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A.F. Molland and S.R. Turnock

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by

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SUMMARY

Performance tests were carried out in the 3.5m x 2.5m working section wind tunnel at the University of Southampton to investigate the behaviour of a semi-balanced skeg rudder behind a ship propeller. The semi-balanced skeg rudder had a mean chord of 667mm, span of 1000mm, taper ratio of 0.8, and with a NACA0020 section. Results were obtained for four different propeller advance ratios of 0.25, 0.36, 0.51 and 0.94 corresponding to propeller rpm of 2,850, 2100, 1460 and 800 with a tunnel wind speed of 10 m/s. The four-bladed propeller had an 800mm diameter, a mean pitch ratio of 0.95 P/D and was based on a modified Wageningen B4.40. Rudder force characteristics were obtained for rudder incidences between -40^{o} and 35^{o}, for three skeg angles of -5.4^{o}, -0.4^{o} and 4.6^{o}. The corresponding change in propeller performance due to the rudder was also assessed. Pressure measurements were made at 25 positions around the chord at one span and the influence of propeller thrust loading observed. A photographic record was made of a tuft study of the flow over the rudder surface.

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NOMENCLATURE

A	-	Rudder Area (m^2)
AR_g	-	Rudder Geometric Aspect Ratio
c	-	Mean Rudder Chord (m)
S	-	Rudder Span (m)
c_{tip}	-	Rudder Tip Chord (m)
c_{root}	-	Rudder Root Chord (m)
D	-	Propeller Diameter (m)
n	-	Revolutions per second
V	-	Freestream Wind speed (m/s)
d	-	Aerodynamic Drag (N)
L	-	Aerodynamic Lift (N)
N	-	Normal Force (N) - normal to rudder centre-line
Mx	-	Aerodynamic Moment about x-axis (Nm)
My	-	Aerodynamic Moment about y-axis (Nm)
Mz	-	Aerodynamic Moment about z-axis (Nm)
X	-	Longitudinal Separation of Rudder Leading Edge at height of propeller axis and propeller plane of rotation (m)
Y	-	Longitudinal Separation of Rudder Stock and propeller plane of rotation
Q	-	Torque (Nm)
T	-	Thrust (N)
C_l	-	Lift coefficient per unit span
C_L	-	Non-dimensional Lift (sideforce)
C_n	-	Normal force per unit span
C_d	-	Drag coefficient per unit span
C_D	-	Non-Dimensional drag
CP_c	-	Chordwise centre of pressure, % chord from leading edge
CP_s	-	Spanwise centre of pressure, % span from root
C_{Mz}	-	Non-dimensional Moment about rudder stock
C_{Mx}	-	Non-dimensional moment about rudder root chord
C_{My}	-	Non-dimensional moment about y axis
C_p	-	Non-Dimensional Pressure Coefficient
K_T	-	Thrust Coefficient ($T/\rho\ n^2D^4$)
K_Q	-	Torque Coefficient ($Q/\rho\ n^2D^5$)
η	-	Propeller efficiency ($J\ K_T/2\pi\ K_Q$)
J	-	Advance Ratio (V/nD)
α	-	Rudder incidence
β	-	Skeg incidence
ρ	-	Air Density (kg/m^3)

1.0 INTRODUCTION

The performance of a ship rudder working downstream of a propeller will be influenced by the flow regime within the impinging propeller race. This report detailing the behaviour of semi-balanced skeg rudder, a rudder type fitted to many single screw vessels, is part of an investigation into the mutual interaction between a ship rudder and propeller.

Goodrich and Molland [1] carried out free-stream wind tunnel tests of skeg-rudders, but it was noted in the discussion that the presence of an upstream propeller will affect the performance characteristics, especially that of rudder stall angle. The current tests reported to quantify the influence of a propeller for a representative ship propeller and rudder combination. Detailed information of the actual physical interaction between a propeller and rudder is essential in developing improved ship manoeuvring models and in the design of rudders and propellers.

The tests were carried out in the 3.5m x 2.5m closed return wind tunnel at the University of Southampton. The use of air as a working fluid rather than water significantly eases the measurement of data and test procedures. Also, high rudder Reynolds Numbers could be achieved thus minimising scaling effects. An existing rudder rig and dynamometer, as described in [1], was utilised and a new propeller rig developed and constructed for use in the wind tunnel [2].

2.0 DESCRIPTION OF MODELS

2.1 Semi-Balanced Skeg-Rudder

A model skeg-rudder with a mean chord of 667mm and, span of 1000mm and NACA0020 section was constructed from Jelutong using the method of manufacture described in Turnock [2]. Table I presents the rudder particulars and Fig. 1 its overall dimensions. The geometry of the rudder with its taper ratio of 0.8 is identical to that of Rudder No. 2 used by Goodrich and Molland [1], although for these tests a larger mean chord of 667mm was used. By careful sealing of the gap between skeg and rudder an all-movable rudder geometry is obtained. The tests carried out on this all-movable rudder geometry (Rudder No. 1) are reported in Molland and Turnock [3]. The model was pressure tapped although for this investigation pressure measurements were only obtained at 1 spanwise station 880mm from the rudder root. A roughness strip was applied to both sides of the rudder, starting 5.7% of the chord from the leading edge and consisting of 100 grade carborundum grit (0.15mm diameter) densely covering 12mm wide double-sided tape.

2.2 Modified Wageningen B4.40 Propeller

A four-bladed propeller with a diameter of 800mm and a blade area ratio of 0.40 was manufactured for the experiments. The design was modelled on a Wageningen B4.40 with suitable modifications. These modifications are detailed in [4] and consisted of altering the blade root shape to allow an adjustable pitch design with four separate blades and a split hub, removing rake and decreasing blade sweep to reduce centripetal loading moments at the root, and increasing the overall hub/diameter ratio from 0.167 to 0.25. In appearance the hub/blade root region is similar to that of a typical controllable pitch propeller.

The split hub was manufactured from aluminium alloy and a positive clamping action allows the four blades to be rotated and then clamped at the desired pitch ratio setting. The four blades were manufactured using hybrid carbon/glass fibre composite laid up in the same split female mould to produce identical blades. The production of the composite blades is detailed in [5]. Overall details of the propeller are summarised in Table II.

For these tests a mean propeller pitch ratio of 0.95 was used. The open-water propeller characteristics obtained for this model are given in Ref.[6].

3. APPARATUS AND TESTS

3.1 General

The tests were carried out in the 3.5m x 2.5m low-speed wind tunnel at the University of Southampton. The models in the tunnel are shown in Fig. 2 and the overall rig is shown in Fig. 3. The rig consists of two independent units which allow free-stream (open water) tests to be carried out independently on rudders and propellers as well as the investigation of their interaction.

3.2 Rudder Rig

The rudder was mounted through the tunnel floor and the gap between the rudder and skeg root and the floor in each case was approximately 2.5mm (0.004c). Rudder forces and moments were measured using the five-component strain gauge dynamometer described in [1]. Maximum design loads and moments for the dynamometer are as follows: Lift: 756N, Drag: 378N, Torque: 136N.m, Moment about x-axis 463N.m, Moment about y-axis: 237N.m. The measurement components of the dynamometer are connected to a strain gauge bridge unit with a built in stabilised power supply.

Pressure measurements over the surface of the rudder were obtained using a compressed air stepping scanivalve which for each step exposes each of four differential pressure transducers to one of 36 input ports. This allows pressure data to be measured from a maximum of 144 individual pressure tubes. For these tests pressures were measured at 25 locations as indicated in Figure 1.

3.3 Propeller Rig

Full details of the propeller rig are given in [2]. The rig is designed in such a way that the propeller can be adjusted vertically, longitudinally and at an angle of attack to the flow if required. The tests reported on were carried out with the propeller's axis of rotation 600mm above the wind tunnel floor and in the flow direction. The propeller rotates anti-clockwise when viewed from aft (looking upstream). The aerofoil fairing around the propeller support tubes and propeller drive belt has a NACA63040 profile with a chord of 550mm and 25% maximum thickness. The trailing edge of the fairing is located 0.5 of the propeller diameter (400mm) upstream of the propeller's plane of rotation. The fairing around the propeller drive shaft has a diameter equal to the minimum hub diameter (180mm).

An in-line strain gauge dynamometer mounted close to the propeller was used to measure the delivered thrust and torque. The dynamometer has the capability of measuring up to 750N thrust and 110 Nm torque. The design and static calibration of this dynamometer is detailed in [7]. The two measurement components of the dynamometer are connected via a slip-ring assembly to a strain gauge bridge unit with a built in stabilised power supply.

A variable frequency inverter is used to control the 30 kw electric motor drive and the propeller rpm can be continuously varied in small discrete steps between 0 and 3000 rpm.

3.4 Data Acquisition System

The large number of individual data readings required the use of an automated system for data acquisition. Bridge output signals from the five-component rudder dynamometer, the rudder pressure transducers and the propeller thrust/torque dynamometer are measured using a digital voltmeter. The voltmeter and input channels, together with the measurement of revs, are controlled by software running on an RM personal computer and the results stored on floppy discs for subsequent analysis. More details of the data acquisition system can be found in Ref. [3].

3.5 Tests

The results descrbied were obtained during two series of two-week testing periods carried out in March and August 1990. The rudder and propeller models were mounted on the tunnel centre-line at a longitudinal separation $X/D = 0.34$, which is the distance between the propeller plane of rotation and the rudder leading edge at the height of the propeller axis.

Wind speed was set using the wind tunnel speed controller and measured using a Betz manometer. For given propeller revolutions the wind speed controller was varied as necessary to compensate for the wind speed imparted by the propeller. A wind speed of 10 m/s was chosen for the majority of the tests being a compromise between achieving an adequate Reynolds Number and enabling a satisfactory range of propeller J values to be achieved. Based on a free-stream velocity of 10 m/s and rudder chord, the nominal Reynold's Number was therefore 0.4×10^6. It should be added that velocities induced by the propeller at the higher thrust loadings led to effective Reynolds Numbers of up to 1.0×10^6 over much of the rudder. Results presented in [8] indicate that tests at these conditions should preclude any significant scale effect.

Nominal propeller revolutions of 800, 1450, 2100 and 2850 rpm were set for each rudder test condition leading, at a wind speed of 10 m/s to nominal J values of 0.91, 0.51, 0.34 and 0.27 and nominal K_T/J^2 values of 0.05, 0.88, 2.30 and 4.53. Propeller thrust and torque measurements were recorded for all test conditions.

Rudder force measurements were carried out over a range of incidences between -35^o and 40^o to include stall were possible. Three skeg angles of -5.4^o, -0.4^o and 4.6^o were used.

Pressure measurements were made for a rudder incidence of $+20^o$ at a span of 880mm from the rudder root for wind speeds of 5m/s, 10m/s, 15m/s and 20 m/s and for a range of propeller rpm between 400 and 2900 rpm.

In addition a free-stream test was carried out for rudder angles between -35^{o} and 40^{o} at a wind speed of 25m/s.

4.0 DATA REDUCTION AND CORRECTIONS

A computer programme Ref. [3] was used to provide the data in coefficient form. The program incorporates the rudder dynamometer five-component interaction matrix and correction formulae and the resolution of forces and moments from instrument axes to stream axes as necessary. A cross plot of raw rudder data yielded the angular misalignment of the rudder rig which amounted to 0.4^{o} and this correction was applied to all measured angles before insertion in the program.

The acquisition of rudder surface pressure together with reference static and dynamic pressures from the tunnel allowed direct calculation of the local pressure coefficient C_p. Chordwise integration of C_p is carried out to give the normal force coefficient C_n at the span position considered.

The analysis program incorporates the propeller dynamometer calibrations hence allowing direct calculation of the propeller coefficients.

Tunnel boundary corrections were investigated but found to be unnecessary, as effects such as tunnel blockage for the 3.5m x 2.5m working section were found to have a negligible influence for the rudder size and propeller diameter tested.

5.0 PRESENTATION OF DATA

The notation of rudder incidence and coefficients used in the presentation is given in Fig. 4, noting that the propeller rotates in an anti-clockwise direction when viewed from aft. All force coefficients have been non-dimensionalised using the free-stream velocity of 10 m/s and actual total rudder area (S.c), including both movable rudder and skeg.

The data are presented in terms of J values rather than directly as thrust loading (K_T/J^2). This is to eliminate ambiguity between the use of the propeller free-stream (open water) thrust coefficient and the actual measured thrust coefficient in the presence of the rudder. The latter is generally larger than that in the free-stream for the same free-stream J value.

6.0 DISCUSSION OF RESULTS

6.1 Rudder in Free-Stream

Fig. 5 presents free-stream results at a skeg angle of -0.4^{o} together with those obtained for the similar rudder, tested in the same rudder rig and reported in Ref.[1].

The results are very similar providing a validation of the experimental set up and data acquisition procedures for the current tests.

The characteristic discontinuity in the lift characteristic is observed at an incidence of 10^o. This is due to the flow separating over the skeg. The delay of overall stall due to the skeg arrangement is also seen, stall occurring at about 36^o.

6.2 Influence of Propeller on Rudder Performance

6.2.1 Propeller Thrust Loading

Figures 6 and 7 present results at wind speeds of 10m/s and 20m/s respectively. The effect on the rudder characteristics is the same as that previously reported for all-movable rudders (Ref. [3]). That is for increased thrust loading:

1) for positive thrust loading ($J < 1.04$) there is an increase of lift-curve slope above that of free-stream;

2) the drag component due to lift increases;

3) chordwise centre of pressure CPc moves forward from the free-stream position

4) spanwise centre of pressure CPs increases for positive incidence and decreases for negative incidence.

The stall behaviour is not as clear cut as that for the all-movable rudder. However, even for the lowest thrust loading tested, lift continues to increase with rudder incidence. It is difficult to discern the discontinuity observed in the free-stream lift characteristic even for the low thrust loadings, the rotational flow generated by the propeller appearing to delay separation over the skeg. Further tests at high rudder incidence $>40^o$ are required to ascertain the overall stall behaviour of the skeg rudder.

It is interesting to note in Fig.7 that the effect of negative thrust loading ($J=1.88$) is to reduce the sideforce generated the rudder for all incidence. It appears that the propeller is removing energy from the flow over the rudder. This can be seen more clearly in Figure 8 which plots against a base of thrust loading the rudder lift-curve slope at zero rudder incidence. The behaviour for negative thrust loading is a continuation of that at low positive thrust loading. The value of slope for zero thrust loading is 0.0467 which is higher than the free-stream value of 0.042. For high thrust loadings the rate of increase of lift-slope decreases, as was found for the all-movable rudders.

6.2.2 Skeg Angle

Figure 9 shows the rudder characteristics for three thrust loadings with the skeg angle set at -5.4^o and Fig. 10 gives the same data for a skeg angle of $+4.6^o$. Overall the behaviour is very similar to that with the skeg at -0.4^o. This is compared directly in Figs. 11 to 13 for advance ratios of 0.94 to 0.36. Only at the low thrust loading ($J=0.94$) is there any perceptible difference in the lift and drag performance. However, the position of the centre of pressure is more sensitive to the skeg angle.

6.2.3 Effect on pressure distribution

Figure 14 shows the chordwise pressure distribution at one span position for a range of propeller thrust loadings. The shape of the pressure distribution remains the same for all thrust loadings tested. The good comparison shows the Reynolds number independence of the results. The only deviation occurs when comparing an advance ratio of J=0.38 (5m/s and 1000rpm) with J=0.36 (10m/s and 2100 rpm). It is likely that at 5m/s and 1000 rpm there is some scale effect.

The integrated local normal force Cn is found to be proportional to the propeller open water thrust loading and this is shown in Figure 15 for the range of thrust loadings tested.

6.3 Influence of Rudder on Propeller Performance

The rudder blocks the flow passing through the propeller and this results in a higher propeller thrust and corresponding increase in propeller torque. Figure 16 shows the effect on thrust of rudder incidence and advance ratio and Fig. 17 the effect on propeller torque.

6.4 Photographic Tuft Study

Figure 18 shows for rudder angles of -30° to $+30^{\circ}$ the influence of thrust loading on a regular distribution of white wool tufts evenly spread over both sides of the rudder. Stalled regions are seen as a blurred oscillation of the tuft. The flow over the rudder tip can be clearly seen as can the downstream influence of the skeg.

7.0 Conclusion

The semi-balanced skeg rudder has a similar behaviour behind a propeller as an all-movable rudder. The effect of increasing propeller thrust loading is to increase the sideforce generated by the rudder. Changing the angle of the skeg to the flow had little effect on the lift performance of the rudder unlike in the free-stream where a change of skeg angle shifts the lift characteristic. This is due to the dominating influence of the propeller.

