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THE 25TH AMERICAN TOWING TANK CONFERENCE ON EXPERIMENTAL INVESTIGATION OF HULL LATERAL FORCE DISTRIBUTION USING A PARTLY CAPTIVE HYDROELASTIC MODEL HELD IN IOW

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EXPERIMENTAL INVESTIGATION OF HULL LATERAL FORCE DISTRIBUTION USING A PARTLY CAPTIVE HYDROELASTIC MODEL

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presented at

The 25th American Towing Tank Conference
Iowa City, Iowa
24-25 September 1998

ABSTRACT

Experiments were carried out at the Institute for Marine Dynamics to determine the distribution of lateral forces and moments on a warship hull form with the objective of eventually modeling these components in a numerical maneuvering simulation. Total forces and moments were obtained from instrumentation included in IMD's horizontal Planar Motion Mechanism, and local shear forces, bending moments, and torques were measured at five locations along the instrumented elastic backbone of the segmented model. For modeling the maneuvering characteristics, interest centered on deriving the distribution of lateral force from these measurements. The test program consisted of varying the model static yaw angle and roll angle (drift and heel) for a range of forward speeds in calm water at deep departure and operational light conditions. In most experiments the model was free to pitch and heave; however, the model was fixed in pitch and heave in a subset of the tests for comparison.

This paper gives a general description of the model design, instrumentation, backbone calibration procedure, data collected and analysis procedure. Representative results illustrating the distribution of lateral force for a number of test conditions are provided along with some observations on their potential for modeling the maneuvering behavior of long slender vessels.

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INTRODUCTION

Traditional surface ship (or model) maneuvering experiments such as the Dieudonné spiral, Kempf overshoot (zigzag) and turning circle tests provide standard empirical means of evaluating the directional stability of the vessel as well as the ability of the control surfaces to effect a change in direction. Alternatively, a Planar Motion Mechanism can be used to predict model maneuvering performance by measuring the global hydrodynamic forces acting on the model hull and control surfaces, and using this data to predict the performance of the ship. However, knowledge of the distribution of lateral forces and moments along the hull is important for improving the numerical simulation of ship maneuverability. For some ship types, existing numerical simulation tools may not provide a reliable prediction capability even in the initial design stage. There are limited experimental data on the lateral force distribution available from captive model experiments, but these mostly pertain to high block coefficient commercial hull forms [1]. For slender twin-screw vessels, further data gathering, analysis, and validation are required to make numerical simulation a reliable tool for maneuvering performance prediction.

As a basis for modeling the maneuvering of frigates and other slender warships, the Institute for Marine Dynamics (IMD), in collaboration with the Defence Research Establishment Atlantic (DREA), recently carried out a series of captive model experiments with a segmented hydroelastic model of the Canadian Patrol Frigate (CPF) — the Halifax class [2]. The model was mounted on IMD's new horizontal Planar Motion Mechanism (PMM) which measures global forces and moments in the horizontal plane and provides easy yaw angle adjustment. Lateral force and moment distributions were derived from local shear force and bending moment measurements on the instrumented backbone. All experiments were carried out in calm water. There were two phases to the project: the principal test series, with a bare hull model, was done in the IMD Towing Tank in March 1997, and a more limited test series, with the model fully appended, was done in the IMD Ice Tank in June 1997[1].

Previous model force distribution experiments have generally favoured an individual force balance between each segment and a captive strongback [1], providing direct measurement of the segment forces. Burcher has reported innovative "force build-up" tests that provided indirect measurement with minimal instrumentation [3]. Although the direct measurement of segment force is advantageous for error control, availability of the hydroelastic CPF model prompted us to use the indirect approach for the present test program. The model was

[1] Performing the tests in the Ice Tank was purely a matter of convenience and tank availability. It does not imply the tests were carried out in ice covered water.

designed for, and has been principally used for, wave load experiments [4,5].

This paper describes the experimental technique and difficulties encountered during the recent tests, and presents some preliminary results from analysis of the data. The discussion section includes initial observations on how these data may be applied to numerical modeling.

DESCRIPTION OF THE TEST FACILITIES

The IMD horizontal PMM was designed to be fitted under the existing towing carriage in either of two towing tank environments at IMD - the 200 m by 12 m by 7 m Towing Tank or the 90 m by 12 m by 3 m Ice Tank. The PMM is normally used to rotate and translate a ship model in the horizontal plane in order to derive standard maneuvering coefficients. Standard PMM maneuvering experiments include static drift, pure sway, pure yaw or a combination of yaw and sway. The towing carriage is employed to provide a forward speed component. The IMD PMM is different from most traditional designs in that the model is connected via vertical posts and the motions are stimulated from above the model through lateral motion of the posts rather than transversely moving two horizontal struts. The IMD PMM is capable of much larger motion amplitudes than commonly available, with a maximum sway amplitude of ±4 m and yaw amplitude of ±90 degrees. The following global forces/motions are measured on the PMM frame above the model: sway force, yaw force, surge force, roll force, as well as yaw and sway displacement and rate. Model motions induced using the PMM are controlled through a software suite run on a dedicated PC located in the towing carriage control room. Additional information on the IMD PMM is provided in Reference [6]. For the experiments described in this paper, the PMM was used as a convenient tool to alter the static yaw angle and to measure the global forces on the model.

