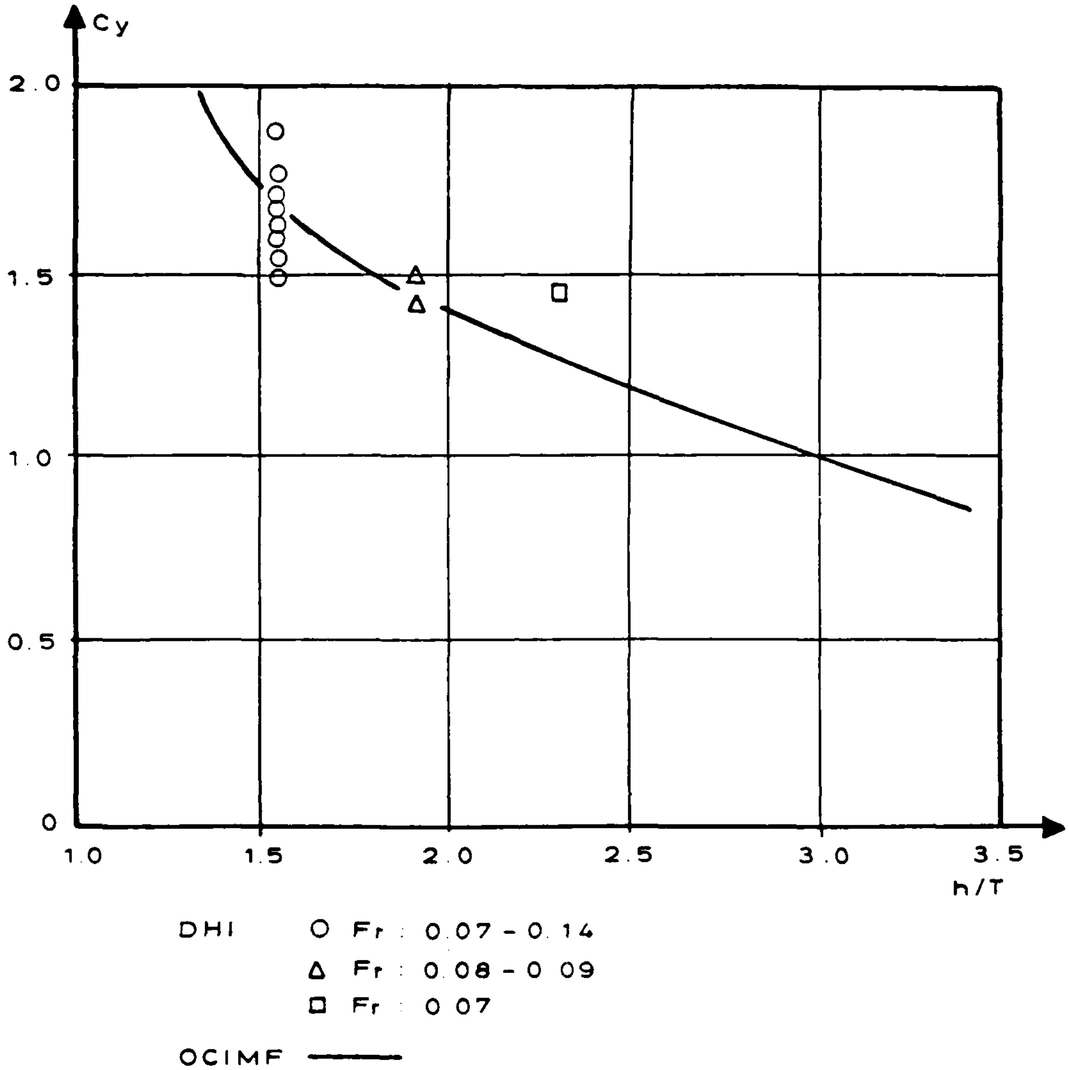


TURBULENCE LATTICE



NORMAL FLOW

danish hydraulic institute		NAVAL CIVIL ENGINEERING LABORATORY	
		Ships moored in a current	
file 5525	date 02-MAJ-86	VELOCITY PROFILES	dwg no
scale	init	AT h = 0.244 m (MODEL SCALE)	4.2