8.0 ACKNOWLEDGMENTS

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APPENDIX A RUDDER DYNAMOMETER

RUDDER DYNAMOMETER pt48.rud Free-stream V=25m/s

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-0.40	25.00	0.00	-0.0070	-0.008	0.013	0.003	-0.0100	0.0120	-10.055	122.382
-5.40	25.00	0.00	-0.2100	-0.211	0.023	0.022	-0.1420	0.0190	24.732	50.311
-10.40	25.00	0.00	-0.4190	-0.422	0.054	0.029	-0.2800	0.0400	28.471	49.538
-12.90	25.00	0.00	-0.4350	-0.442	0.081	0.016	-0.2960	0.0570	31.809	50.712
-15.40	25.00	0.00	-0.4620	-0.473	0.102	0.016	-0.3360	0.0730	32.076	55.047
-20.40	25.00	0.00	-0.6030	-0.617	0.148	0.019	-0.4350	0.1040	32.316	54.498
-25.40	25.00	0.00	-0.7680	-0.785	0.214	0.016	-0.5520	0.1530	33.352	54.393
-30.40	25.00	0.00	-0.8930	-0.927	0.310	-0.008	-0.6350	0.2210	36.228	53.679
-35.40	25.00	0.00	-0.9350	-0.983	0.380	-0.023	-0.6610	0.2820	37.706	53.919
-0.40	25.00	0.00	-0.0060	-0.006	0.015	0.002	-0.0090	0.0120	-0.710	122.019
4.60	25.00	0.00	0.2110	0.213	0.026	-0.014	0.1270	0.0040	28.608	42.042
9.60	25.00	0.00	0.3540	0.359	0.061	-0.010	0.2230	0.0410	32.599	45.733
12.10	25.00	0.00	0.3990	0.408	0.084	-0.009	0.2730	0.0560	33.124	50.914
14.60	25.00	0.00	0.4530	0.465	0.104	-0.012	0.3130	0.0710	32.742	51.614
19.60	25.00	0.00	0.5960	0.612	0.151	-0.014	0.4190	0.1040	33.169	52.757
24.60	25.00	0.00	0.7560	0.777	0.215	-0.010	0.5330	0.1520	34.079	53.029
29.60	25.00	0.00	0.9020	0.933	0.301	0.005	0.6400	0.2160	35.929	53.602
34.60	25.00	0.00	0.9820	1.034	0.398	0.026	0.6810	0.2870	37.939	52.464
39.60	25.00	0.00	0.7690	0.902	0.486	0.046	0.4750	0.3340	40.513	46.658

RUDDER DYNAMOMETER eaj1v1.skg 800rpm 10m/s J=0.94 Skeg=0.0

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-35.40	10.00	807.80	-1.1465	-1.241	0.529	-0.041	-0.8010	0.2905	38.731	48.683
-30.40	10.00	784.46	-1.0463	-1.094	0.378	-0.017	-0.7203	0.1960	36.898	48.399
-25.40	10.00	783.87	-0.9053	-0.938	0.280	-0.002	-0.6183	0.1437	35.628	48.639
-20.40	10.00	783.76	-0.8523	-0.879	0.229	0.008	-0.5827	0.1163	34.497	49.287
-15.40	10.00	772.65	-0.7140	-0.727	0.147	0.020	-0.4650	0.0710	32.496	46.789
-10.40	10.00	784.85	-0.4773	-0.485	0.092	0.023	-0.3160	0.0403	30.099	48.894
-5.40	10.00	738.60	-0.3230	-0.323	0.016	0.022	-0.1940	-0.0070	28.681	41.981
-0.40	10.00	773.10	-0.0240	-0.024	0.048	0.010	-0.0317	0.0097	82.989	-105.775
4.60	10.00	737.50	0.0745	0.072	-0.028	-0.021	0.0545	-0.0235	3.879	57.472
9.60	10.00	783.32	0.4577	0.467	0.089	-0.026	0.2670	0.0160	29.837	39.286
14.60	10.00	771.45	0.6360	0.653	0.150	-0.005	0.3865	0.0470	34.536	41.744
19.60	10.00	771.82	0.7165	0.749	0.222	0.003	0.4590	0.0840	35.884	44.218
24.60	10.00	784.34	0.8243	0.867	0.281	0.005	0.5403	0.1373	36.016	45.848
29.60	10.00	784.05	0.9303	0.982	0.350	0.009	0.6250	0.1793	36.089	47.512
34.60	10.00	806.53	1.1930	1.281	0.528	0.038	0.8200	0.2875	38.282	47.881

RUDDER DYNAMOMETER eaj2v1.skg 1460rpm 10m/s J=0.51 Skeg=0.0

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-35.40	10.00	1462.47	-2.2955	-2.508	1.100	-0.073	-1.5195	0.6865	38.317	47.737
-30.40	10.00	1461.50	-2.2932	-2.395	0.824	-0.016	-1.4952	0.5060	36.036	47.076
-25.40	10.00	1461.50	-2.1373	-2.191	0.607	0.037	-1.3780	0.3843	33.718	46.842
-20.40	10.00	1461.62	-1.7680	-1.801	0.414	0.082	-1.1327	0.2470	30.845	46.221
-15.40	10.00	1460.09	-1.3660	-1.380	0.238	0.087	-0.8450	0.1385	29.074	44.162
-10.40	10.00	1462.13	-0.9003	-0.912	0.150	0.077	-0.5373	0.0860	26.891	42.116
-5.40	10.00	1460.36	-0.6790	-0.671	-0.057	0.029	-0.3160	-0.0090	31.095	29.197
-0.40	10.00	1461.86	-0.0347	-0.036	0.068	0.034	0.0267	0.0215	92.925	101.872
4.60	10.00	1460.21	0.2990	0.299	0.016	0.001	0.2690	-0.0050	35.600	71.989
9.60	10.00	1461.68	0.8597	0.869	0.127	-0.023	0.6313	0.0603	32.652	55.748
14.60	10.00	1460.14	1.4420	1.475	0.316	-0.008	0.9890	0.1405	34.876	49.789
19.60	10.00	1461.88	1.7357	1.772	0.408	-0.016	1.2557	0.2400	34.461	53.855
24.60	10.00	1461.85	2.0983	2.183	0.662	0.051	1.4827	0.3827	37.725	51.534
29.60	10.00	1462.07	2.1323	2.251	0.804	0.085	1.5963	0.5070	39.157	55.403
34.60	10.00	1462.35	2.3120	2.480	1.016	0.116	1.7230	0.6565	40.069	54.709

RUDDER DYNAMOMETER eaj3v1.skg 2100rpm 10m/s J=0.36 Skeg=0.0

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-35.40	10.00	2150.70	-4.1330	-4.414	1.805	-0.016	-2.7015	1.1435	35.743	47.388
-30.40	10.00	2161.14	-3.8080	-3.977	1.369	0.105	-2.5153	0.8920	32.744	48.417
-25.40	10.00	2161.22	-3.3703	-3.438	0.918	0.181	-2.1833	0.6080	30.121	47.461
-20.40	10.00	2160.95	-2.6803	-2.721	0.599	0.193	-1.7070	0.3810	28.313	46.177
-15.40	10.00	2149.16	-2.0320	-2.057	0.370	0.178	-1.2565	0.2250	26.726	44.271
-10.40	10.00	2160.86	-1.3730	-1.384	0.190	0.145	-0.7953	0.1120	24.950	40.433
-5.40	10.00	2181.50	-0.7250	-0.733	0.117	0.117	-0.3790	0.0280	19.372	34.316
-0.40	10.00	2168.70	-0.0788	-0.079	0.053	0.043	0.1125	0.0250	28.122	-18.007
4.60	10.00	2181.87	0.5310	0.531	0.023	0.001	0.5510	0.0050	35.657	86.018
9.60	10.00	2160.13	1.2573	1.272	0.190	-0.036	1.0510	0.1043	32.583	65.530
14.60	10.00	2148.88	1.9730	2.000	0.362	-0.041	1.5395	0.2065	33.305	59.708
19.60	10.00	2161.06	2.6460	2.701	0.622	-0.053	2.0577	0.4060	33.404	59.344
24.60	10.00	2161.17	3.2793	3.374	0.943	-0.021	2.5340	0.6303	34.731	58.639
29.60	10.00	2161.21	3.9283	4.112	1.411	0.080	3.0197	0.9427	37.327	57.666
34.60	10.00	2150.58	4.0945	4.376	1.773	0.196	3.2095	1.2335	39.845	58.862

RUDDER DYNAMOMETER pblj410.rud 2800rpm 10m/s J=0.26 Skeg=0.0

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-0.40	10.00	2894.13	-0.1950	-0.196	0.117	0.095	0.1650	0.0420	-13.130	-101.501
-10.40	10.00	2892.41	-2.0760	-2.082	0.223	0.239	-0.9980	0.1420	23.913	30.880
-20.40	10.00	2894.30	-4.0110	-4.035	0.791	0.325	-2.2360	0.5430	27.332	39.146
-25.40	10.00	2892.98	-4.8800	-4.943	1.245	0.341	-2.8310	0.8610	28.484	41.708
-30.40	10.00	2894.55	-5.7560	-5.907	1.862	0.291	-3.2860	1.2100	30.455	40.842
-35.40	10.00	2891.14	-6.3960	-6.668	2.511	0.174	-3.8020	1.7580	32.770	44.249
9.60	10.00	2891.71	1.8120	1.845	0.347	-0.040	1.5150	0.2410	33.215	65.641
19.60	10.00	2892.28	3.6910	3.808	0.988	-0.115	2.7840	0.7090	32.355	57.605
24.60	10.00	2893.41	4.6470	4.818	1.424	-0.113	3.4410	1.0480	33.039	56.500
29.60	10.00	2891.64	5.5800	5.836	1.991	-0.051	4.0850	1.4690	34.502	55.796
34.60	10.00	2891.46	6.4920	6.877	2.701	0.066	4.6930	1.9590	36.344	54.851

RUDDER DYNAMOMETER eaj1v2.skg 800rpm 20m/s J=1.88 Skeg=0.0

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-30.40	20.00	805.70	-0.7365	-0.758	0.244	-0.014	-0.5185	0.1455	37.138	51.484
-20.40	20.00	804.92	-0.5145	-0.524	0.120	-0.005	-0.3805	0.0750	36.222	55.694
-10.40	20.00	806.59	-0.2540	-0.260	0.058	0.013	-0.2110	0.0210	30.462	63.894
-0.40	20.00	805.24	0.0365	0.036	0.014	-0.005	-0.0170	-0.0020	20.877	-90.673
9.60	20.00	805.12	0.4030	0.407	0.055	-0.012	0.2070	0.0220	32.437	33.563
19.60	20.00	804.35	0.5630	0.575	0.133	-0.007	0.3370	0.0805	34.308	42.687
29.60	20.00	805.50	0.7215	0.760	0.269	0.014	0.4550	0.1620	37.289	45.119

RUDDER DYNAMOMETER eaj2v2.skg 1460rpm 20m/s J=1.02 Skeg=0.0

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-30.40	20.00	1460.31	-1.0475	-1.088	0.365	-0.002	-0.7360	0.2520	35.507	52.604
-20.40	20.00	1459.99	-0.7330	-0.755	0.194	0.010	-0.4990	0.1310	34.064	50.620
-10.40	20.00	1460.19	-0.4785	-0.486	0.087	0.025	-0.3050	0.0525	30.009	46.302
-0.40	20.00	1460.07	-0.0237	-0.024	0.037	0.009	-0.0093	0.0160	18.673	30.086
9.60	20.00	1460.06	0.4345	0.442	0.082	-0.016	0.2915	0.0475	31.790	49.340
19.60	20.00	1460.26	0.6570	0.686	0.200	0.005	0.4775	0.1270	36.077	54.305
29.60	20.00	1460.09	0.9685	1.022	0.364	0.022	0.6955	0.2475	37.497	53.717

RUDDER DYNAMOMETER eaj3v2.skg 2100rpm 20m/s J=0.71 Skeg=0.0

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-30.40	20.00	2116.71	-1.4790	-1.571	0.583	0.005	-1.0030	0.3900	35.057	50.117
-20.40	20.00	2083.71	-1.2330	-1.254	0.284	0.026	-0.7745	0.2005	33.299	45.946
-10.40	20.00	2084.13	-0.6520	-0.662	0.113	0.051	-0.3960	0.0730	27.632	43.266
-0.40	20.00	2083.52	-0.0370	-0.038	0.042	0.019	0.0125	0.0280	90.110	154.098
9.60	20.00	2083.98	0.5935	0.601	0.097	-0.015	0.4350	0.0640	32.942	55.717
19.60	20.00	2084.04	1.1190	1.153	0.294	0.017	0.8105	0.1940	36.849	54.411
29.60	20.00	2083.86	1.3615	1.433	0.505	0.044	1.0305	0.3540	38.475	57.292

RUDDER DYNAMOMETER eamj1v1.skg 800rpm 10m/s J=0.94 Skeg=-5.0

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-40.40	10.00	804.35	-1.3630	-1.392	0.546	-0.063	-0.8680	0.3210	39.929	44.948
-30.40	10.00	806.54	-1.0730	-1.175	0.492	0.009	-0.7590	0.2690	34.641	49.835
-20.40	10.00	807.21	-1.0770	-1.069	0.171	0.029	-0.7010	0.1480	32.633	48.765
-10.40	10.00	804.77	-0.4790	-0.496	0.135	0.081	-0.3620	0.0720	18.997	56.908
-5.40	10.00	803.38	-0.2710	-0.275	0.058	0.061	-0.2090	0.0330	13.394	59.197
-0.40	10.00	805.86	0.0310	0.031	0.099	0.054	-0.0540	0.0270	210.803	-193.728
9.60	10.00	805.67	0.4920	0.509	0.143	0.024	0.2460	0.0480	40.045	31.774
19.60	10.00	804.53	0.8100	0.848	0.253	0.037	0.4950	0.1190	39.772	42.186
29.60	10.00	805.23	0.9680	1.043	0.406	0.056	0.6420	0.2040	40.800	45.707

RUDDER DYNAMOMETER eamj2v1.skg 1460rpm 10m/s J=0.51 Skeg=-5.0

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-40.40	10.00	1460.26	-2.4670	-2.763	1.364	-0.115	-1.6360	0.8580	39.552	47.733
-30.40	10.00	1460.27	-2.1490	-2.309	0.900	0.005	-1.4420	0.5960	35.183	49.440
-20.40	10.00	1460.21	-1.8480	-1.867	0.388	0.141	-1.2100	0.2570	27.807	48.054
-10.40	10.00	1460.46	-0.9050	-0.922	0.178	0.133	-0.5900	0.1090	20.987	47.557
-5.40	10.00	1460.32	-0.4780	-0.481	0.060	0.103	-0.2980	0.0540	13.910	45.281
-0.40	10.00	1460.21	-0.0510	-0.051	0.069	0.079	-0.0070	0.0310	-117.874	-2.561
9.60	10.00	1460.29	0.9340	0.956	0.214	0.046	0.6240	0.1010	40.221	48.595
19.60	10.00	1460.16	1.8230	1.863	0.435	0.043	1.2650	0.2650	37.680	51.234
29.60	10.00	1460.07	2.0160	2.167	0.838	0.131	1.4910	0.4900	41.408	53.497

RUDDER DYNAMOMETER eamj3v1.skg 2100rpm 10m/s J=0.36 Skeg=-5.0

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-40.40	10.00	2116.82	-4.2800	-4.702	2.226	-0.126	-2.7930	1.4760	38.062	48.069
-30.40	10.00	2116.43	-3.6350	-3.844	1.399	0.065	-2.3900	0.9570	33.687	48.733
-20.40	10.00	2116.34	-2.7450	-2.765	0.552	0.255	-1.7430	0.3780	26.159	46.353
-10.40	10.00	2116.62	-1.3940	-1.403	0.175	0.211	-0.8240	0.1430	20.366	42.135
-5.40	10.00	2116.38	-0.6460	-0.656	0.135	0.180	-0.3650	0.0990	7.866	39.367
-0.40	10.00	2117.26	0.0080	0.007	0.104	0.122	0.0900	0.0500	1712.130	1209.462
9.60	10.00	2116.57	1.3810	1.407	0.273	0.059	1.0380	0.1560	39.545	57.087
19.60	10.00	2117.04	2.6070	2.673	0.648	0.029	1.9540	0.4150	36.472	56.591
29.60	10.00	2116.44	3.7290	3.961	1.455	0.217	2.7780	0.9580	40.858	55.423

RUDDER DYNAMOMETER eapj1v1.skg 800rpm 10m/s J=0.94 Skeg=+5.0

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-30.40	10.00	805.19	-0.9890	-1.082	0.452	-0.033	-0.7120	0.2170	38.434	49.387
-20.40	10.00	803.38	-0.7490	-0.809	0.308	-0.004	-0.5250	0.1330	35.929	49.006
-10.40	10.00	804.32	-0.4670	-0.477	0.098	-0.001	-0.3180	0.0390	35.609	49.431
-0.40	10.00	803.52	0.1010	0.100	0.157	-0.008	-0.0030	0.0510	27.283	-20.728
4.60	10.00	802.71	0.2210	0.225	0.057	-0.033	0.1260	0.0390	20.608	39.768
9.60	10.00	806.84	0.5580	0.581	0.186	-0.028	0.3020	0.0750	30.539	35.841
19.60	10.00	804.87	0.9210	0.957	0.268	-0.018	0.5640	0.1580	33.493	43.487
29.60	10.00	804.70	1.0540	1.118	0.408	0.007	0.6910	0.2630	36.003	47.850
39.60	10.00	805.67	1.0550	1.284	0.740	0.075	0.6060	0.4470	41.260	41.020

RUDDER DYNAMOMETER eapj2v1.skg 1460rpm 10m/s J=0.51 Skeg=+5.0

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-30.40	10.00	1459.97	-2.2720	-2.392	0.855	-0.049	-1.4520	0.5220	37.429	45.914
-20.40	10.00	1460.38	-1.7150	-1.770	0.465	0.025	-1.1240	0.2890	33.971	47.708
-10.40	10.00	1460.24	-0.9210	-0.932	0.147	0.029	-0.5430	0.0850	32.286	41.469
-0.40	10.00	1460.37	-0.0160	-0.017	0.103	0.001	0.0290	0.0530	30.050	-187.847
4.60	10.00	1460.05	0.4440	0.453	0.126	-0.022	0.3340	0.0430	30.416	56.766
9.60	10.00	1460.33	0.8390	0.854	0.156	-0.051	0.6320	0.0970	29.397	57.389
19.60	10.00	1460.30	1.7550	1.810	0.466	-0.038	1.2450	0.2900	33.294	52.700
29.60	10.00	1460.03	2.2560	2.368	0.822	0.058	1.6780	0.5800	37.816	56.216
39.60	10.00	1460.44	2.5020	2.777	1.332	0.162	1.8530	0.9220	41.228	55.087

RUDDER DYNAMOMETER eapj3v1.skg 2100rpm 10m/s J=0.36 Skeg=+5.0

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-30.40	10.00	2116.71	-3.8070	-3.937	1.291	0.041	-2.4510	0.8740	34.329	47.428
-20.40	10.00	2117.29	-2.6830	-2.735	0.634	0.110	-1.7230	0.4310	31.351	47.038
-10.40	10.00	2117.03	-1.3520	-1.374	0.247	0.078	-0.8090	0.1170	29.721	41.912
-0.40	10.00	2116.91	-0.0830	-0.084	0.080	-0.009	0.0910	0.0400	46.543	-125.254
4.60	10.00	2116.35	0.6120	0.620	0.128	-0.040	0.5600	0.0600	28.989	73.195
9.60	10.00	2116.08	1.2550	1.276	0.228	-0.066	1.0210	0.1440	30.191	63.314
19.60	10.00	2116.55	2.4700	2.518	0.572	-0.102	1.9240	0.4130	31.337	59.971
29.60	10.00	2116.51	3.7470	3.875	1.248	-0.012	2.8800	0.9220	35.069	58.891
39.60	10.00	2117.23	3.7350	4.324	2.269	0.275	2.8950	1.7000	41.732	59.127

APPENDIX B Propeller Dynamometer

PROPELLER pblj110.pro 800 rpm 10m/s J=0.94 Skeg=0.0

Angle	V	RPM	J	Kt	Kq	n	Kt/J2	Kq/J2
-0.40	10.00	810.91	0.9249	0.071	0.023	0.456	0.0828	0.1035
-10.40	10.00	810.09	0.9258	0.051	0.014	0.552	0.0592	0.0739
-20.40	10.00	809.92	0.9260	-0.032	0.020	-1.000	-0.0379	-0.0473
-25.40	10.00	809.68	0.9263	-0.002	0.018	-1.000	-0.0024	-0.0030
-30.40	10.00	809.36	0.9267	-0.021	0.022	-1.000	-0.0248	-0.0311
-35.40	10.00	809.76	0.9262	0.005	0.023	0.033	0.0059	0.0074
9.60	10.00	808.43	0.9277	-0.007	0.020	-1.000	-0.0083	-0.0104
24.60	10.00	808.74	0.9274	-0.018	0.016	-1.000	-0.0213	-0.0266
29.60	10.00	809.24	0.9268	-0.045	0.013	-1.000	-0.0521	-0.0651
34.60	10.00	808.71	0.9274	-0.051	0.020	-1.000	-0.0592	-0.0739