DESCRIPTION OF SEGMENTED HYDROELASTIC MODEL

The design of the CPF model consists of six segments with a continuous elastic backbone which comprises the sole longitudinal structural member. The model, divided into 20 stations, was segmented at Station 2.5, 5, 7.5 10, and 13.7 where Station 0 is the FP and Station 20 is the AP. The last segment was made large in order to accommodate self-propulsion equipment that was not required for the experiments described in this paper. The model was fabricated from fiberglass with 10 mm gaps separating segments. Latex strips were used to cover the gaps to provide watertight integrity without impairing the backbone measurement capability. Main particulars of the model for both load conditions tested are provided in the table below while the body plan is given in Figure 1. The fully appended model included a single centerline rudder locked at zero degrees deflection, segmented bilge keels (with gaps at each model segment interface to break segment-to-segment continuity), sonar dome mounted on the model longitudinal centerline forward and two sets of external shaft brackets supporting propeller shafts, dummy hubs and fairing cones.

Main Particulars of Model

Condition	Deep Departure	Operational Light
Length Overall (mm)	6,735.0	6,735.0
Length Between Perpendiculars (mm)	6,225.0	6,225.0 (design draft)
Beam (mm)	740.0	740.0
Design Draft (mm)	231.5	231.5
Draft at Midships (moulded, mm)	248.5	231.6
Trim by Stern (mm)	-1.9	27.1
Displacement (kg)	577.5	523.9
KG (mm)	316.0	334.8
GM (mm)	56.8	44.4
LCB (aft of midships, mm)	138.8	184.0
VCB (above base, mm)	153.0	not available

A roll frame was installed in Segment 5 to permit up to a ±15 degree adjustment of the model heel angle without impeding the backbone measurement capability or the freedom of the model to move in pitch and heave. Attachment of the roll frame to the PMM frame consisted of a sliding heave post fitted in linear bearings at the forward end of Segment 5 and a grasshopper aft to constrain the model in yaw/sway without sacrificing the pitch and heave freedom. It was possible to clamp the model to prevent pitch and heave motion, however. Due to the segmented nature of the model, there had to be only one connection point with the PMM rather than the normal bow and stern PMM mounting arrangement. A load cell was incorporated in the roll frame design to measure roll load at the model while a linear displacement transducer was installed adjacent to the heave post to measure heave displacement. The roll frame mounted in the model is illustrated in Figure 2. Additional instrumentation in the model included inclinometers to measure model roll and pitch angle.

The elastic backbone was attached to each segment by a single aluminum foundation topped by a wooden base. After all the foundations were installed, the model was assembled and the backbone mounting surfaces were milled to the same horizontal plane to ensure that the backbone could be installed without inducing vertical distortion between segments. The backbone mounting arrangement in the model is illustrated in Figure 3.

BACKBONE DESIGN AND CALIBRATION

The backbone comprised four continuous longitudinal carbon fiber stiffeners housed in a rectangular box fabricated from lexan webs. Solid hardwood blocks were glued inside the backbone and bolted to form the six mounting points to the foundations of the six hull segments. The carbon fiber stiffeners were the only longitudinal strength members in the model. The backbone was centered transversely and the vertical height of its centerline roughly coincides with the ship's vertical neutral axis at amidships. The backbone design is optimized to measure vertical forces and moments as the model was originally designed for tests in severe seas such as those described in References [4,5]. Secondary importance was given to modeling lateral shear and bending stiffness while no effort was made to model torsional behavior correctly.

The backbone was instrumented at each segment joint with strain gauge bridges to measure vertical bending, vertical shear, lateral bending, lateral shear, and torsion. Thus five parameters were measured at five locations; resulting in 25 sets of strain gauges installed on the backbone in full Wheatstone bridge configuration. The backbone was effectively a five-component load cell and was susceptible to channel 'cross-talk'. This meant that when the backbone was loaded, some response in other directions was unavoidable due to minor asymmetry in the cross-sectional properties. The magnitude of this cross-talk was minimized by taking care in the design and construction of the backbone; however, it was generally physically impossible to eliminate cross-talk altogether. The cross-talk of the backbone was thus taken into consideration during the bench calibration procedure which consisted of applying a unidirectional load to the simply supported backbone and measuring the output from all channels simultaneously. The following assumptions are made:

1. the strain gauge bridges at each location of the backbone were treated as one complete set. Thus the gauges at one location were assumed not to influence the strain experienced at other locations;
2. the elastic backbone beam was infinitely stiff for lateral shear; and
3. the calibration was fundamentally linear, and the primary cross-talk was first order only.

The results of the calibration were tabulated and incorporated in a dedicated matrix calibration program which was applied to the backbone output voltages during the data analysis sequence to eliminate the cross-talk influence and to convert the measured strain gauge voltages to physical units prior to further analysis.

Static checks were carried out at the start of each day of testing to verify the output from the PMM load cells and the backbone strain gauges. The check comprised of applying a sequence of known static vertical, longitudinal and lateral loads to the model and comparing the measurements recorded to the previous days results. This verification provided confidence in the consistency and integrity of results throughout the test program.

TEST PLAN

The experiments were carried out in two phases since converting the segmented hydroelastic model from the bare hull to fully appended condition is a time consuming process. The test parameter ranges were as follows, although the appended model tests were quite limited in scope:

1. Model Loading Condition: operational light (bare hull only) and deep departure (bare and appended hull)
2. Model Roll Angle: 0, ± 2.5, ± 5, –10, and –15 degrees.
3. Yaw Angle: 0, ± 2.5, ± 5, ± 10, ± 15, 20, 30, 45, 60, 75, and 90 degrees.
4. Forward Speed: 0.610 to 1.829 m/s (Froude Number, $Fr = 0.075$ to 0.225), with a few higher speed runs.
5. Model freedom of motion: free to pitch and heave, and fixed in pitch and heave (the latter for bare hull only).

Because the PMM was attached to the model at only one location, and because the backbone mounting arrangement had been optimized to withstand vertical forces, many forward speed/yaw angle combinations were impossible due to unacceptably large lateral forces and resultant deflection between segments. An effort made to reinforce the model in way of the backbone foundation in Segment 5 (i.e.: the PMM attachment point) to sustain higher lateral forces met with limited success, and eventually the range of speed/yaw angle combinations for static tests was curtailed and dynamic experiments with the PMM were abandoned.