danish hydraulic institute		NAVAL CIVIL ENGINEERING LABORATORY SHIPS MOORED IN A CURRENT	
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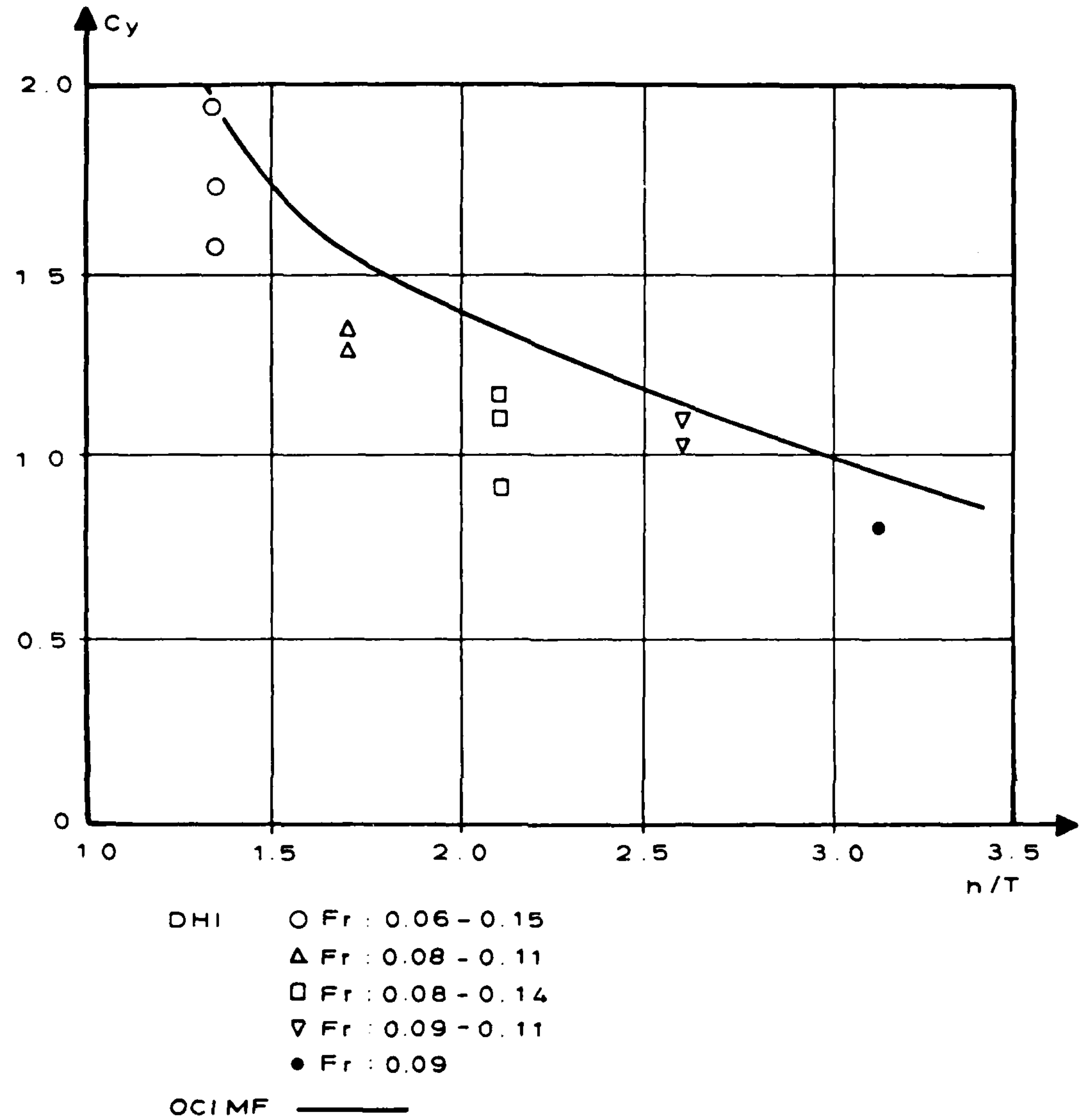
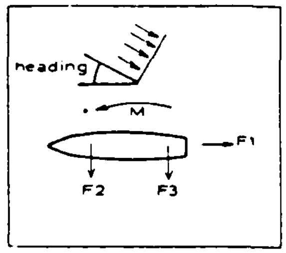
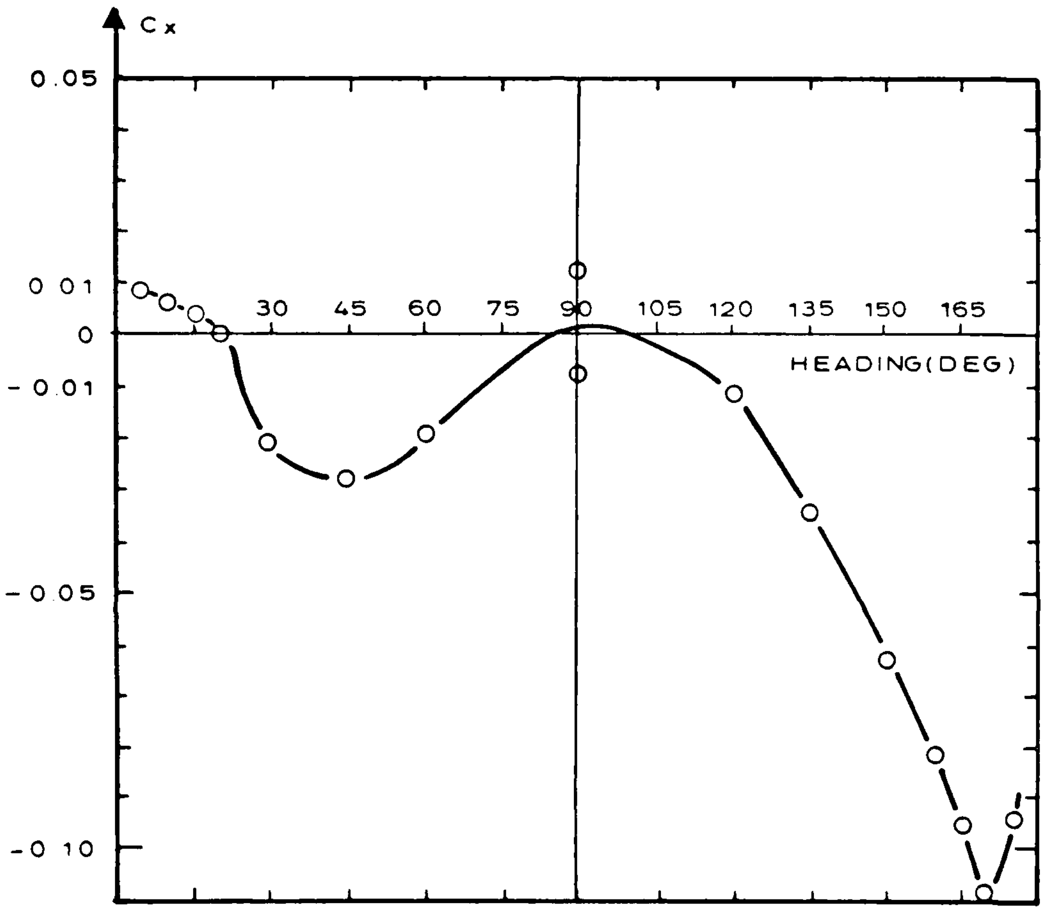
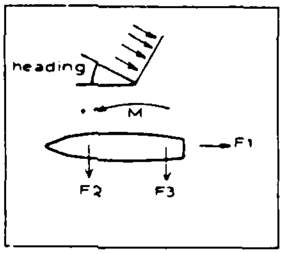