PROPELLER pblj210.pro 1460rpm 10m/s J=0.51 Skeg=0.0

Angle	V	RPM	J	Kt	Kq	n	Kt/J2	Kq/J2
-0.40	10.00	1466.39	0.5115	0.258	0.044	0.473	0.9856	1.2320
-10.40	10.00	1465.75	0.5117	0.235	0.046	0.420	0.8957	1.1196
-20.40	10.00	1464.39	0.5122	0.259	0.047	0.448	0.9856	1.2320
-25.40	10.00	1464.34	0.5122	0.261	0.046	0.459	0.9950	1.2438
-30.40	10.00	1465.30	0.5118	0.238	0.044	0.438	0.9075	1.1344
-35.40	10.00	1464.77	0.5120	0.252	0.047	0.436	0.9595	1.1994
9.60	10.00	1464.65	0.5121	0.242	0.045	0.437	0.9229	1.1536
19.60	10.00	1464.65	0.5121	0.231	0.042	0.449	0.8826	1.1033
24.60	10.00	1465.29	0.5118	0.229	0.045	0.419	0.8755	1.0944
29.60	10.00	1465.56	0.5117	0.239	0.044	0.443	0.9122	1.1403
34.60	10.00	1464.35	0.5122	0.229	0.045	0.416	0.8720	1.0900

PROPELLER pblj310.pro 2100rpm 10m/s J=0.36 Skeg=0.0

Angle	V	RPM	J	Kt	Kq	n	Kt/J2	Kq/J2
-0.40	10.00	2187.97	0.3428	0.311	0.049	0.344	2.6467	3.3084
-0.40	10.00	2187.97	0.3428	0.329	0.050	0.360	2.8005	3.5007
-10.40	10.00	2185.27	0.3432	0.321	0.051	0.341	2.7213	3.4016
-20.40	10.00	2185.07	0.3432	0.328	0.051	0.349	2.7804	3.4755
-25.40	10.00	2185.58	0.3432	0.322	0.050	0.348	2.7319	3.4149
-30.40	10.00	2185.33	0.3432	0.327	0.051	0.348	2.7792	3.4741
-35.40	10.00	2185.12	0.3432	0.317	0.052	0.335	2.6929	3.3661
9.60	10.00	2184.87	0.3433	0.323	0.051	0.346	2.7390	3.4238
19.60	10.00	2185.14	0.3432	0.319	0.052	0.334	2.7071	3.3838
24.60	10.00	2185.39	0.3432	0.331	0.052	0.346	2.8135	3.5169
29.60	10.00	2185.55	0.3432	0.327	0.052	0.344	2.7745	3.4681
34.60	10.00	2184.99	0.3433	0.308	0.050	0.340	2.6136	3.2670

PROPELLER pblj410.pro 2850rpm 10m/s J=0.26 Skeg=0.0

Angle	V	RPM	J	Kt	Kq	n	Kt/J2	Kq/J2
-0.40	10.00	2894.13	0.2591	0.342	0.054	0.263	5.0982	6.3728
-10.40	10.00	2892.41	0.2593	0.345	0.055	0.259	5.1254	6.4068
-20.40	10.00	2894.30	0.2591	0.343	0.054	0.262	5.1006	6.3757
-25.40	10.00	2892.98	0.2592	0.347	0.054	0.264	5.1680	6.4601
-30.40	10.00	2894.55	0.2591	0.355	0.055	0.266	5.2804	6.6006
-35.40	10.00	2891.14	0.2594	0.361	0.055	0.270	5.3621	6.7026
9.60	10.00	2891.71	0.2594	0.347	0.055	0.261	5.1621	6.4527
19.60	10.00	2892.28	0.2593	0.357	0.055	0.266	5.3029	6.6286
24.60	10.00	2893.41	0.2592	0.352	0.055	0.265	5.2378	6.5473
29.60	10.00	2891.64	0.2594	0.343	0.054	0.264	5.1053	6.3817
34.60	10.00	2891.46	0.2594	0.346	0.054	0.265	5.1373	6.4216

Table I Semi-Balanced Skeg Rudder Particulars

Rudder Number	:	0
Mean Chord c mm	:	667
Span S mm	:	1000
Geometric Aspect Ratio AR_G	:	3.0
Taper Ratio C_T/C_R	:	0.80
Thickness/Chord ratio t/c	:	0.20
Section	:	NACA0020 Root and Tip with square ends

Table II Overall Modified Wageningen B4.40 Series Propeller Details

Number of Blades	:	4
Range of revolutions rpm	:	0 to 3,000
Diameter mm	:	800
Boss Diameter (max) mm	:	200
Mean Pitch Ratio	:	0.95 (set for tests)
Blade Area Ratio	:	0.40
Rake (deg)	:	0^o
Blade Thickness Ratio t/D	:	0.050
Section shape	:	Based on Wageningen B series
Blade Outline Shape	:	Based on Wageningen but with reduced skew