DATA REDUCTION

This paper only covers the lateral force distribution; however, other forces and moments may be derived in a similar fashion. Notation is segment $i = 1$ (forward), ..., 6 (aft), and the boundary between segment i and segment $i+1$ — the nominal location of each strain gauge cluster — is $x_{i,i+1}$. The lateral force Y_i on segment i, is simply assumed to act somewhere between $x_{i-1,i}$ and $x_{i,i+1}$. For these captive experiments, the backbone is modeled as two beams — one directed forward, the other aft — which are cantilevered from the PMM at a point somewhere within Segment 5; that is, between $x_{4,5}$ and $x_{5,6}$.

With the backbone assumed to be rigid, the PMM measures the sum of segment forces ($Y_{PMM} = \Sigma Y_i$) and the lateral shear force measurements ($LSF_{i,i+1}$) are the sum of segment forces outboard of the measuring point. The individual segment forces are therefore:

$$
\begin{aligned}
Y_1 &= LSF_{1,2} \\
Y_2 &= LSF_{2,3} - LSF_{1,2} \\
Y_3 &= LSF_{3,4} - LSF_{2,3} \\
Y_4 &= LSF_{4,5} - LSF_{3,4} \\
Y_5 &= Y_{PMM} - LSF_{5,6} - LSF_{4,5} \\
Y_6 &= LSF_{5,6}
\end{aligned}
$$

These equations illustrate the classic difficulty with indirect measurement of force distribution in this fashion: most of the segment forces are derived from the difference between measurements of similar magnitude. Uncertainty in the results for Segments 2 to 5 is therefore generally higher than for the forward and aft segments. We have not done a detailed error analysis for this preliminary examination of the data, but the repeatability of duplicated runs provides a qualitative assessment of one aspect of the problem. The following table gives statistics for repeatability ΔY_i expressed as a percentage of Y_{PMM} for (a) nominally identical runs and (b) runs with nominally symmetrical port/starboard yaw.

Repeat-ability, %		Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6
(a), 5 runs	Mean:	1.15	1.40	1.02	1.31	1.10	0.88
	Std. Dev.:	1.02	1.75	1.10	1.11	1.15	0.55
(b), 16 runs	Mean:	2.29	6.53	12.93	5.37	14.02	5.53
	Std. Dev.:	3.33	10.63	20.74	8.66	15.67	6.17
(a)+(b), 21 runs	Mean:	2.02	5.31	10.10	4.40	10.95	4.42
	Std. Dev.:	2.96	9.51	18.70	7.72	14.70	5.72

Group (a) exhibits significantly better repeatability (i.e.: to within about 1%) than Group (b). This is consistent with some port/starboard asymmetry in the model or set-up as suggested by the force data in the next section.

RESULTS

Measured sideforce was converted to sideforce per unit length and nondimensionalized. However, proprietary restrictions limit us to presenting only a limited selection of comparative results here, and ordinates, except for the zero, are not identified on the graphs.

The baseline for comparison is the bare hull in the deep departure condition, with zero roll, and free to pitch and heave. Baseline results at low Froude number are shown in Figure 4(a) for yaw to 15 degrees, and in Figure 4(b) for yaw to 90 degrees. A port/starboard asymmetry is evident in Figure 4(a). For all yaw angles, the sideforce distribution is peaked at Segment 1, falling negative in Segment 4, and increasing again further aft. It is easier to follow the influence of yaw in Figure 5, where the same data are plotted by segment.

Not unexpectedly, roll angle appears to be a weak parameter for sideforce on the bare hull. Figure 6 is a representative case: although there is a small systematic decrease in sideforce magnitude on the forward segments as roll goes from zero to −15 degrees, it is of the same order as the previously noted repeatability. This does not justify including roll in a first-order sideforce model of the bare hull.

Froude number is likewise a weak parameter, as shown on Figure 7. The repeatability scatter, mostly at the lowest speed, swamps any *Fr* effect, except for Segment 1 which demonstrates a small increase of sideforce with Froude number. The degree of scatter is such that regression lines were omitted from this figure.

The loading condition has a significant effect as illustrated in Figure 8. In deep departure condition, the sideforce magnitude on Segments 1, 2, and 5 is greater than for operational light, while on Segment 4 it is less. The total sideforce, Y_{PMM}, was greater in the deep departure condition.

Of interest for the experimental technique is the effect of fixing the model in pitch and heave, Figure 9. There is some reduction in sideforce aft with the model fixed. Since the free model generally trimmed with a small bow-down angle and downward squat, fixing the model was equivalent to a lighter loading.

With appendages added, additional sideforce is evident at yaw angles greater than 5 degrees, Figure 10. The most prominent effects are of the sonar dome on Segment 2, of the bilge keels on Segment 5, and of the shaft brackets and rudder on Segment 6. The additional sideforce on the forward and (to a somewhat lesser extent) aft segments becomes pronounced as yaw increases.

DISCUSSION

For modeling the hydrodynamic forces on a ship, it is customary to superimpose individual contributions from the hull, appendages, and propulsors [7,8,9]. This allows approximations, such as assuming that Froude number is significant only for the hull, and facilitates modification to the appendages, etc., in preliminary design. The hull contribution is significant and, in a number of respects, the most difficult to estimate by semi-empirical or analytical methods.

Flow about the hull is highly three-dimensional in a turn, and an obvious simplification is to regard the hull as a series of segments, each at a local angle of yaw, and each of which is then more amenable to sideforce estimation than is the whole hull. Segmented hull measurements, such as those discussed in this paper, provide an experimental basis for estimation and validation. This model is open to the objection that it does not completely account for three-dimensionality in a turn, but there is reason to expect that it provides an acceptable approximation.