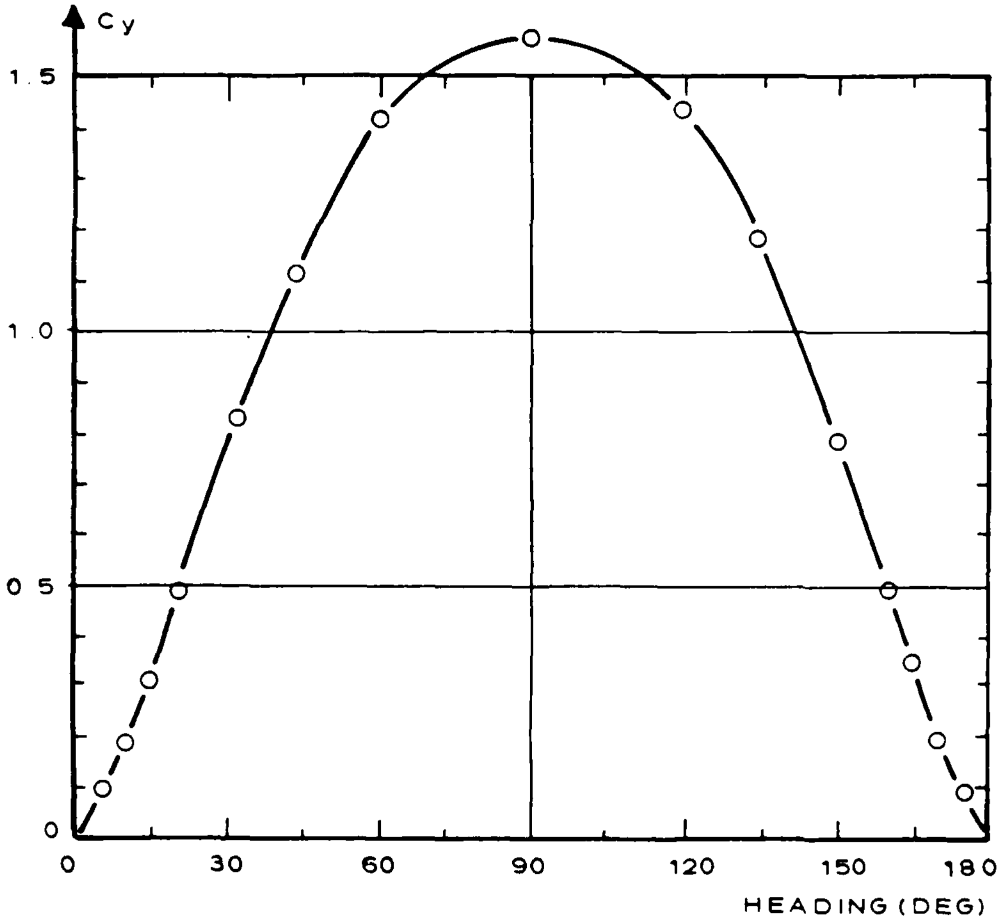
danish hydraulic institute		NAVAL CIVIL ENGINEERING LABORATORY SHIPS MOORED IN A CURRENT	
5525	date 2.5.86	Cy-h/T RELATION	6.1
	CAJ/GJ	TEST: 2000 ET SEQ	



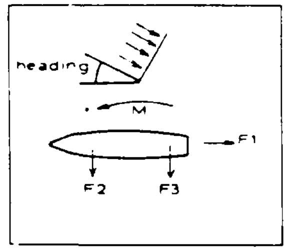


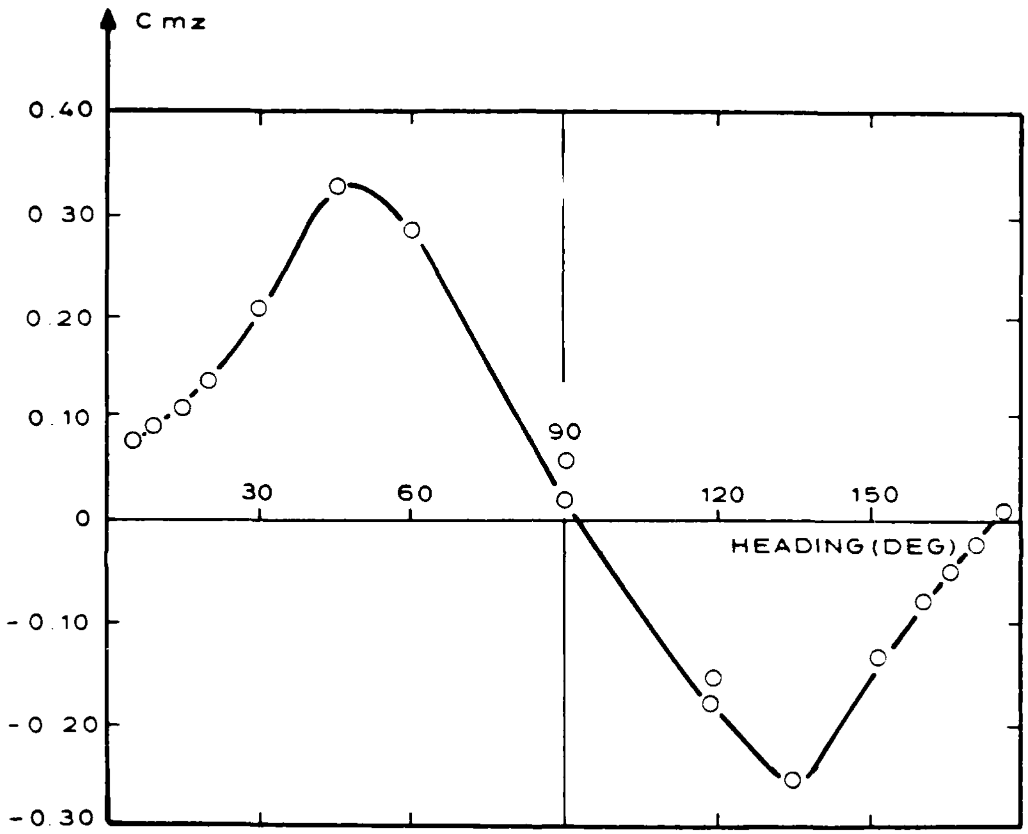
danish hydraulic institute	NAVAL CIVIL ENGINEERING LABORATORY	
	SHIPS MOORED IN A CURRENT	
5525 2.5.86	Cx - HEADING	7.1
CAJ/GJ	TEST: 3200 ET SEQ	