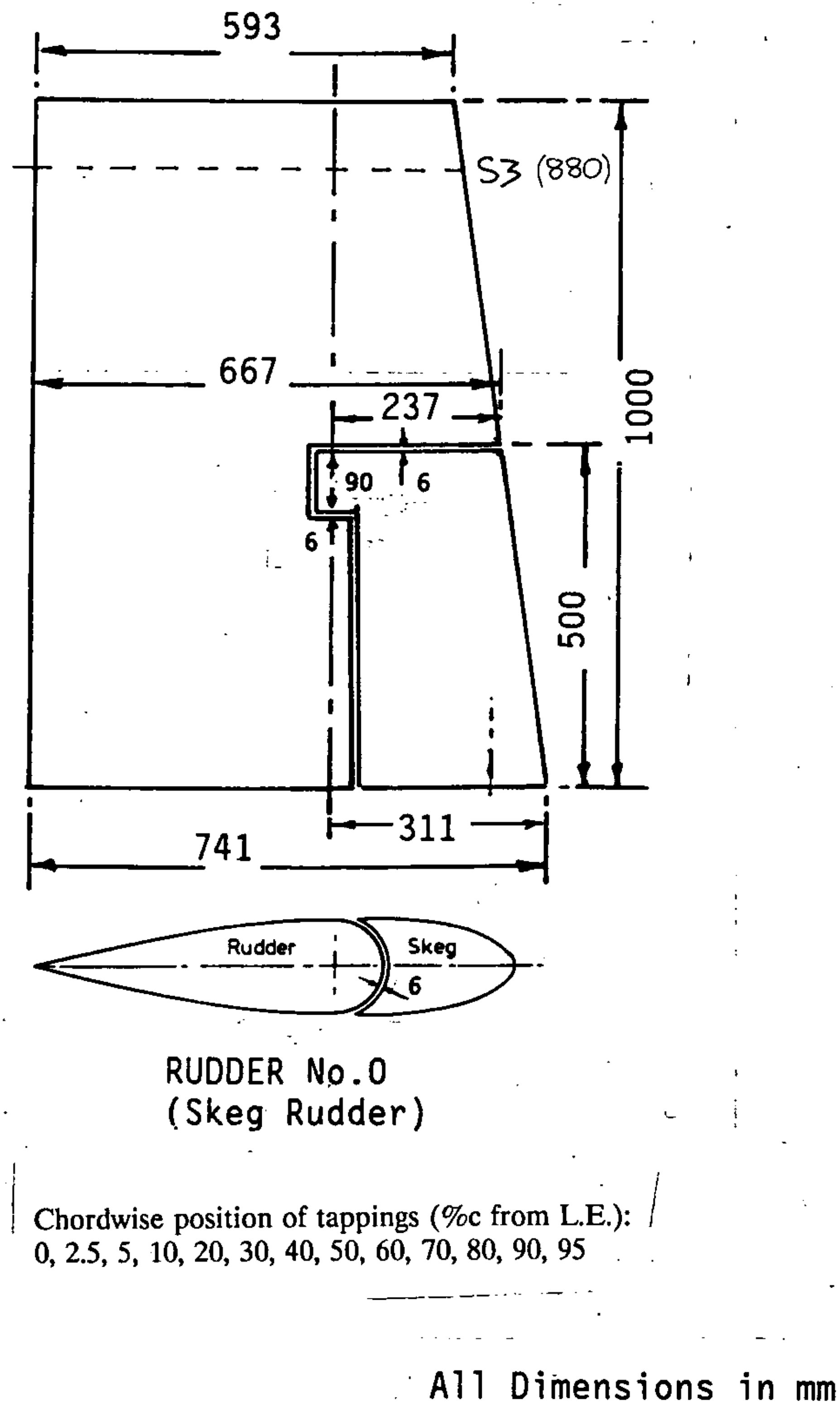


Figure 1 Overall dimensions of model semi-balanced skeg-rudder

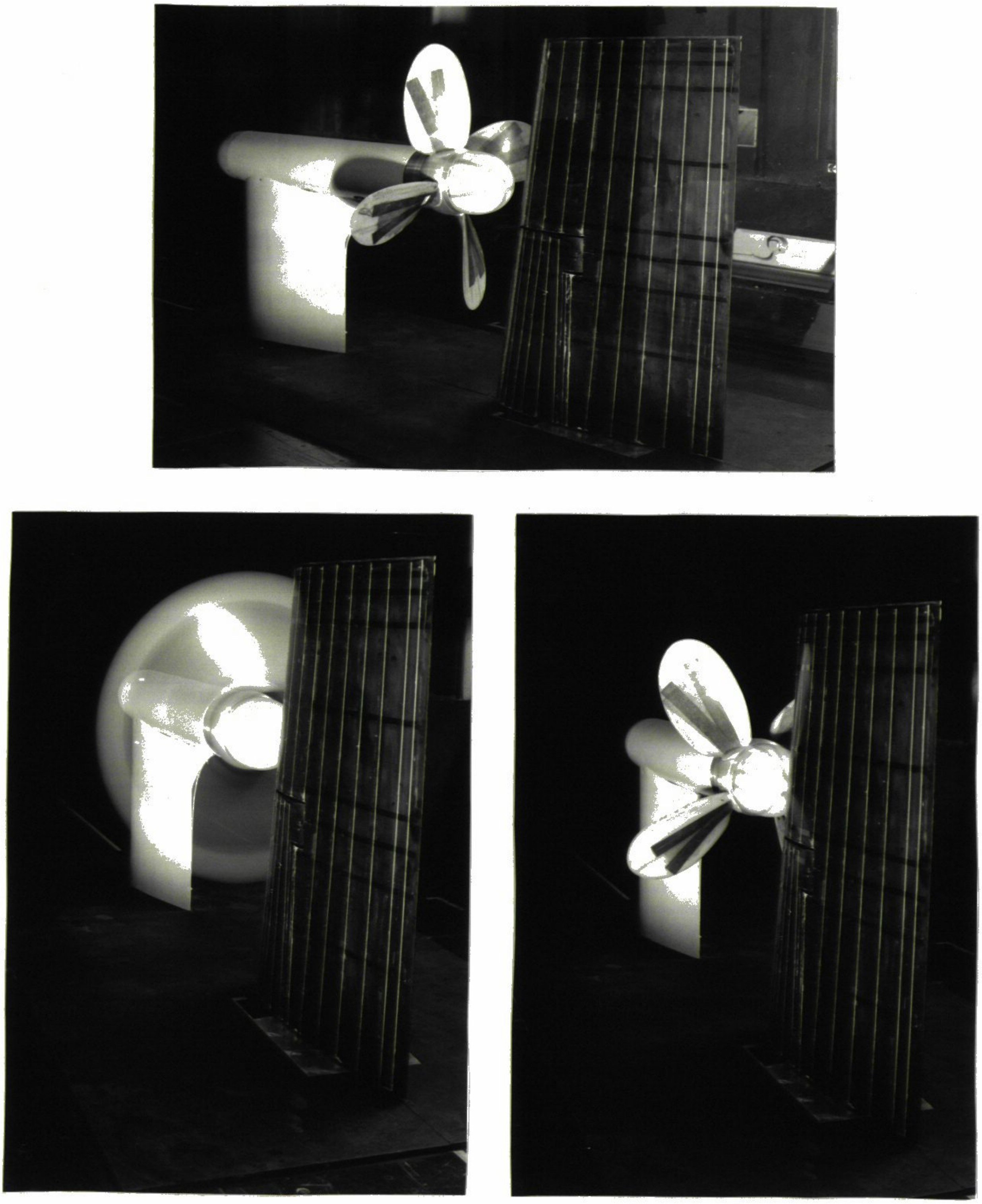


Figure 2 Views of rig overall installed in wind tunnel working section

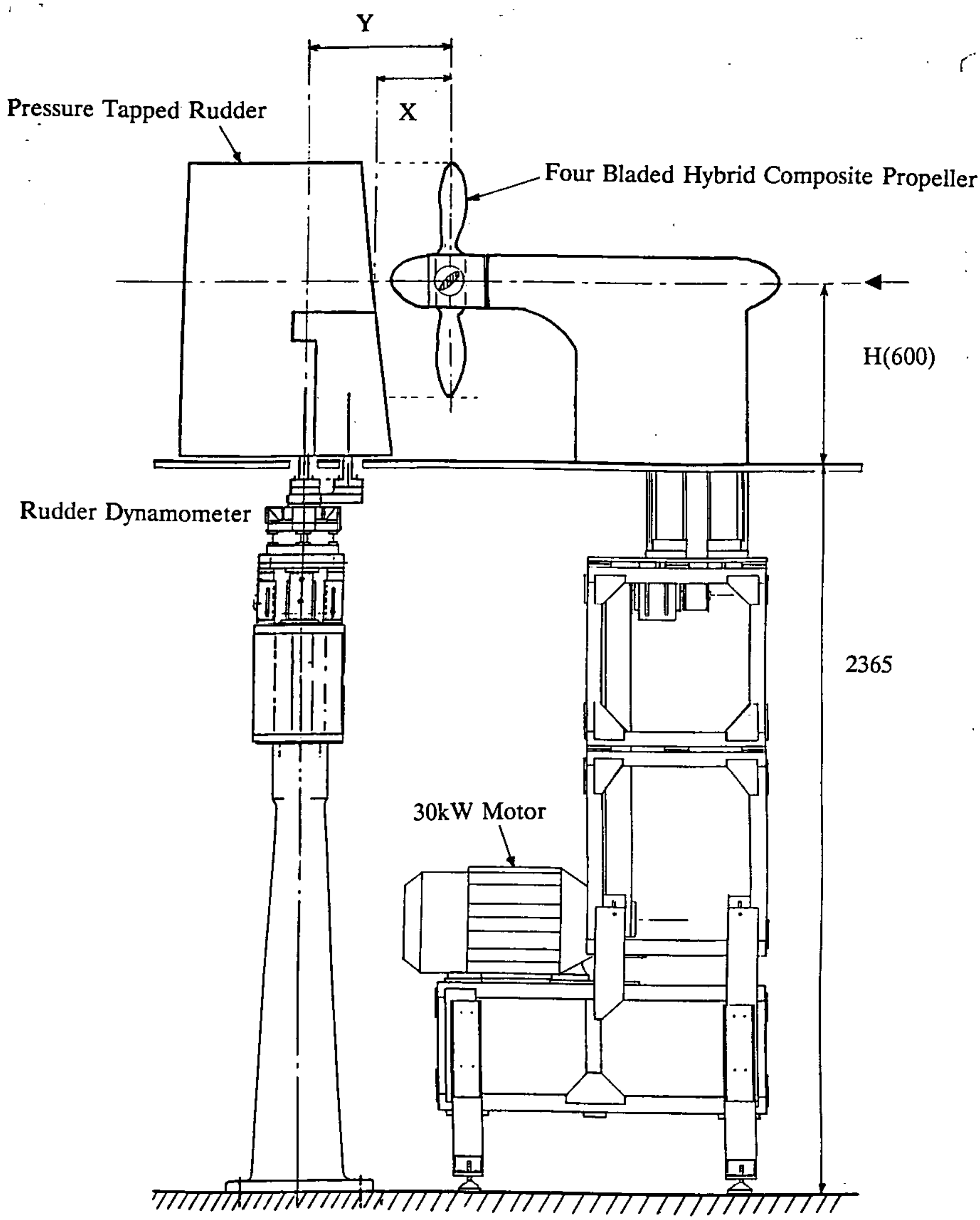


Figure 3 Side view of overall rudder and propeller rigs

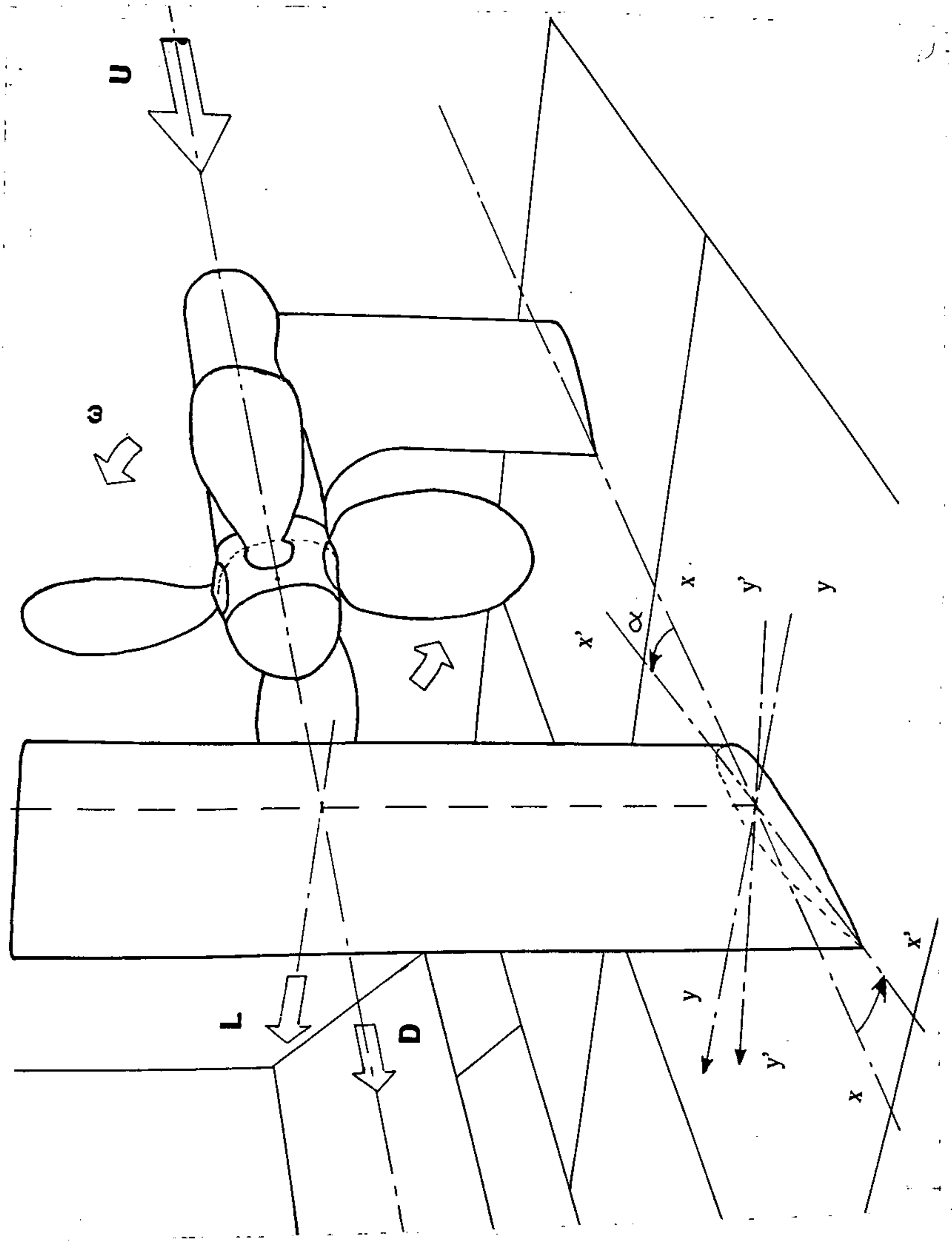


Figure 4 Schematic view of rudder-propeller models

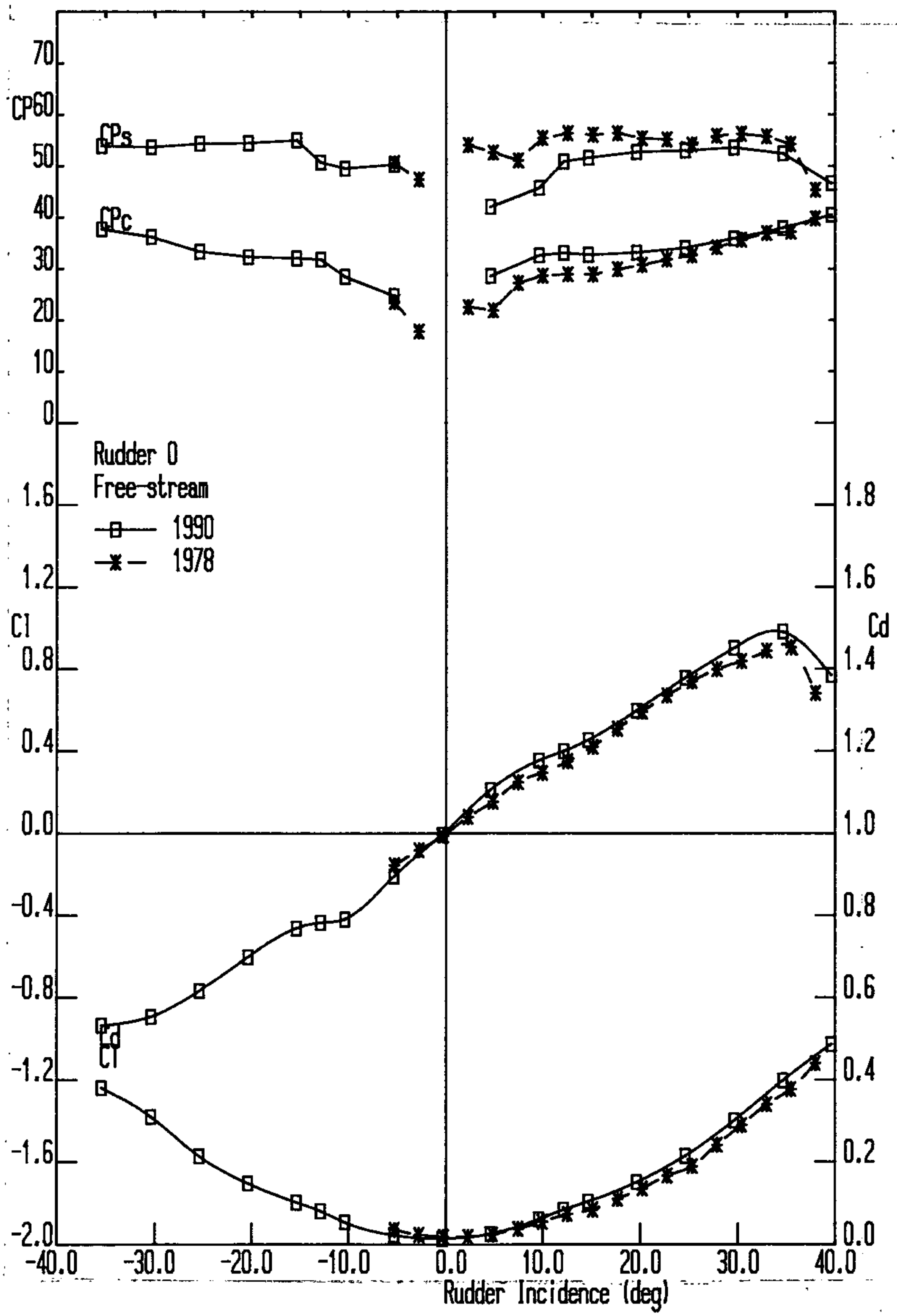


Figure 5. Free-stream semi-balanced skeg-rudder performance: comparison of 1978 and 1990 tests

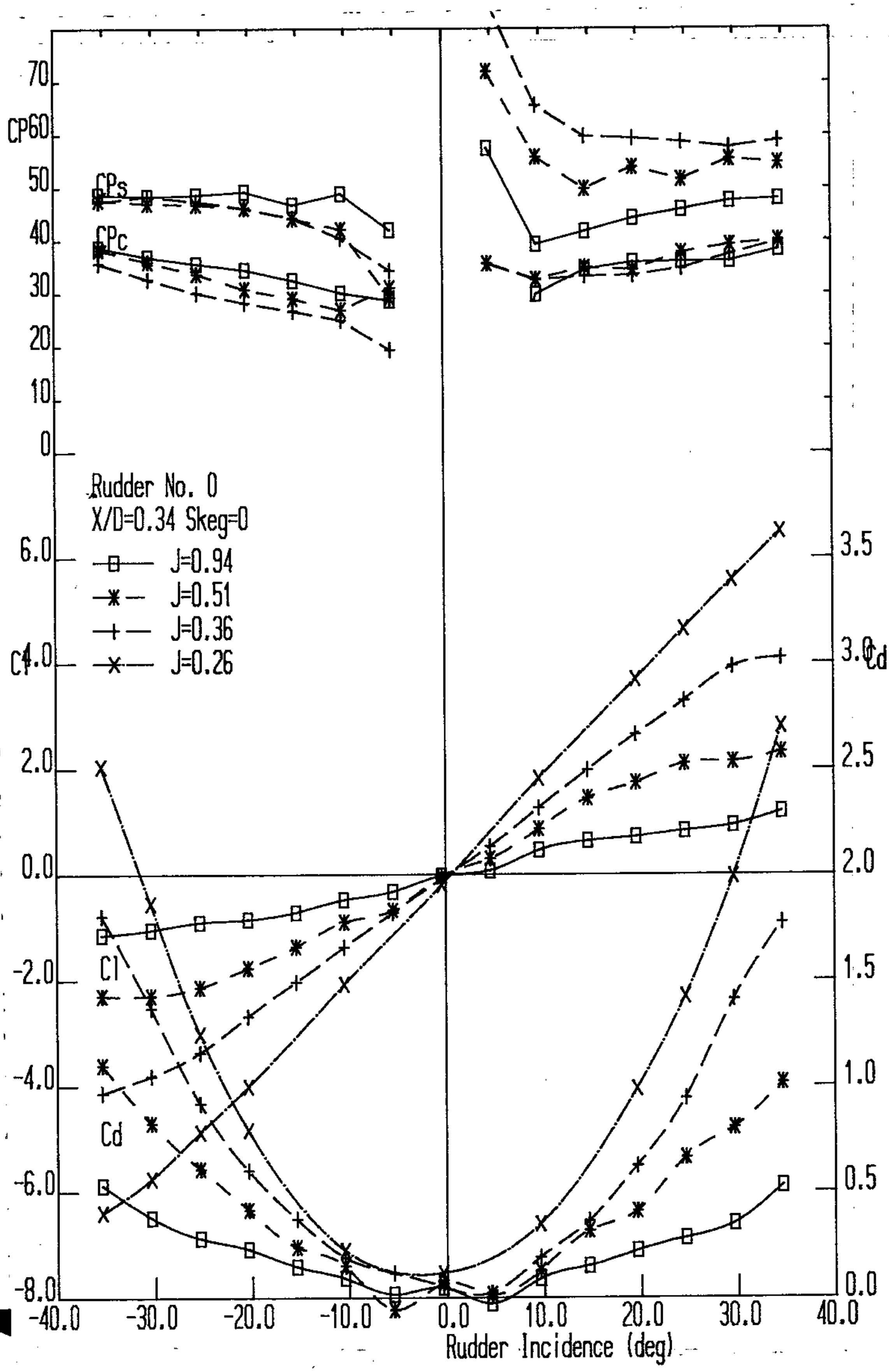


Figure 6 Variation of semi-balanced skeg-rudder performance with thrust loading for a skeg angle of -0.4° at a wind speed of 10m/s

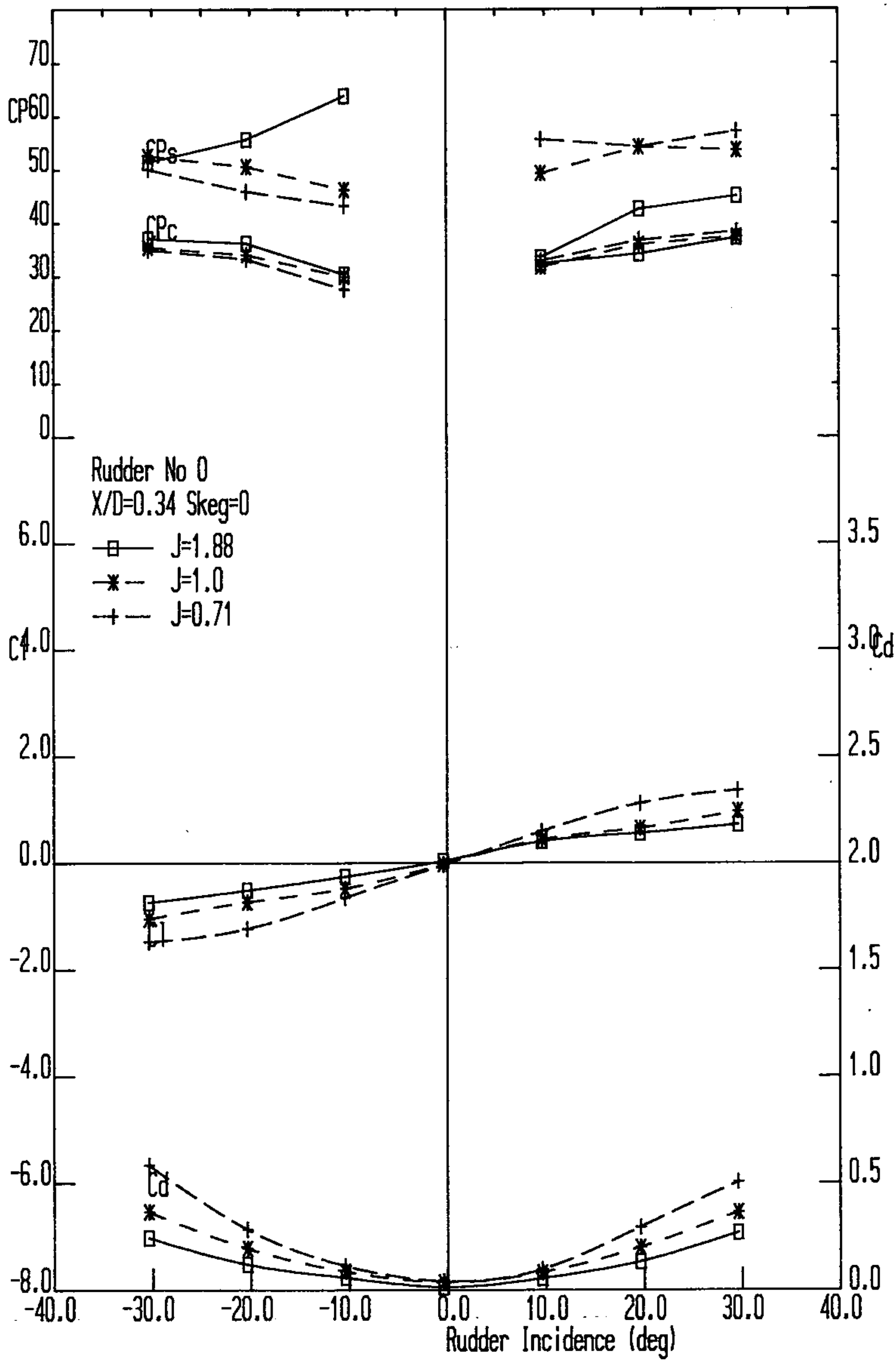


Figure 7 Variation of semi-balanced skeg-rudder performance with thrust loading for a skeg angle of -0.4^{0} at a wind speed of 20m/s

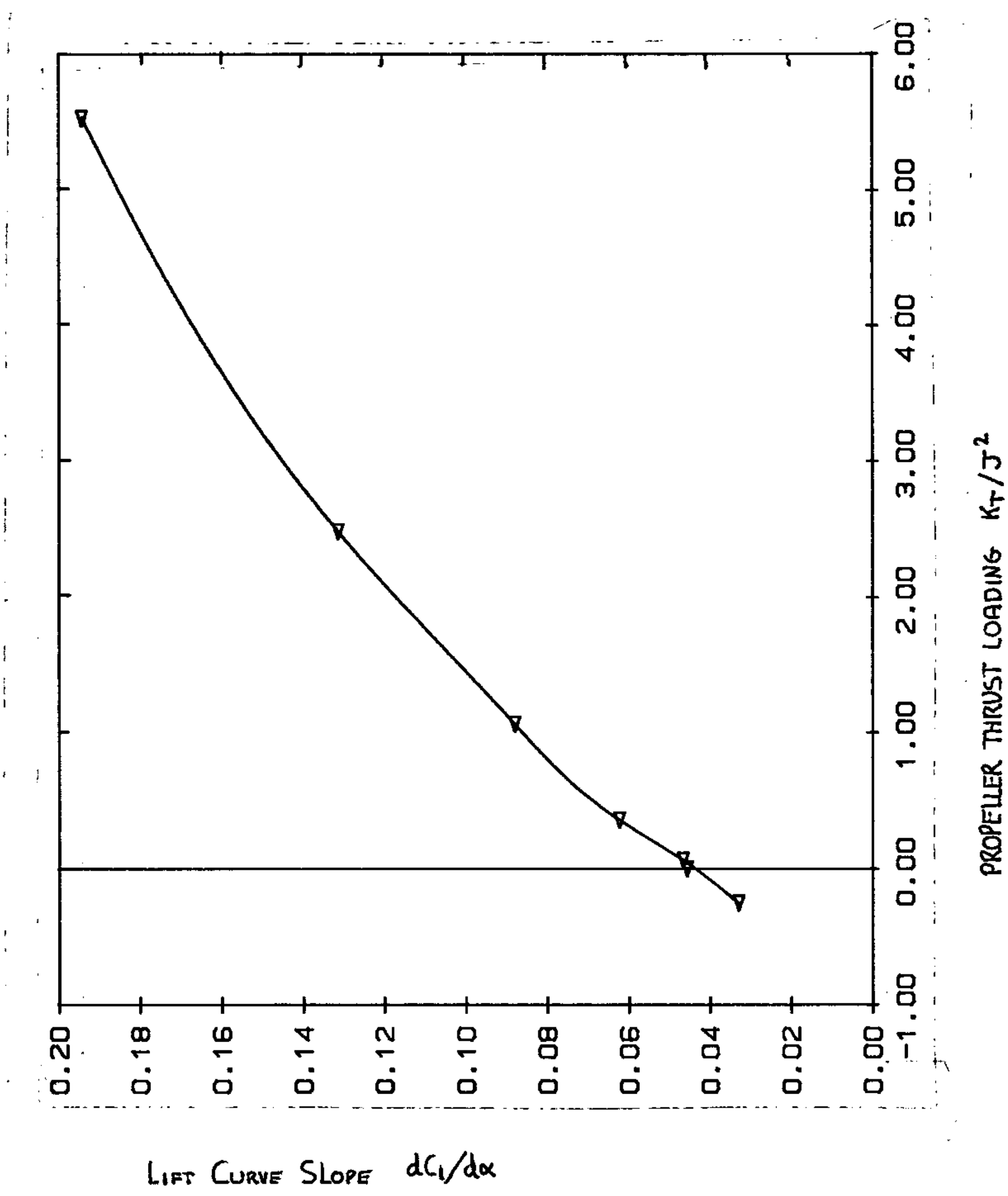


Figure 8 Influence of propeller thrust loading on rudder lift-curve slope

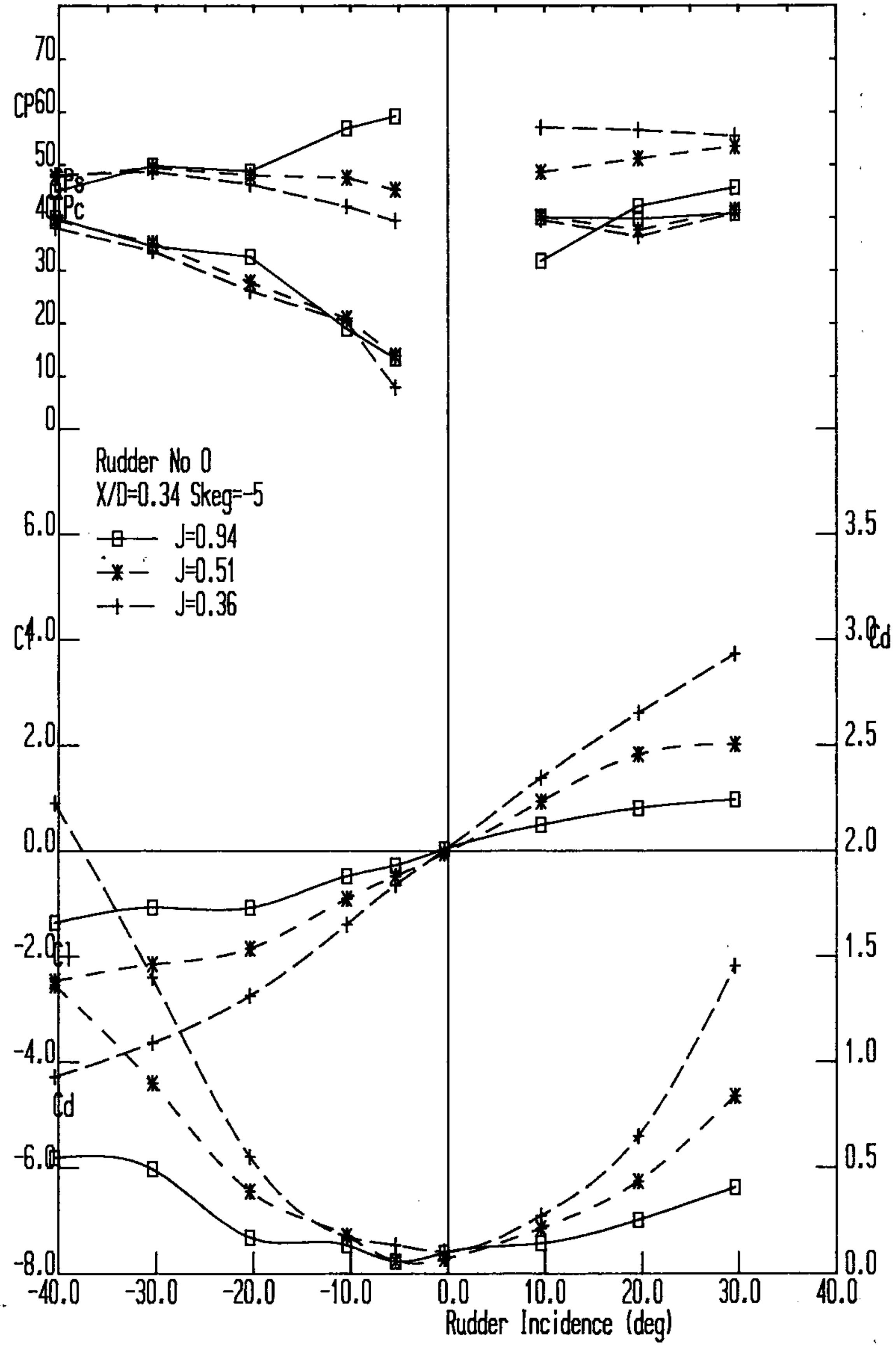


Figure 9 Variation of semi-balanced skeg-rudder performance with thrust loading for a skeg angle of -5.40° at a wind speed of 10m/s