Hooft with others, has combined this approach with semi-empirical estimation of the sideforce on each hull segment [1,10,11]. His formulation of segment sideforce is analogous to the familiar expression for lift on an airfoil at incidence:

$$Y_i = Y'_{i(\beta)} \sin\beta + Y'_{i(\beta|\beta|)} \sin\beta\,|\sin\beta\,|$$

where β is the angle of yaw, and $Y'_{i(\beta)}$ denotes the linear coefficient and $Y'_{i(\beta|\beta|)}$ denotes the nonlinear, or crossflow drag, coefficient. It is evident in Figure 5 that both these coefficients cannot be constants if the data is to be fitted at yaw angles greater than about 20 degrees. Hooft regards the linear coefficient as a constant, and the crossflow drag as a function of yaw, in effect bundling the residual three-dimensional effects, higher-order yaw effects, etc., into this term. In that the linear coefficient can be related to circulation [10,11], this is a rational formulation, but a more detailed mathematical description of the drag components is required for it to be generally applicable.

At modest yaw angles, treating both coefficients of the above equation as constants results in a reasonable fit to the present data. In Figure 11, the data from Figure 5 for $\beta = \pm 15$ degrees is plotted with regression lines obtained by fitting $Y'_{i(\beta)}$ for $\beta = \pm 5$ degrees, then fitting $Y'_{i(\beta|\beta|)}$ to $Y_i - Y'_{i(\beta)} \sin\beta$ for $\beta = \pm 15$ degrees. There is generally a small offset in the data, notably for Segment 3, which must be attributed to a systematic error in the measurements. With the exception of Segment 4, the signs of both the linear and crossflow drag coefficients are positive. Negative coefficients imply negative crossflow; this is observed at midships for commercial hull forms at similar yaw angles, but is more pronounced in the present case.

In the present context, further work is required to determine whether this approach is an adequate basis for predicting the maneuvering characteristics of frigates and similar small slender warships. It is also necessary to confirm that three-dimensionality in a turn will be adequately represented.

CONCLUDING REMARKS

The experiments described here were carried out to determine hull lateral force distribution as a function of yaw angle, roll angle, and forward speed as well as loading condition in order to further develop and improve warship maneuvering prediction simulations. The segmented hydroelastic model was mounted via a single connection point to the new IMD large amplitude PMM so that the global forces and moments were measured using the PMM instrumentation while the lateral force and moment distributions were derived from shear force and bending moment measurements on the backbone. A matrix calibration procedure was required to correct for cross-talk between channels on the backbone. It was found necessary to omit high speed/yaw angle runs in the initial test matrix due to the inherently weak link between the model and the PMM.

Apart from yaw angle itself, the most sensitive parameter identified for the lateral force distribution was the loading condition. Since holding the model fixed in pitch and heave, as opposed to leaving it free, is equivalent to a change in loading, this has implications for how the model should be supported for doing similar experiments. Roll angle, for the bare hull, and Froude number were relatively weak parameters. The appended model showed increases in local lateral force corresponding to the presence of the appendages.

This paper presents preliminary results and analysis. Our initial assessment is that these data, together with a relatively simple formulation for hull sideforce, may provide an adequate approximation for similar hulls with yaw angles (actual or local, i.e., arising from a turn) up to 15 or 20 degrees.

ACKNOWLEDGEMENTS

The authors would like to thank DREA for providing funding in support of these experiments. In addition, the support of numerous IMD scientific and technical staff was much appreciated.

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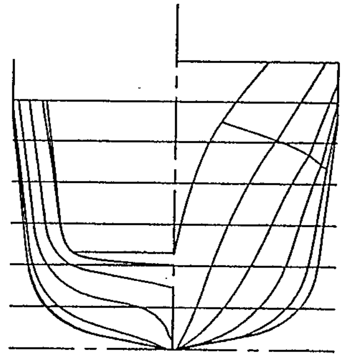

Figure 1: Body Plan

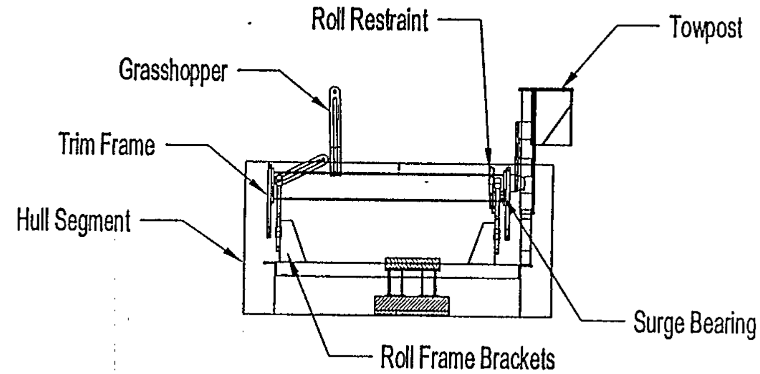

Figure 2: Roll Frame Assembly (Profile View)