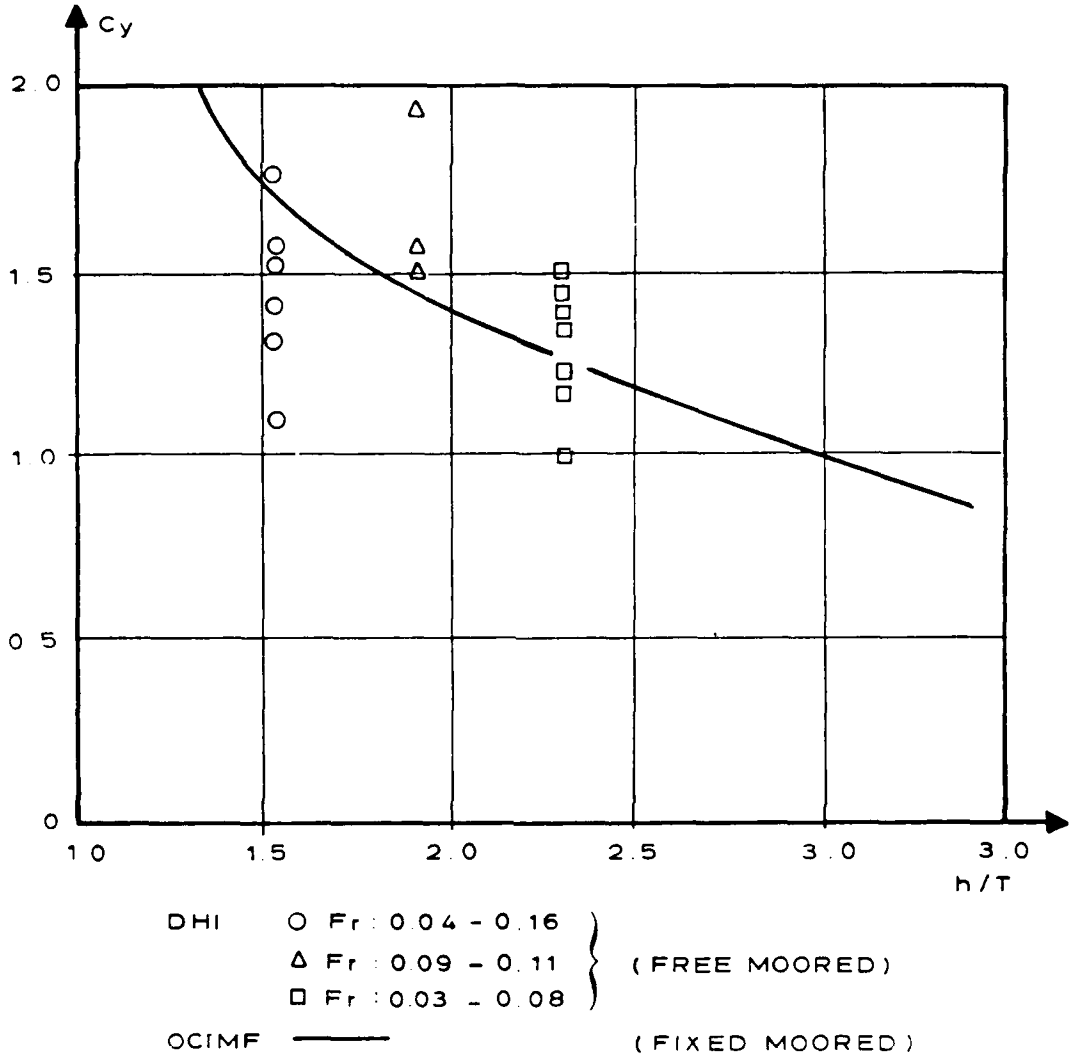


danish hydraulic institute		NAVAL CIVIL ENGINEERING LABORATORY	
		SHIPS MOORED IN A CURRENT	
5525	date 2.5.86	Cy - HEADING	dwg no
	CAJ/GJ	TEST 3200- SERIES	7.2

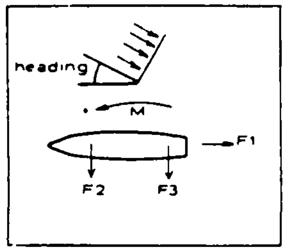


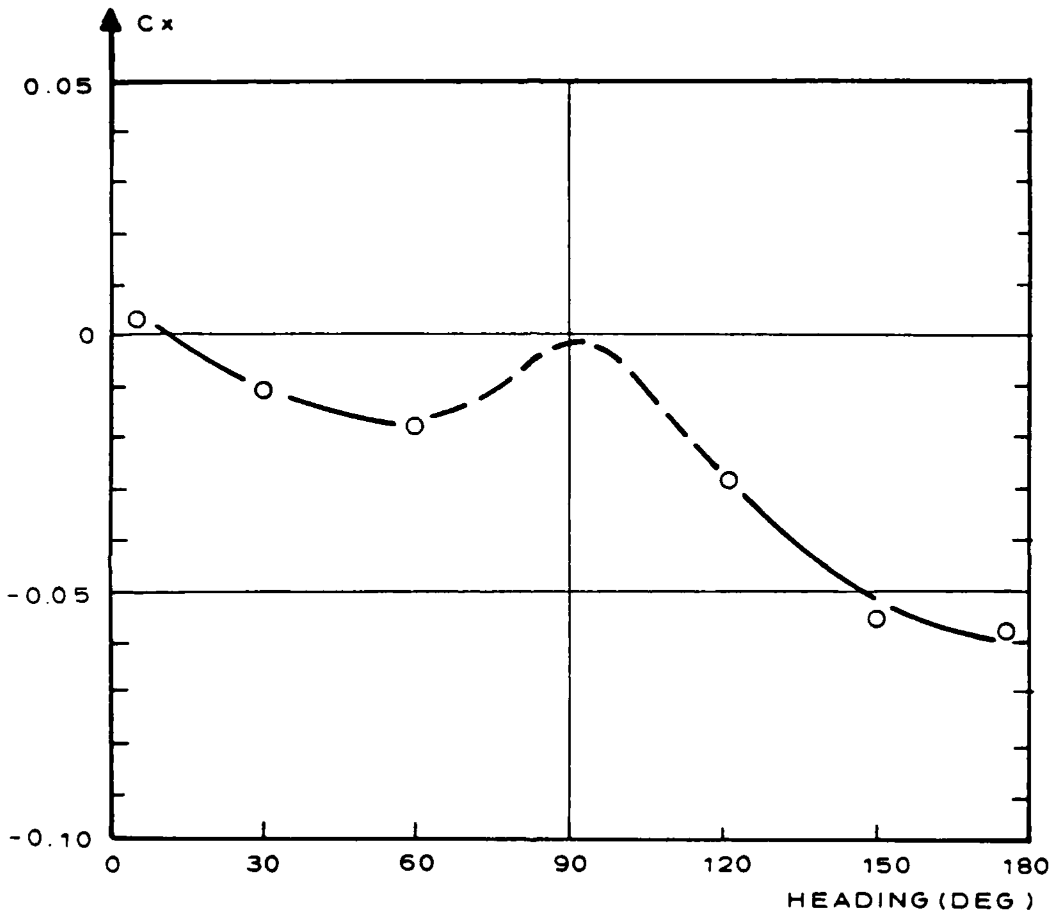


danish hydraulic institute	NAVAL CIVIL ENGINEERING LABORATORY	
	SHIPS MOORED IN A CURRENT	
5525 2.5.86	Cmz - HEADING	7.3
CAJ/GJ	TEST : 3200 ET SEQ	