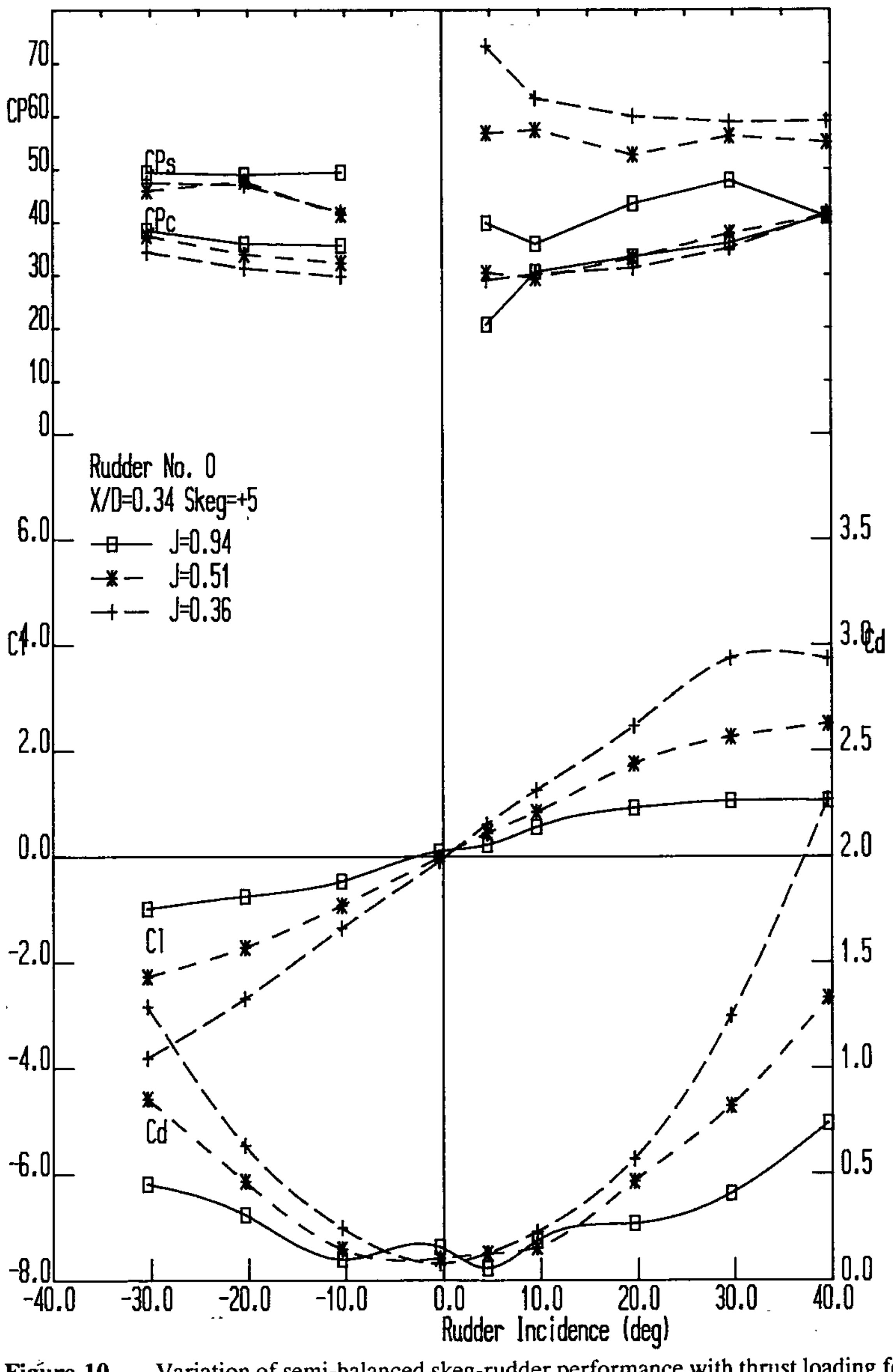


Figure 10 Variation of semi-balanced skeg-rudder performance with thrust loading for a skeg angle of $+4.6^{\circ}$ at a wind speed of 10m/s

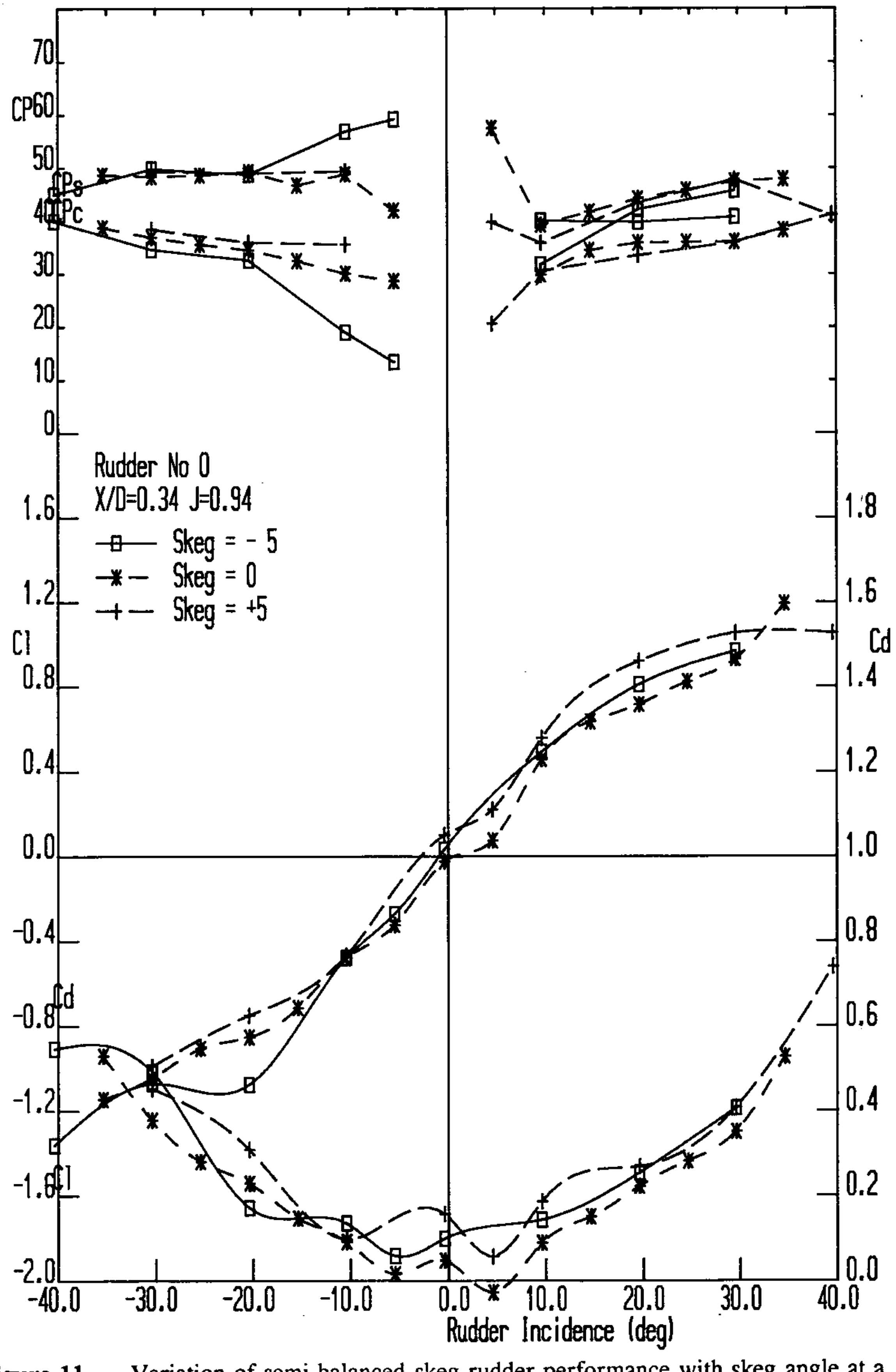


Figure 11 Variation of semi-balanced skeg rudder performance with skeg angle at a propeller advance ratio of 0.94

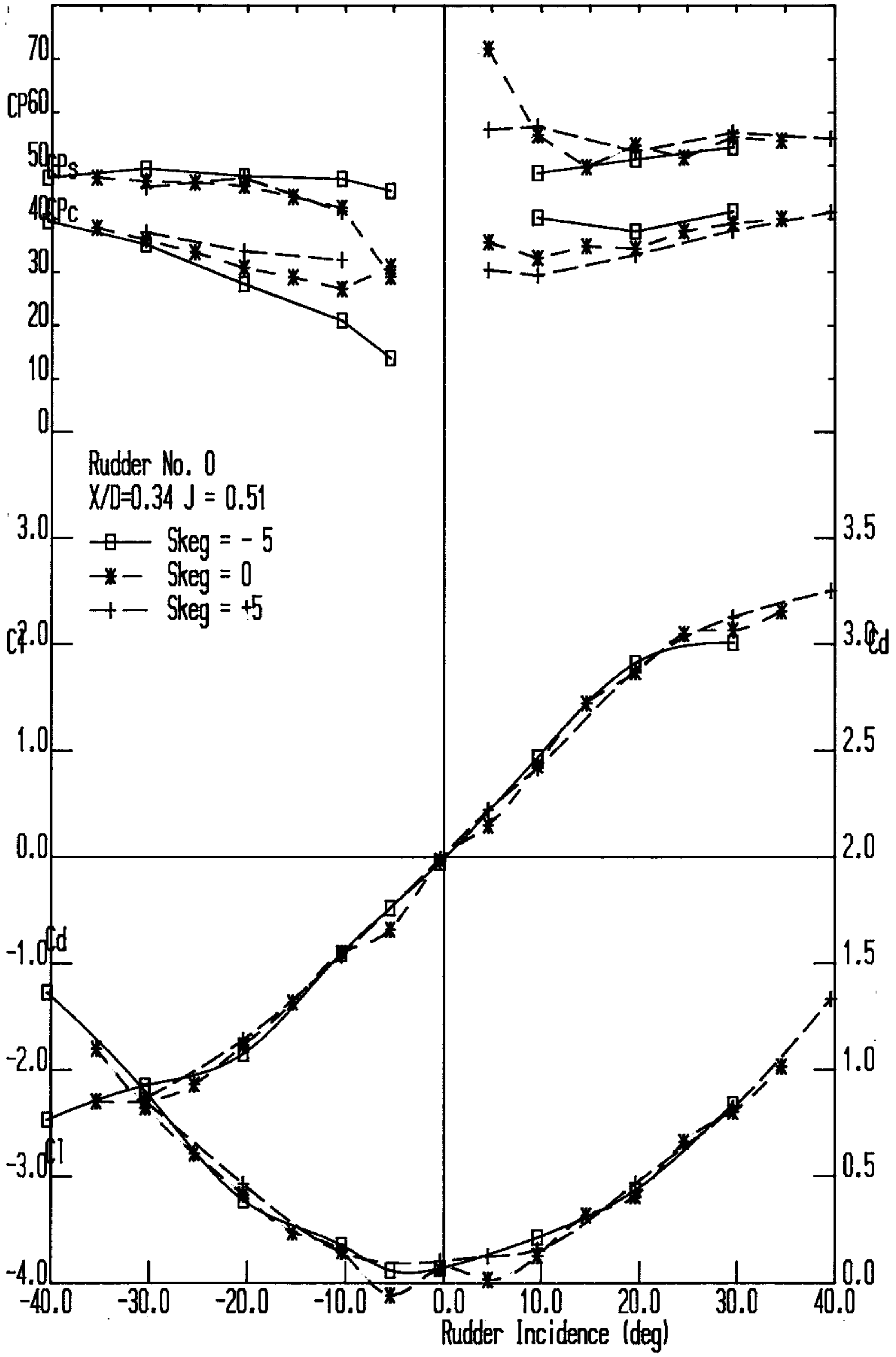


Figure 12 Variation of semi-balanced skeg rudder performance with skeg angle at a propeller advance ratio of 0.51

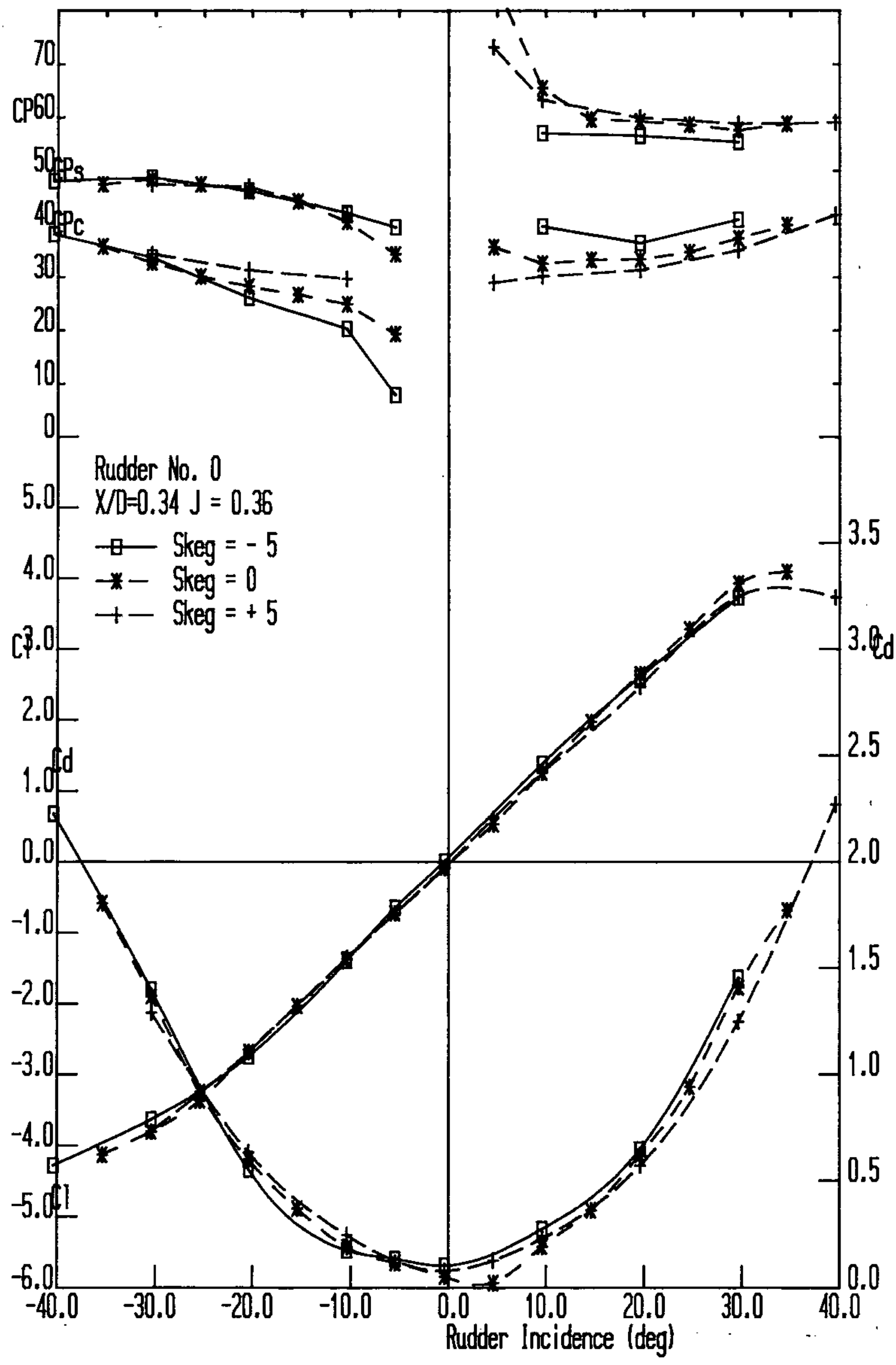


Figure 13 Variation of semi-balanced skeg rudder performance with skeg angle at a propeller advance ratio of 0.35