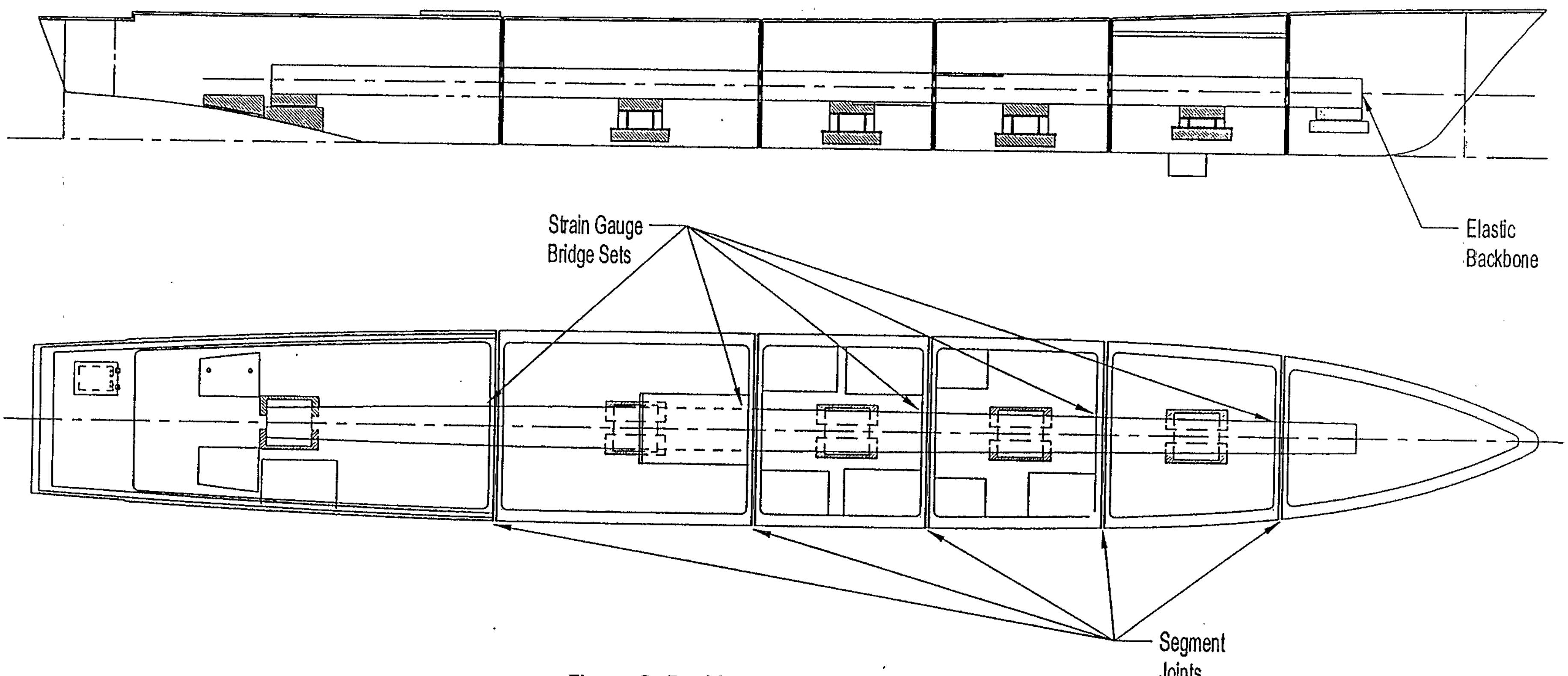

Figure 3: Backbone Mounting Arrangement

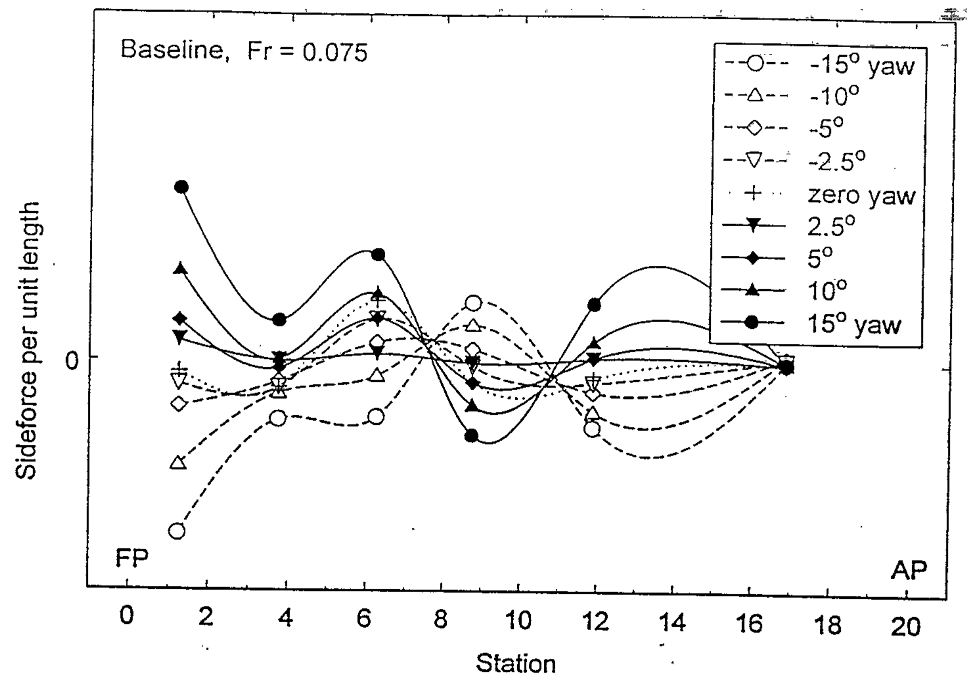

Figure 4(a): Baseline Lateral Forces Distribution, ±15 degrees Yaw Angle

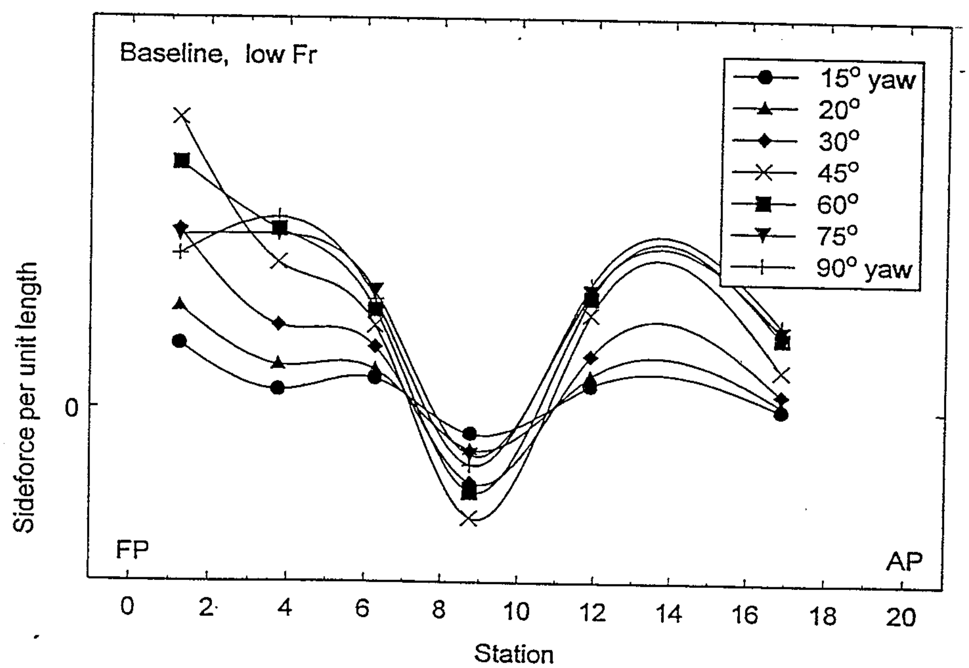