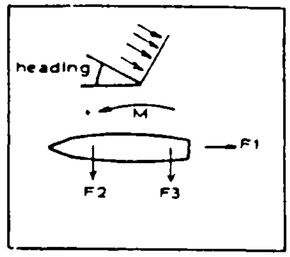


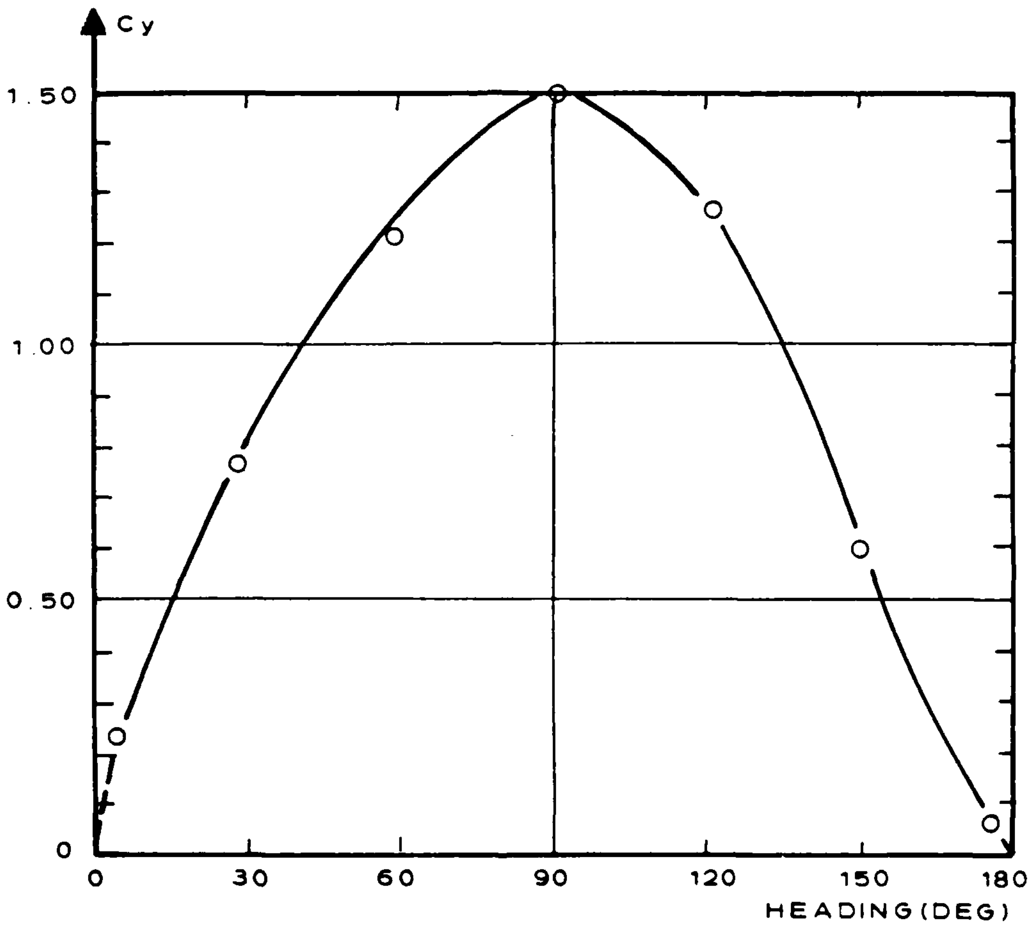
danish hydraulic institute		NAVAL CIVIL ENGINEERING LABORATORY	
		SHIPS MOORED IN A CURRENT	
5525	date 2 5 86	Cy - h/T RELATION	dwg no
	CAJ/GJ	TEST 4000 ET SEC	8.1



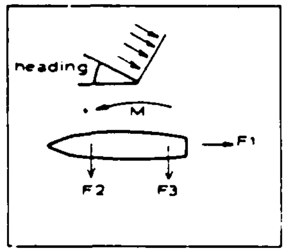


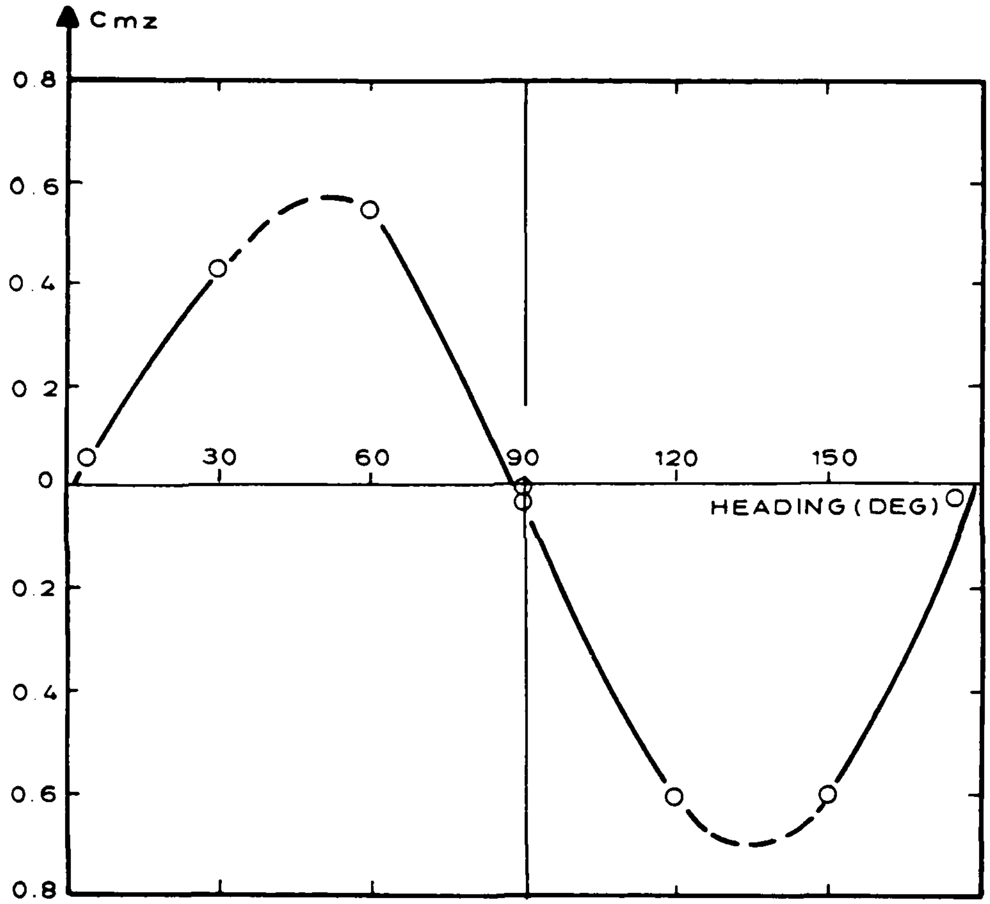
danish hydraulic institute	NAVAL CIVIL ENGINEERING LABORATORY	
	SHIPS MOORED IN A CURRENT	
5525 date 2.5.86	Cx - HEADING AT Fr = 0.105	dwg no
CAJ/GJ	TEST: 5300 ET SEQ 4302: 90° 4305: 90°	9.1a