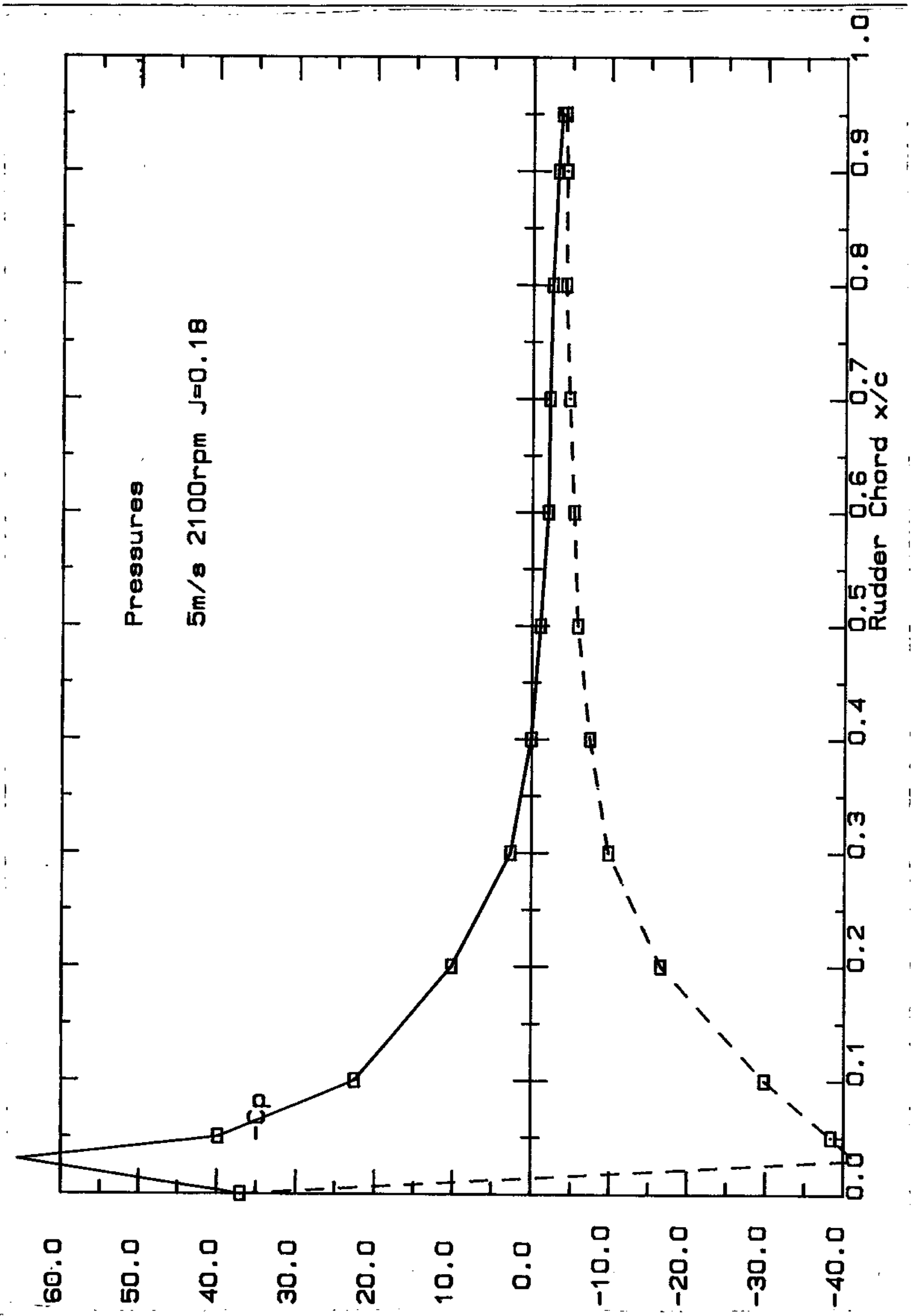


Figure 14 Chordwise pressure distributions for 13 thrust loadings between J=0.18 and J=1.88

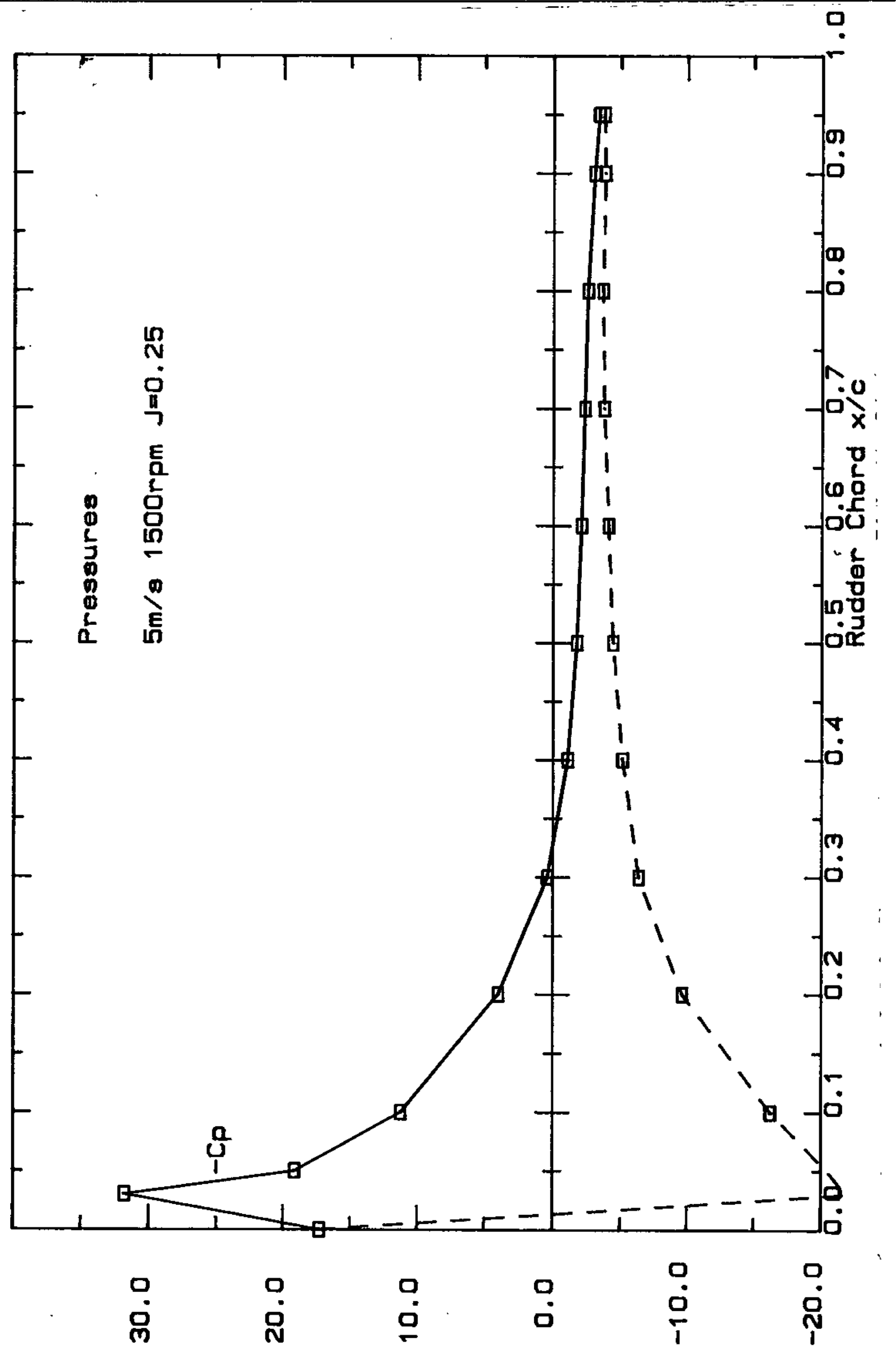
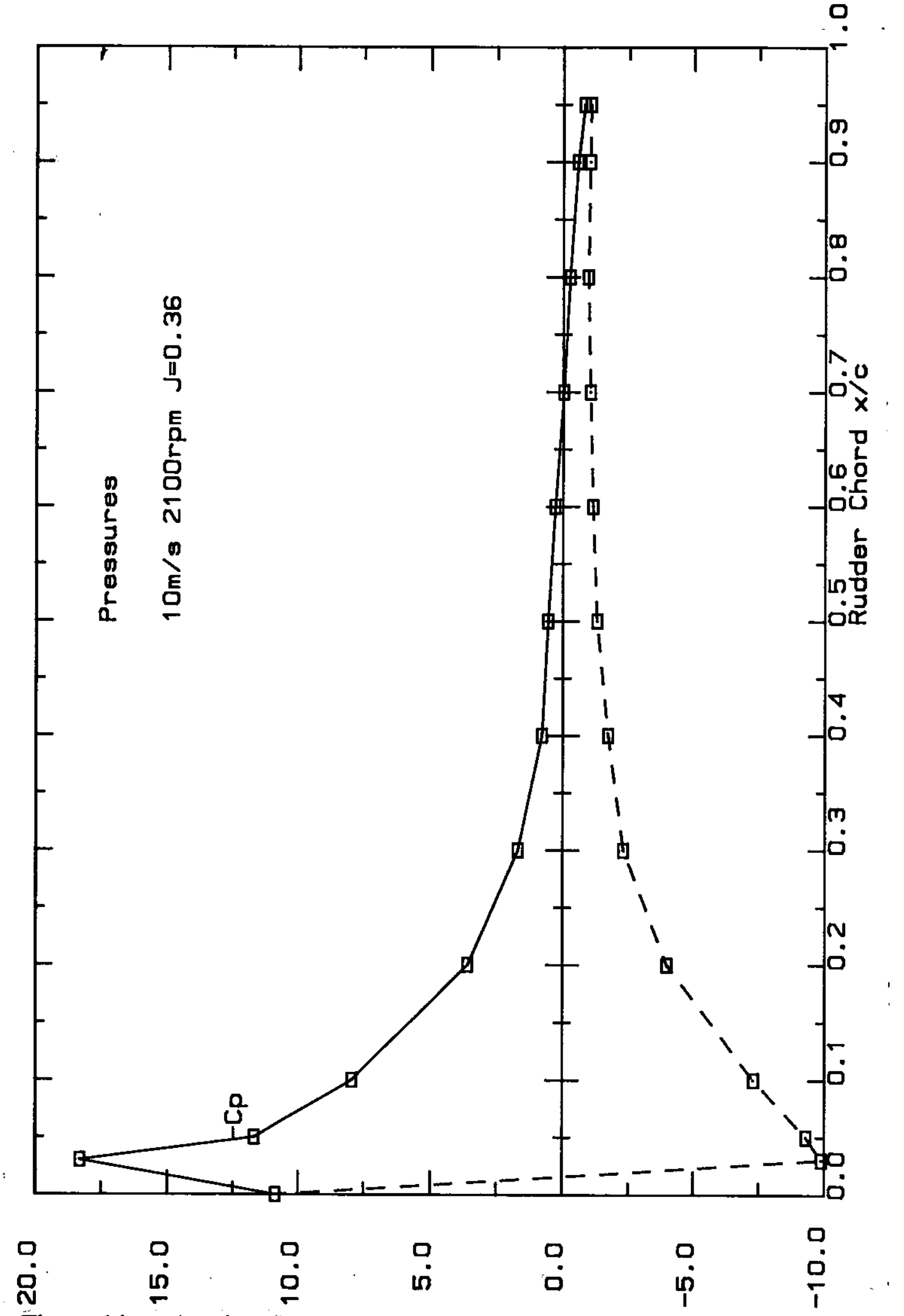


Figure 14 (continued)



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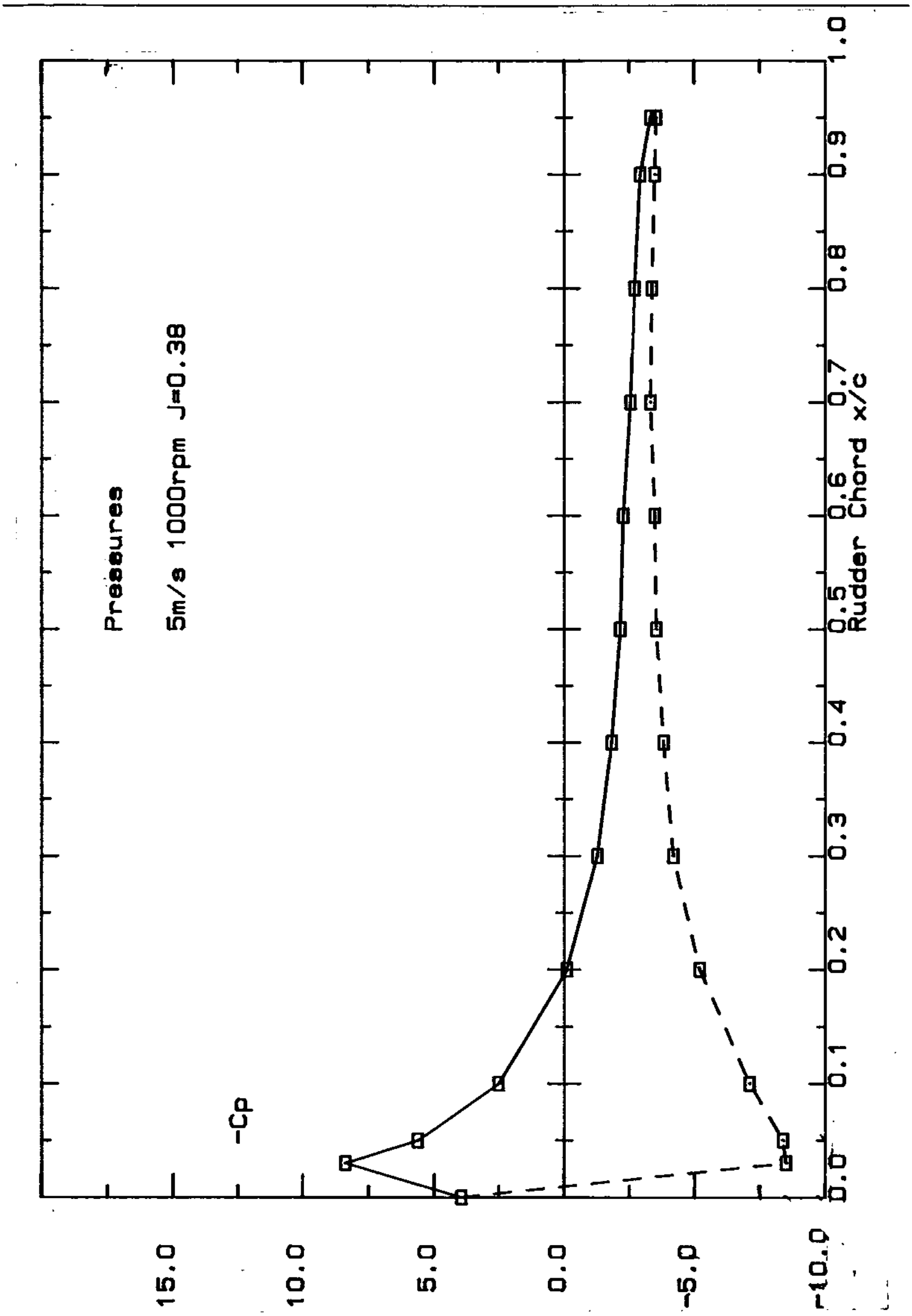

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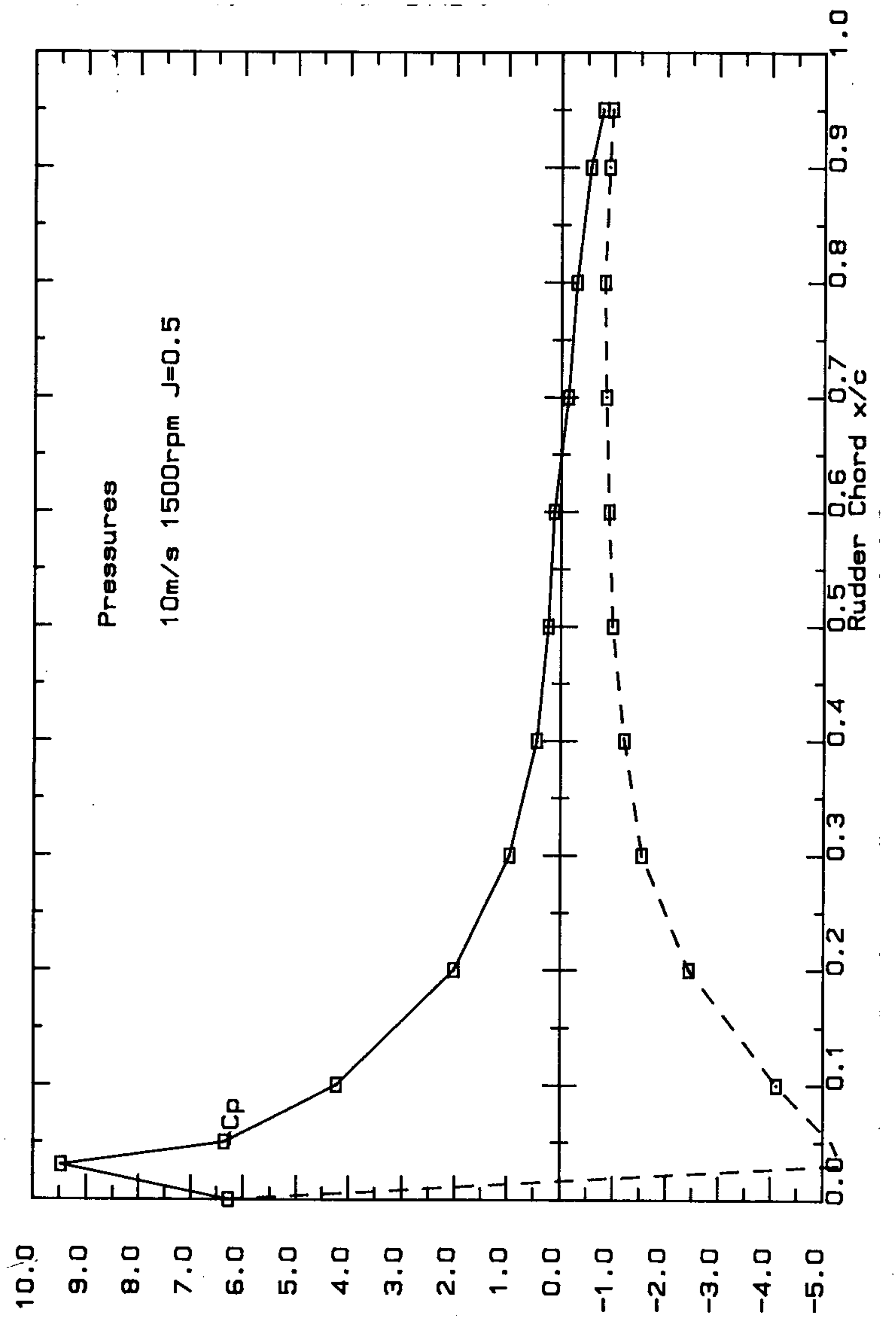