Figure 4(b): Baseline Lateral Force Distribution, 15 to 90 degrees Yaw Angle

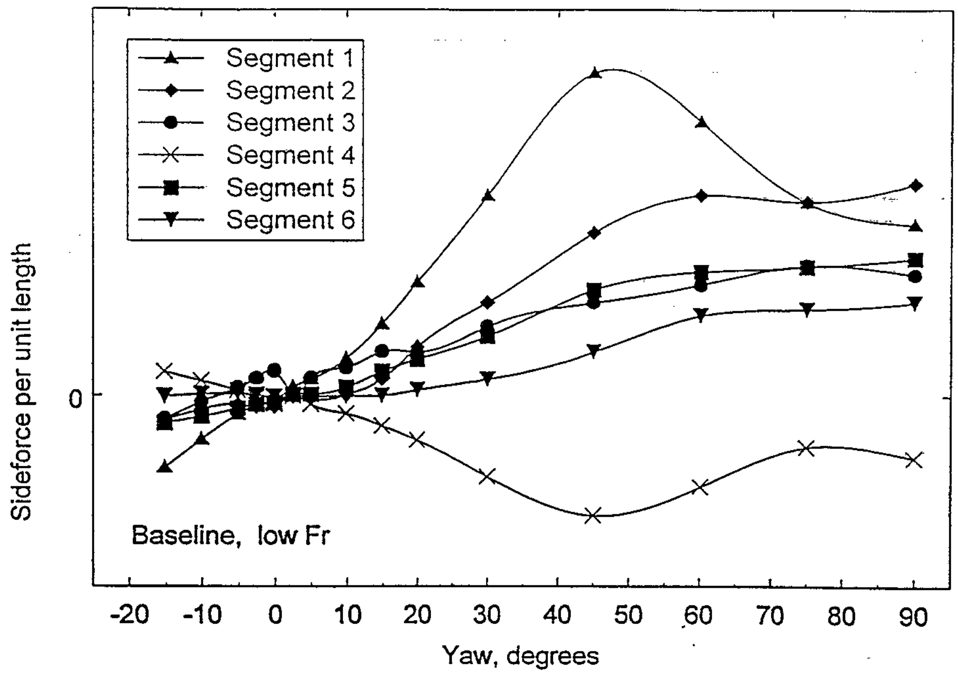

Figure 5: Baseline Lateral Force Distribution Plotted by Segment

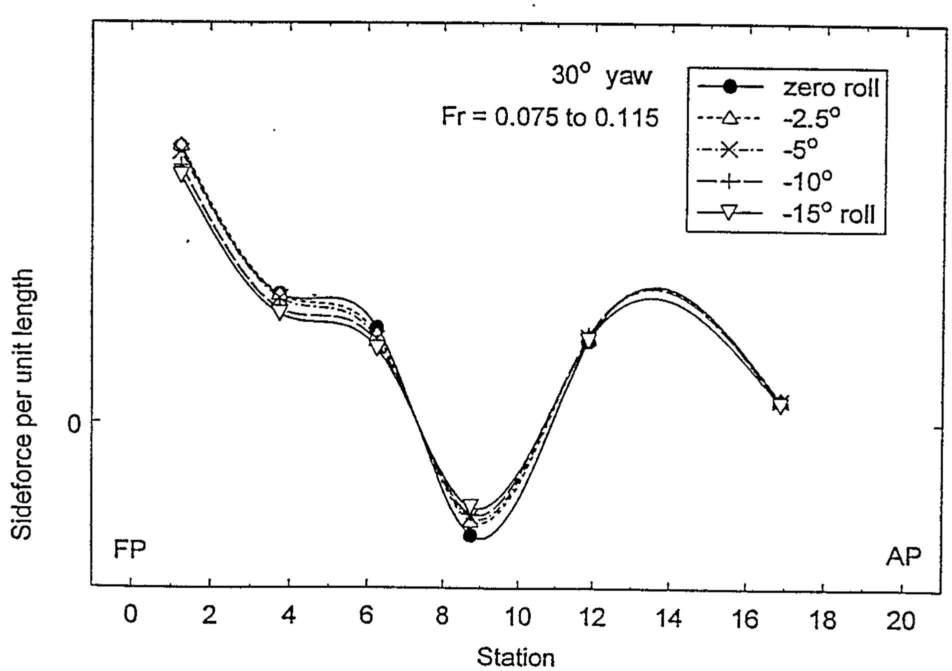

Figure 6: Variation with Roll Angle