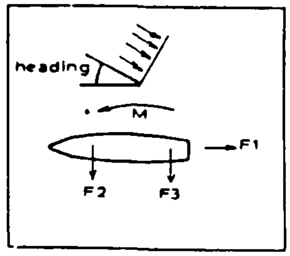


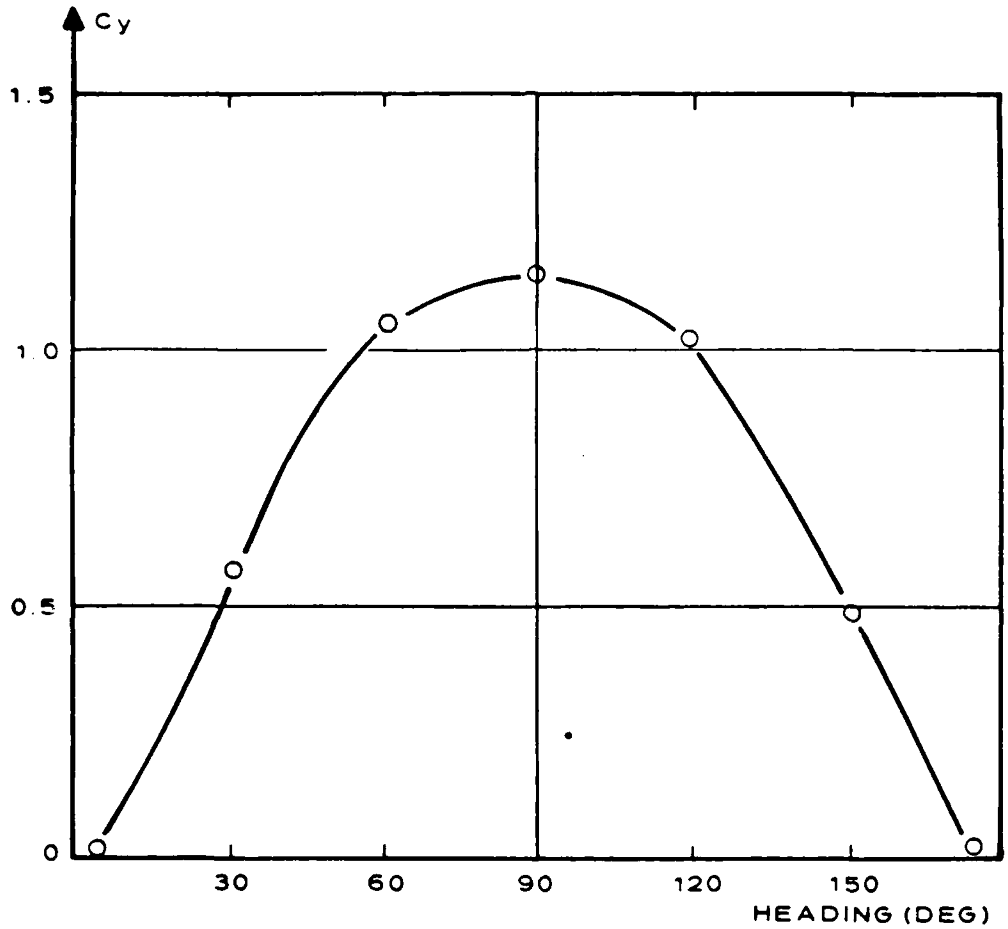
danish hydraulic institute		NAVAL CIVIL ENGINEERING LABORATORY	
		SHIPS MOORED IN A CURRENT	
5525	date 2.5.86	Cy - HEADING AT Fr = 0.105 TEST: 5300 ET SEQ 4302: 90° .4305: 90°	dwg no 9.1 b
	CAJ/GJ		



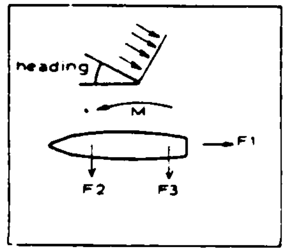


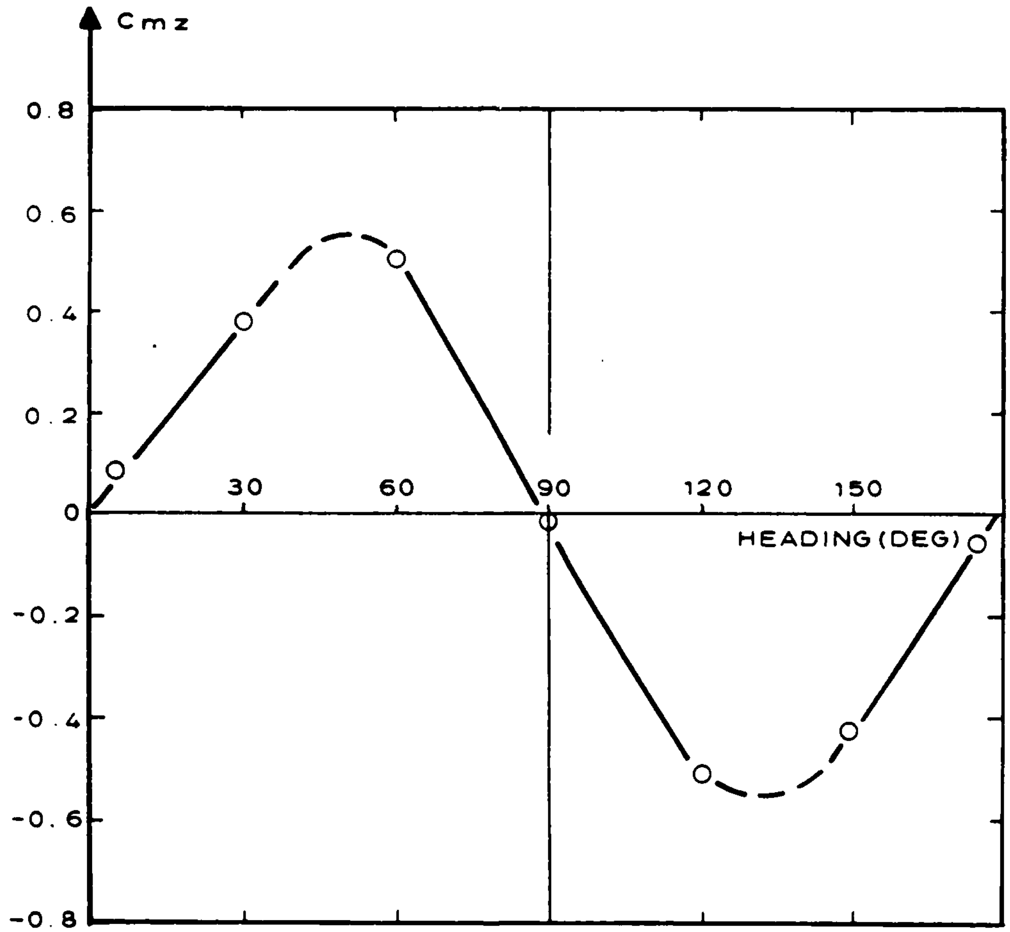
danish hydraulic institute		NAVAL CIVIL ENGINEERING LABORATORY	
		SHIPS MOORED IN A CURRENT	
5525	date 2.9.86	C_{mz} - HEADING AT Fr = 0.105 TEST : 5300 ET SEQ 4302 : 90° 4305 : 90°	9.2
	CAJ / GJ		