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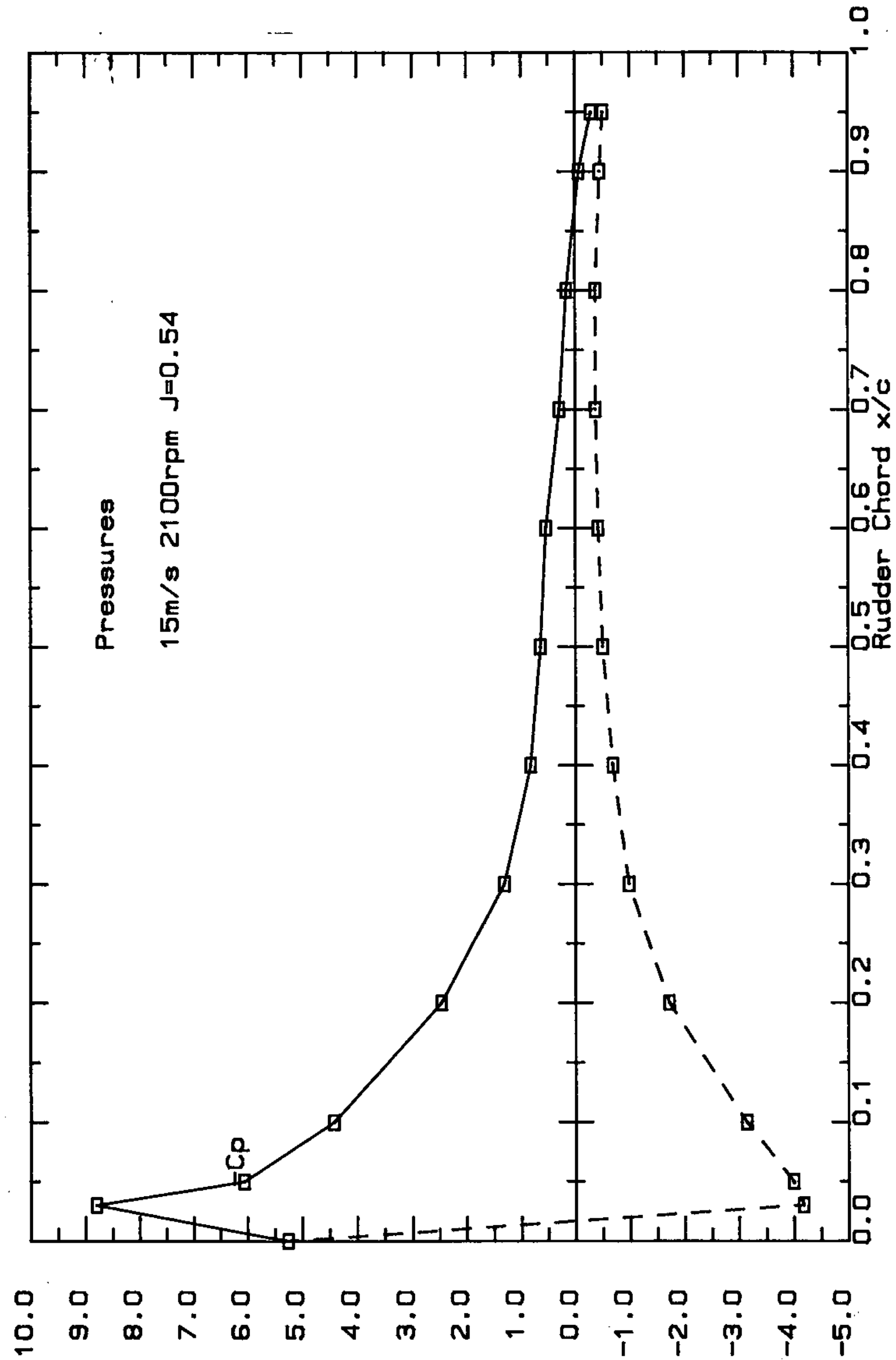

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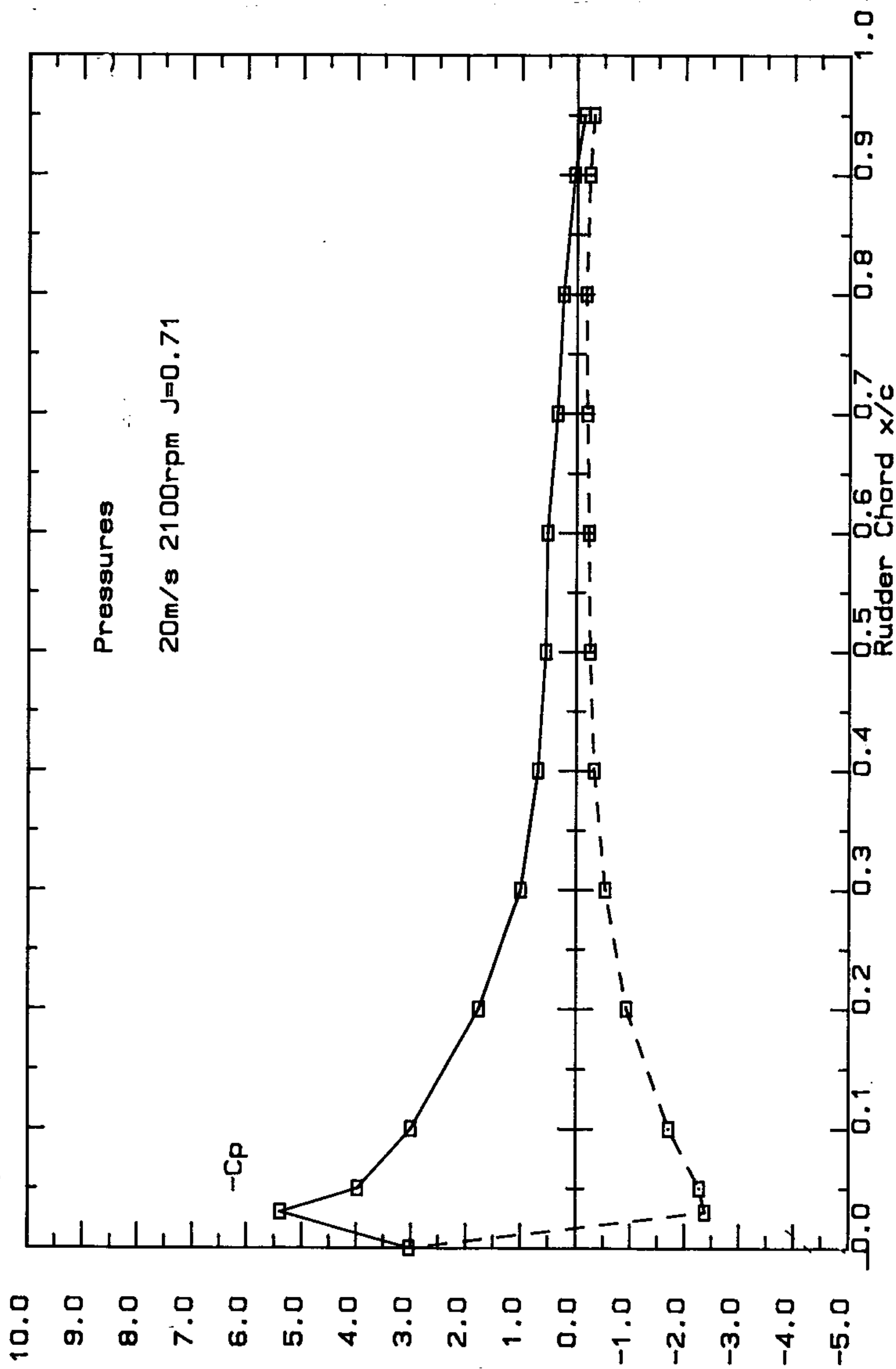

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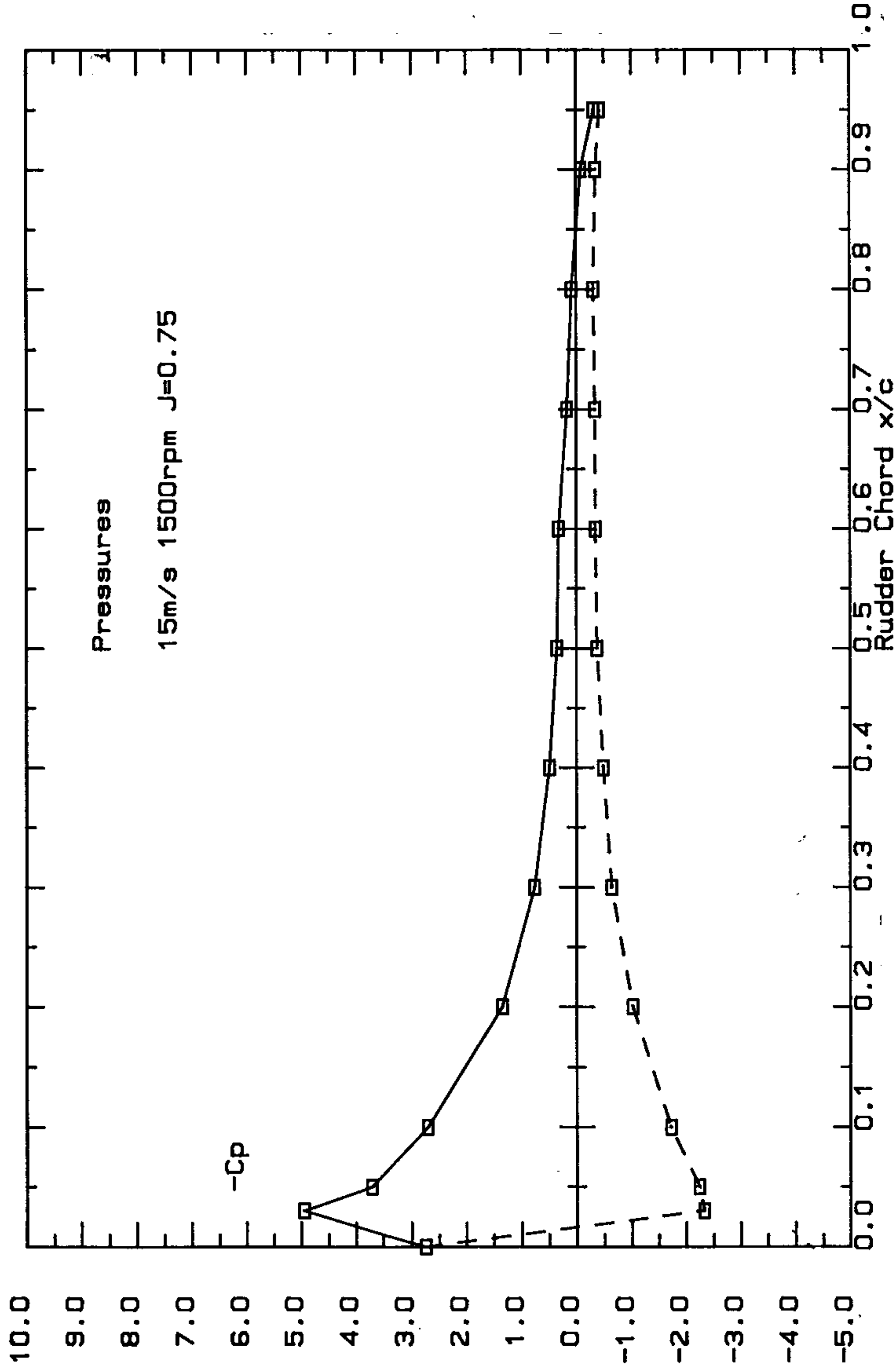

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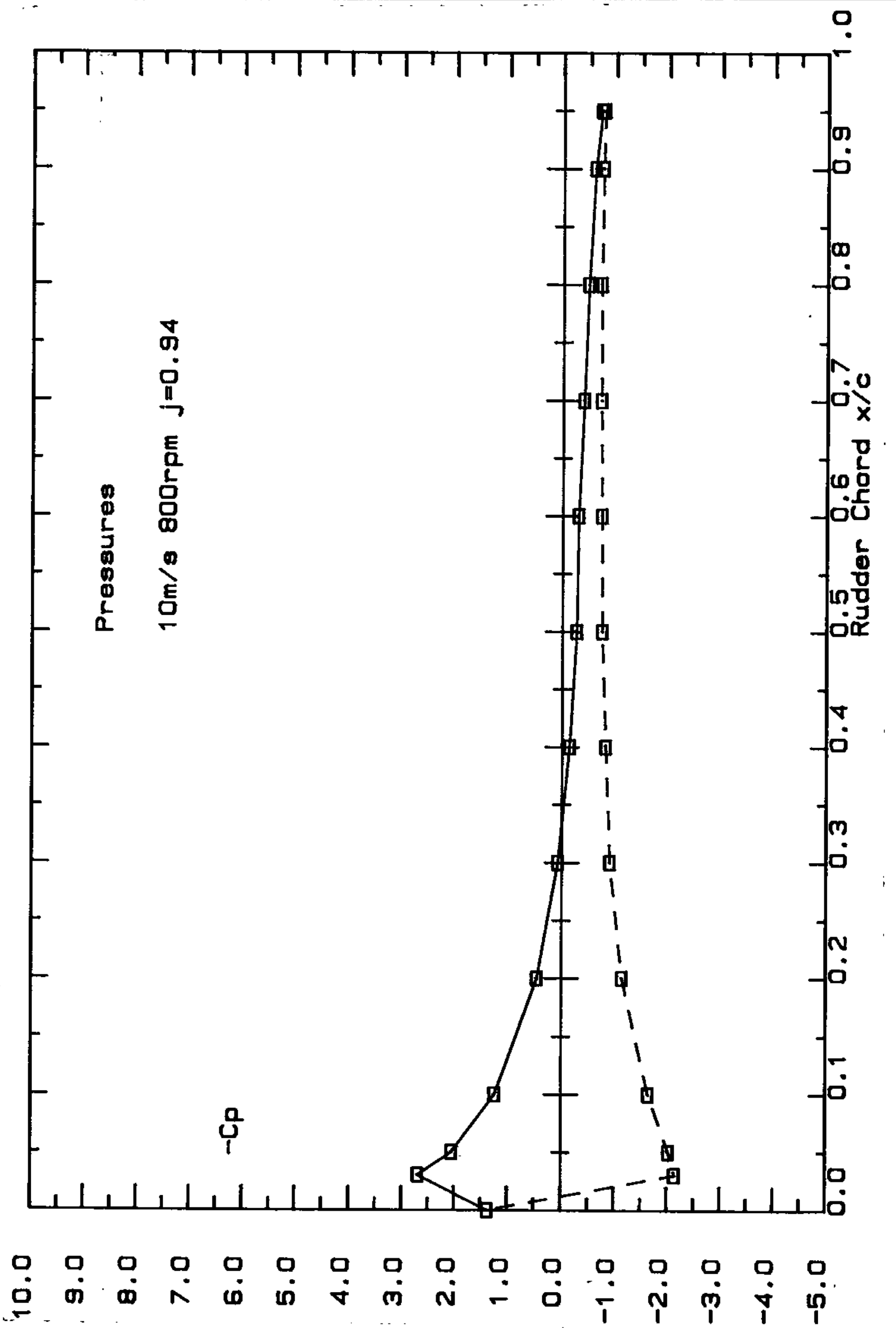

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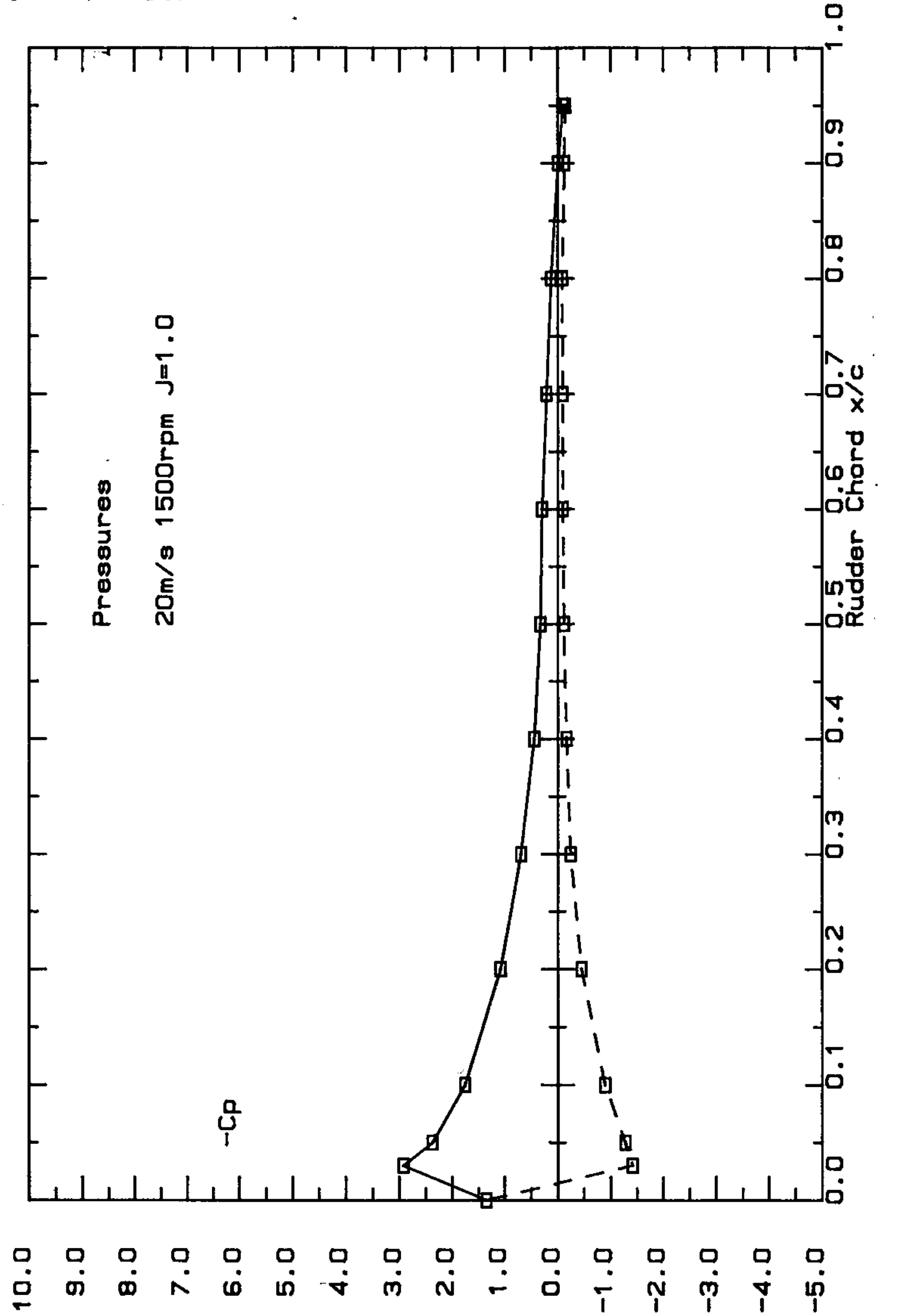