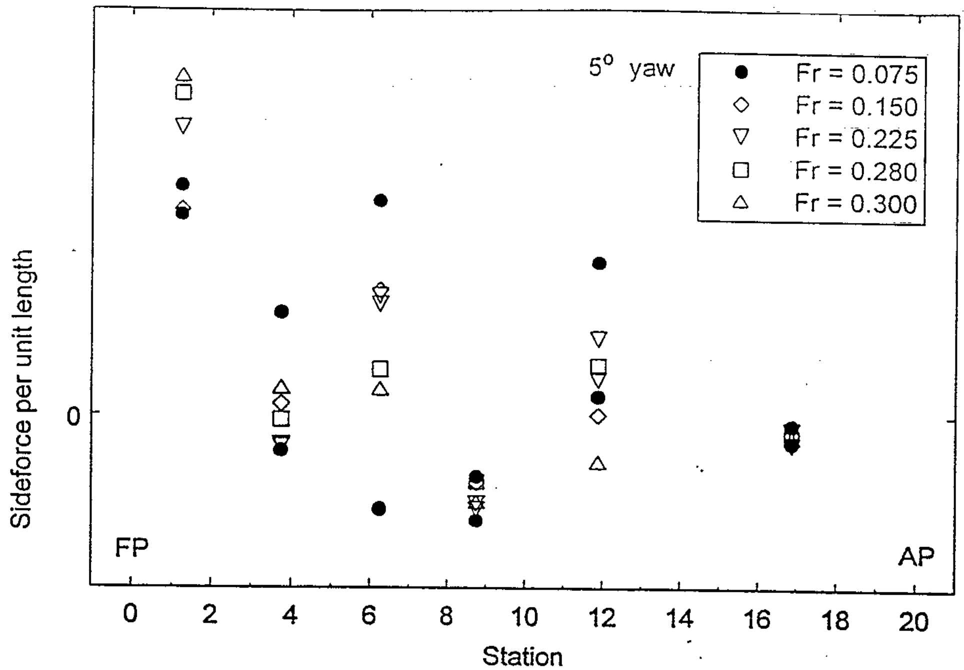

Figure 7: Variation with Froude Number

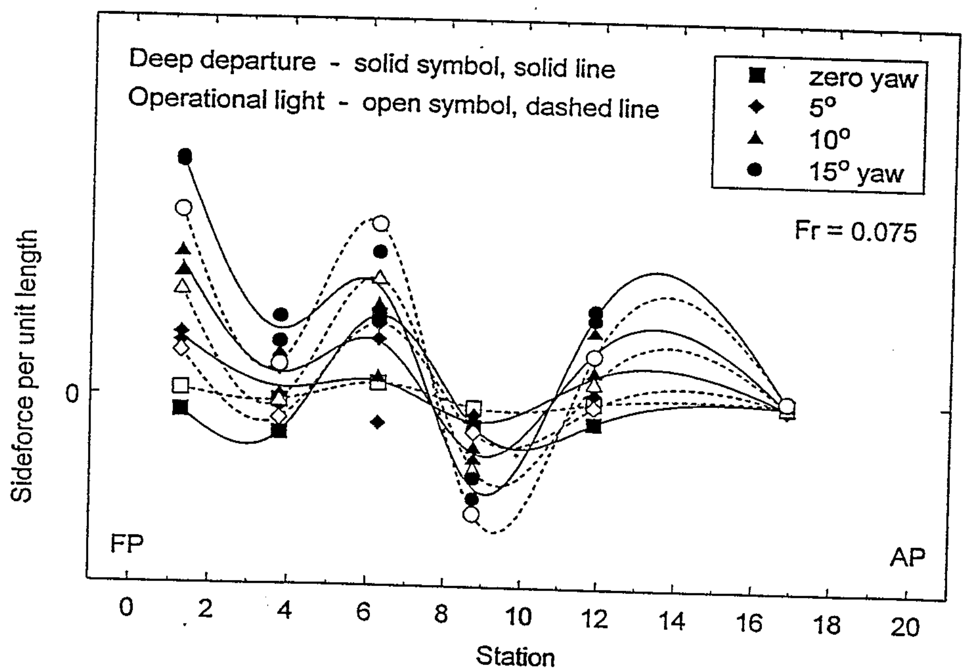

Figure 8: Variation with Loading Condition

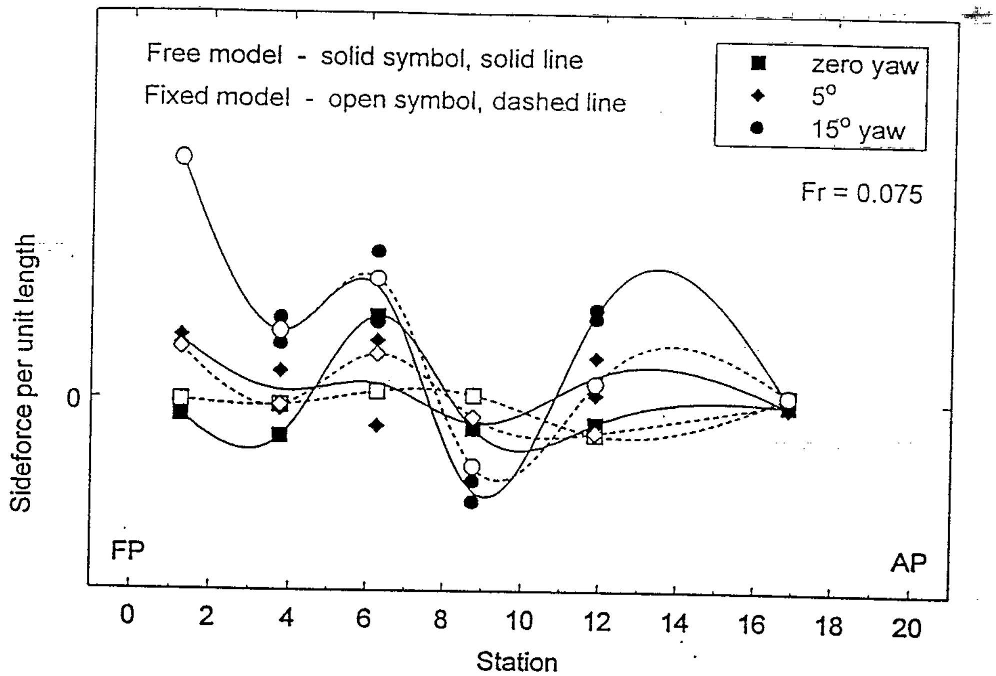

Figure 9: Variation with Model Support