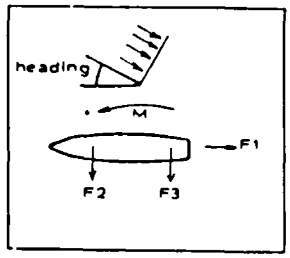


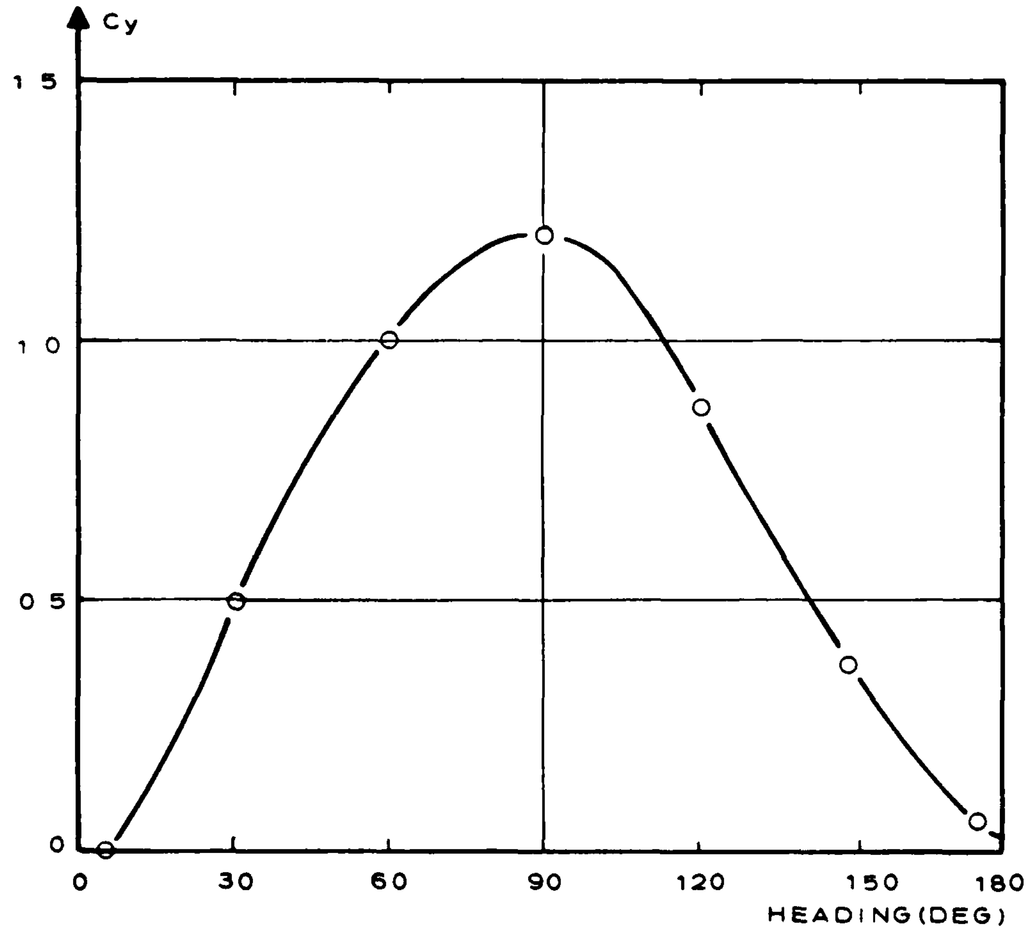
danish hydraulic institute	NAVAL CIVIL ENGINEERING LABORATORY	
	SHIPS MOORED IN A CURRENT	
5525 date 2.5.86	Cy - HEADING AT Fr = 0.08 TEST: 5200 ET SEQ 4301 : 90°	dwg no 9.3
CAJ/GJ		



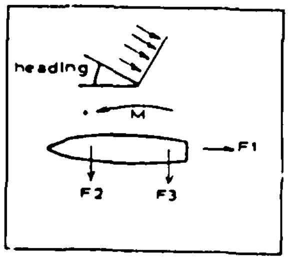


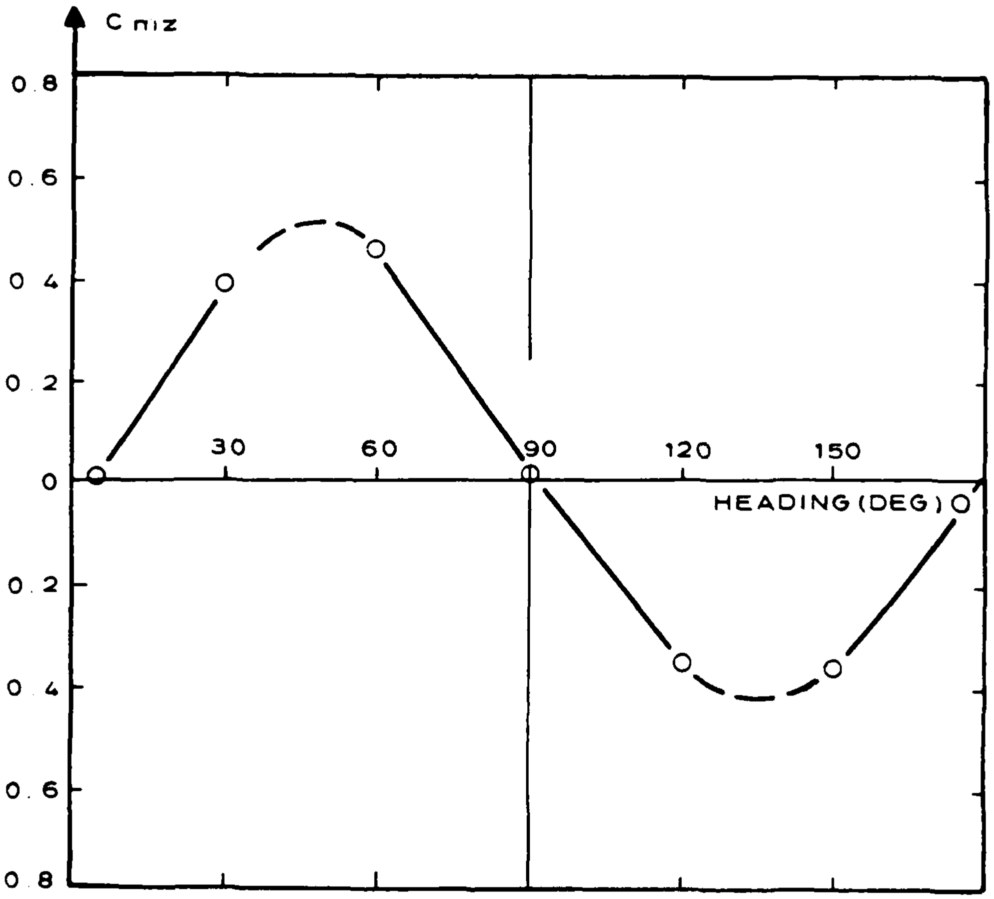
danish hydraulic institute		NAVAL CIVIL ENGINEERING LABORATORY	
		SHIPS MOORED IN A CURRENT	
5525	date 2.9.86	Cmz - HEADING AT Fr = 0.08	dwg no
	CAJ/GJ	TEST: 5200 ET SEQ 4301: 90°	9.4



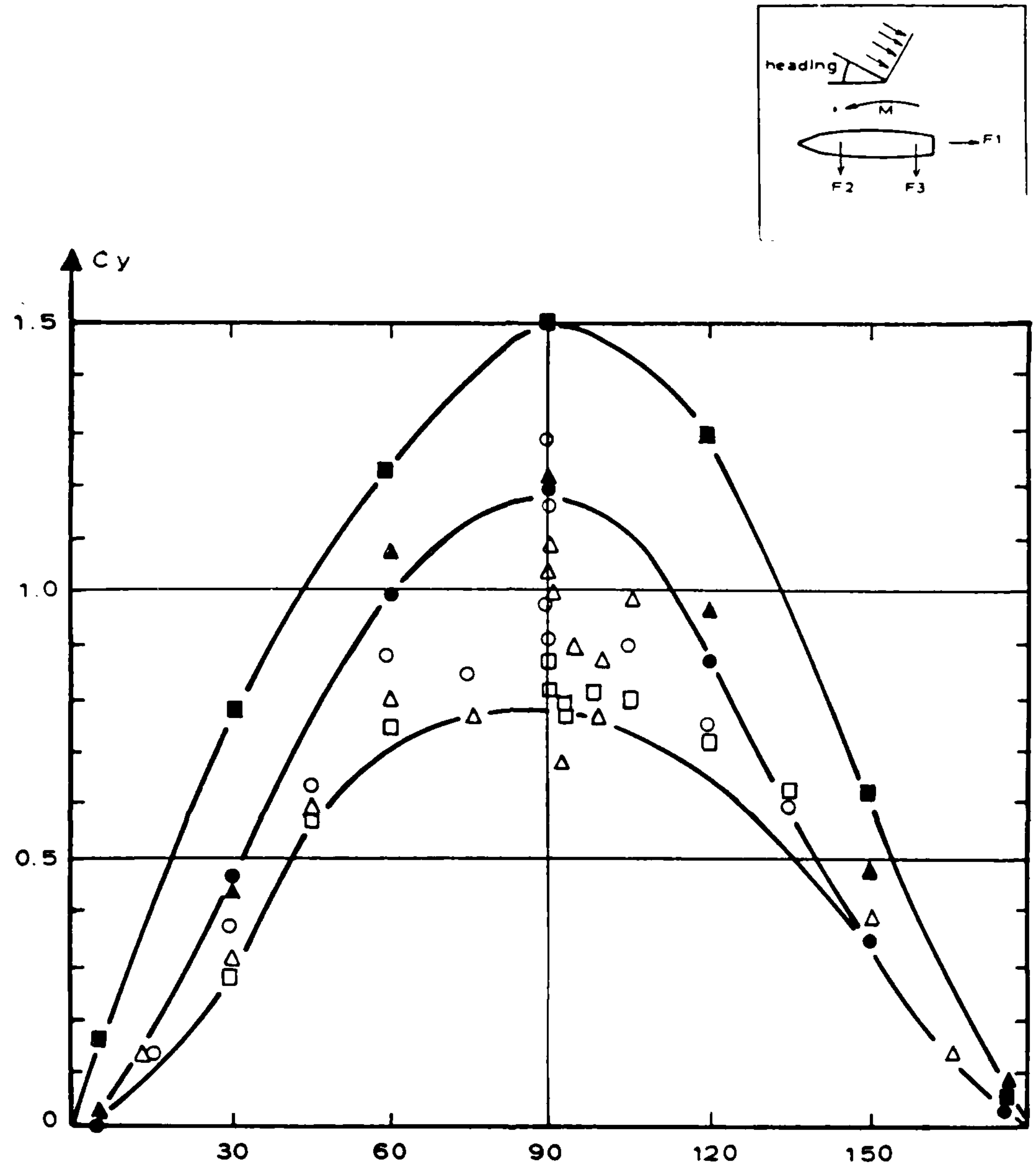


danish hydraulic institute		NAVAL CIVIL ENGINEERING LABORATORY	
		SHIPS MOORED IN A CURRENT	
5525	date 2 5 86	Cy - HEADING AT Fr = 0.04 TEST 5100 ET SEQ 4300 90°	dwg no 9 5
	CAJ/GJ		





danish hydraulic institute	NAVAL CIVIL ENGINEERING LABORATORY	
	SHIPS MOORED IN A CURRENT	
5525 2.5.86	Cmz - HEADING AT Fr = 0.04	9.6
CAJ/GJ	TEST 5100 ET SEQ 4300 90°	



Fr	CURRENT, FREE DHI 86	TOW - TEST, FIXED OTC 81 REF / 3 /
0.04	●	○
0.08	▲	△
0.11	■	□

danish hydraulic institute	NAVAL CIVIL ENGINEERING LABORATORY	
	SHIPS MOORED IN A CURRENT	
5525 date 2.5.86	COMPARISON BETWEEN RECENT FIXED MODEL TOW TESTS AND FREE MODEL CURRENT TESTS	dwg no 9.7
CAJ/GJ		

END

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