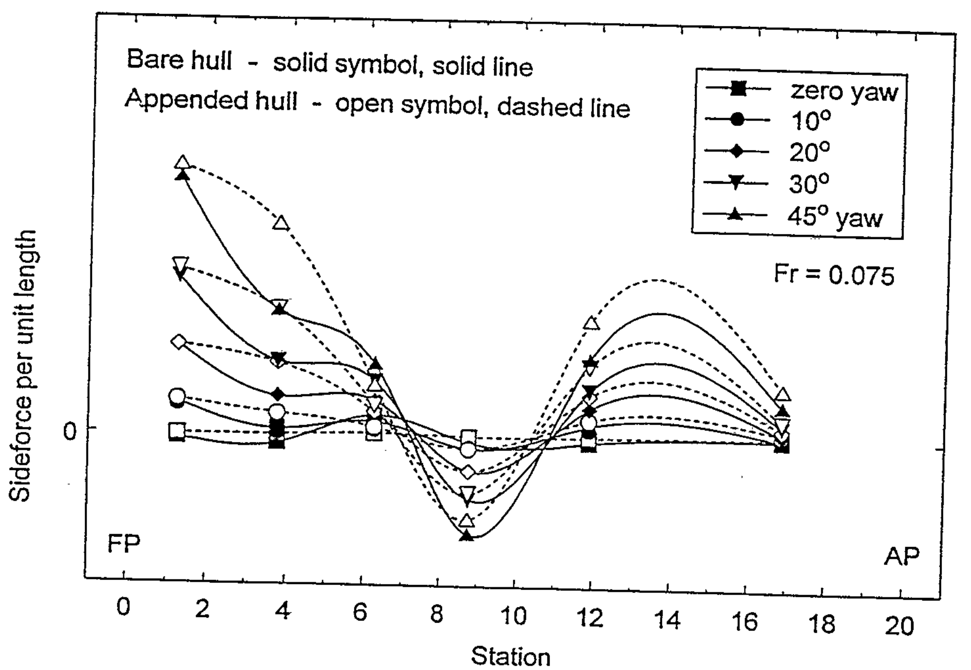

Figure 10: The Effect of Appendages

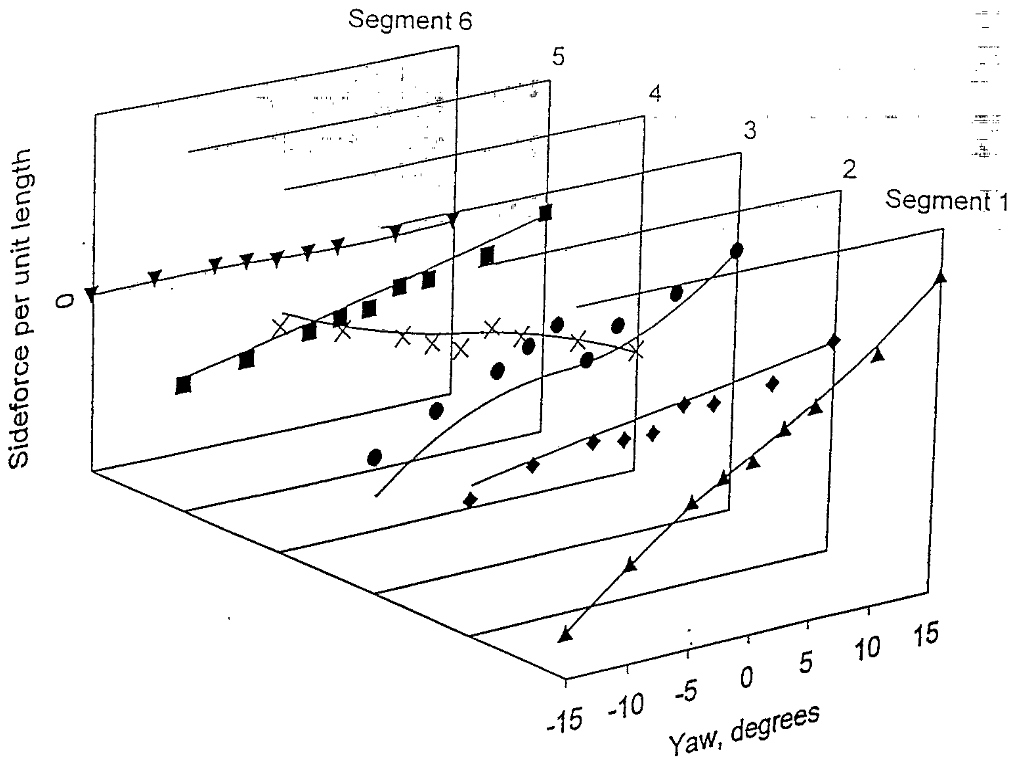

Figure 11: Simple Two-Coefficient Regression for ± 15 degrees Yaw Angle

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