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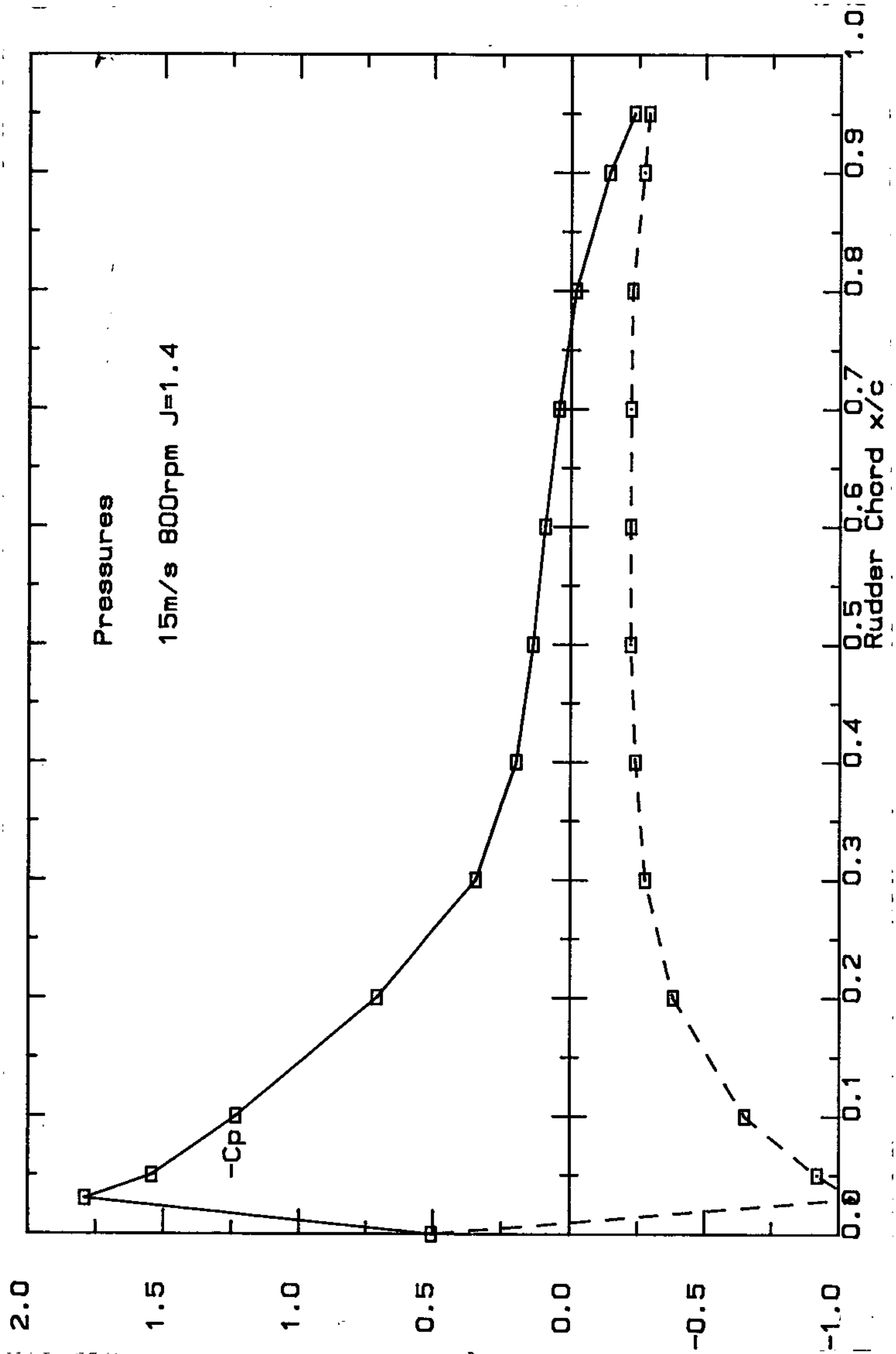

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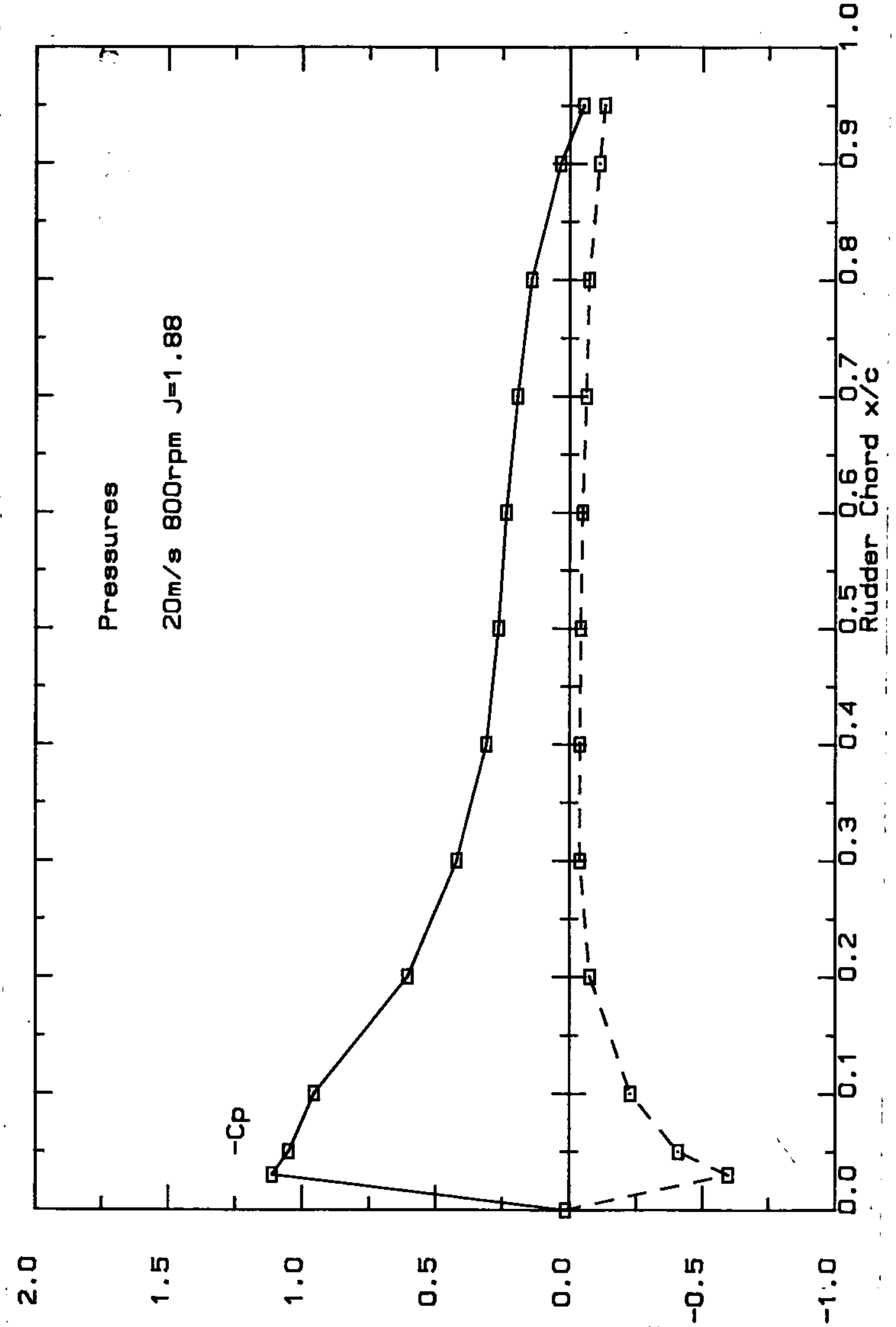

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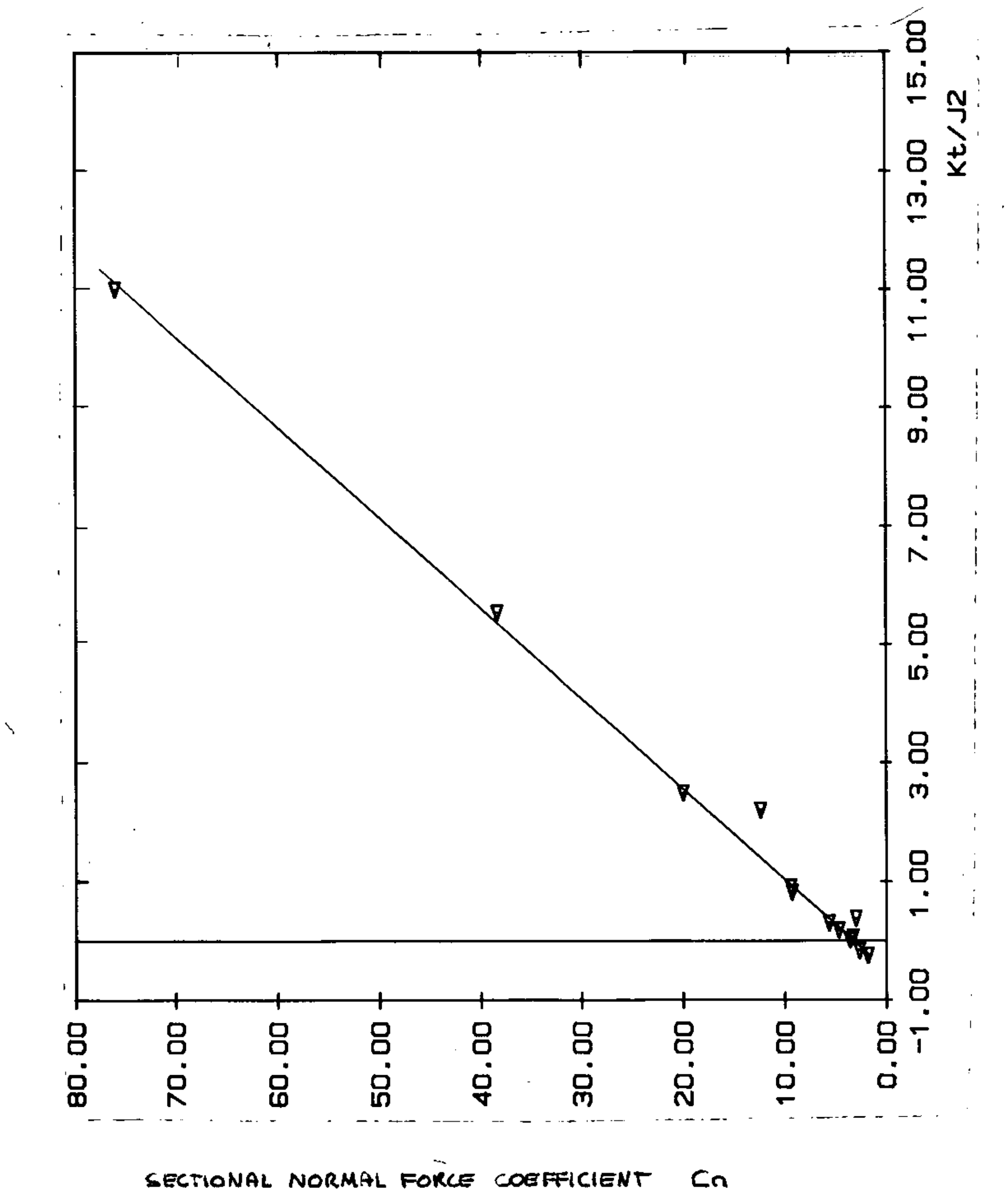


Figure 15 Effect of propeller thrust loading on local Cn at span S3

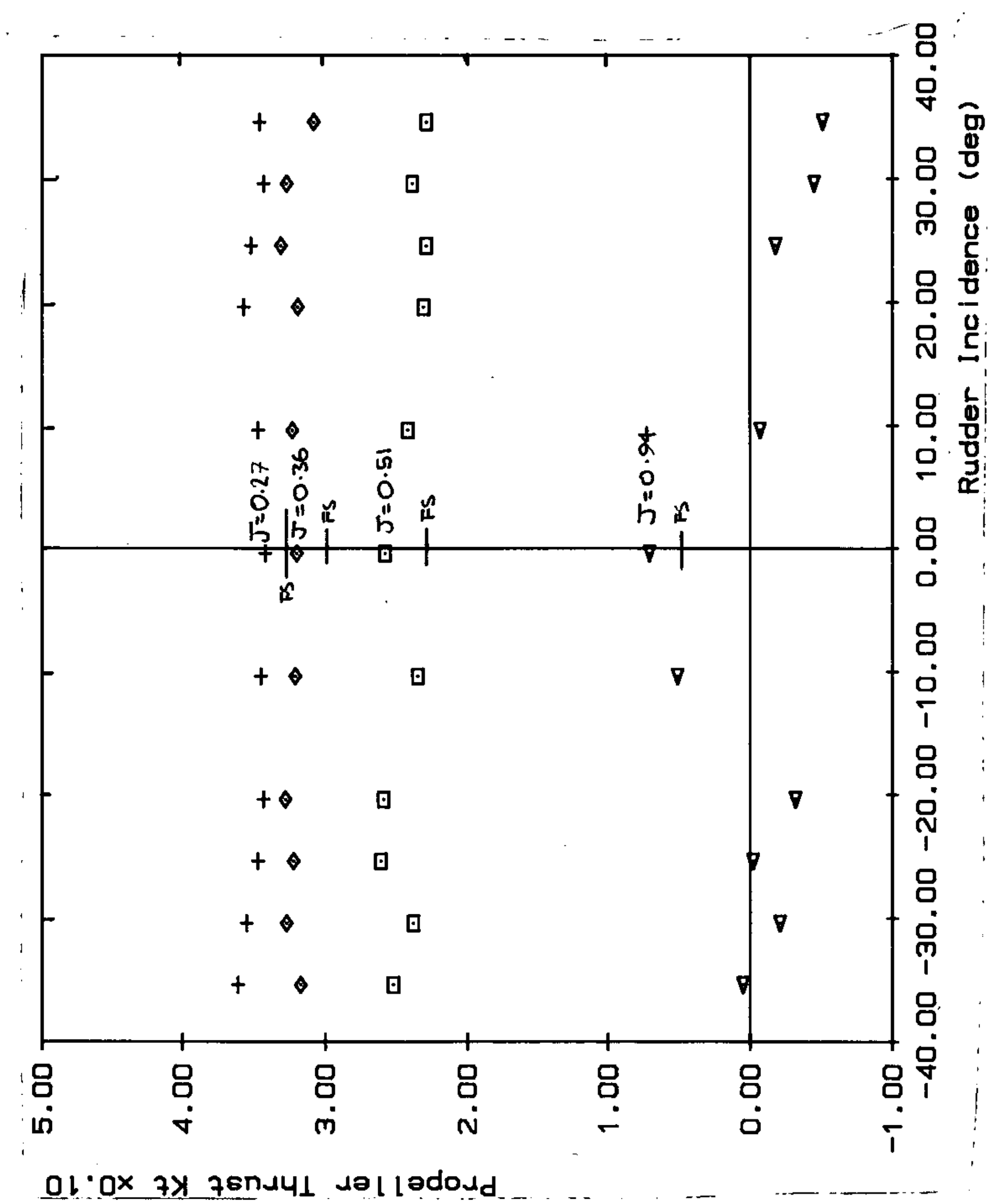


Figure 16 Influence of rudder angle on propeller thrust for different advance ratio

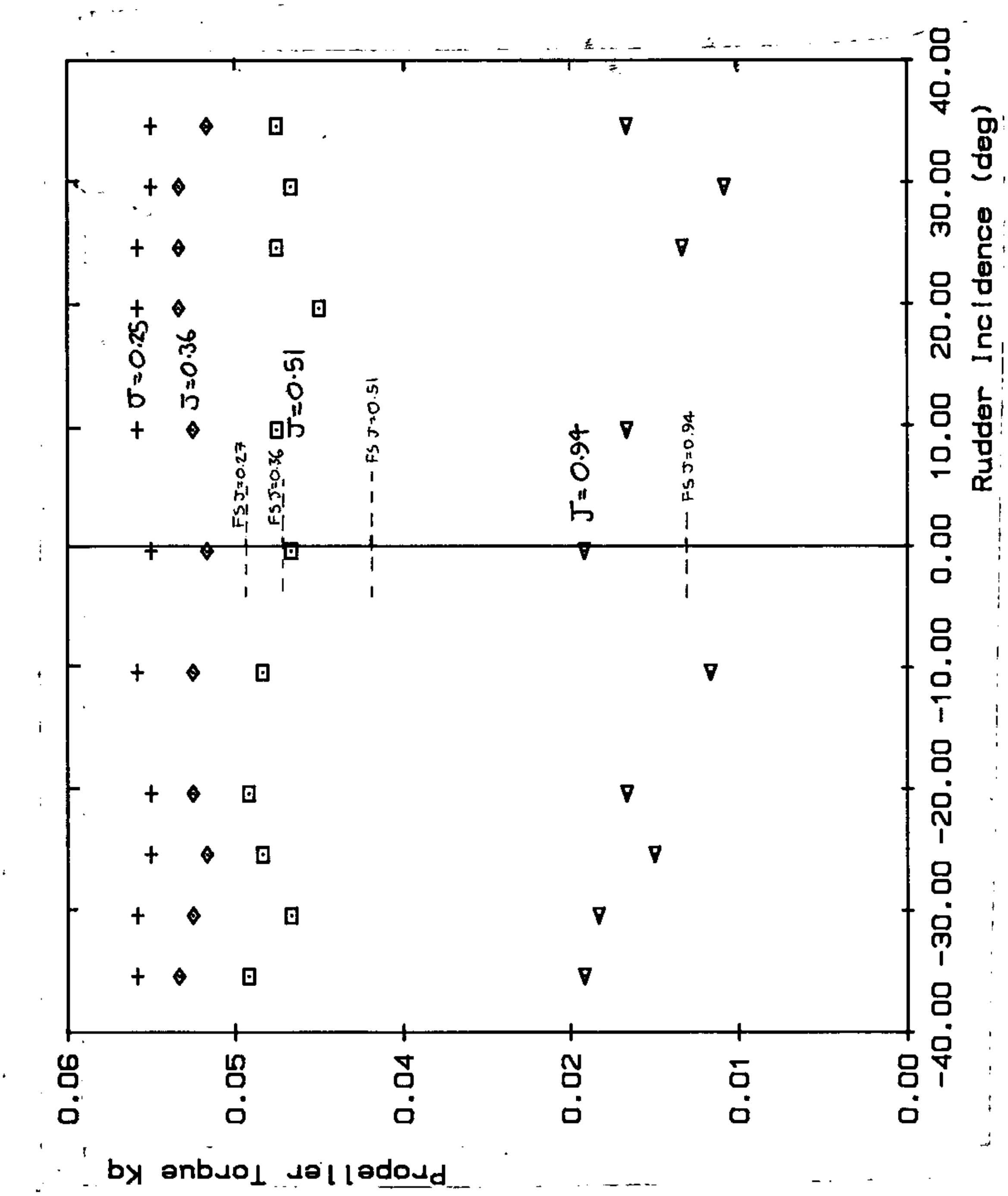
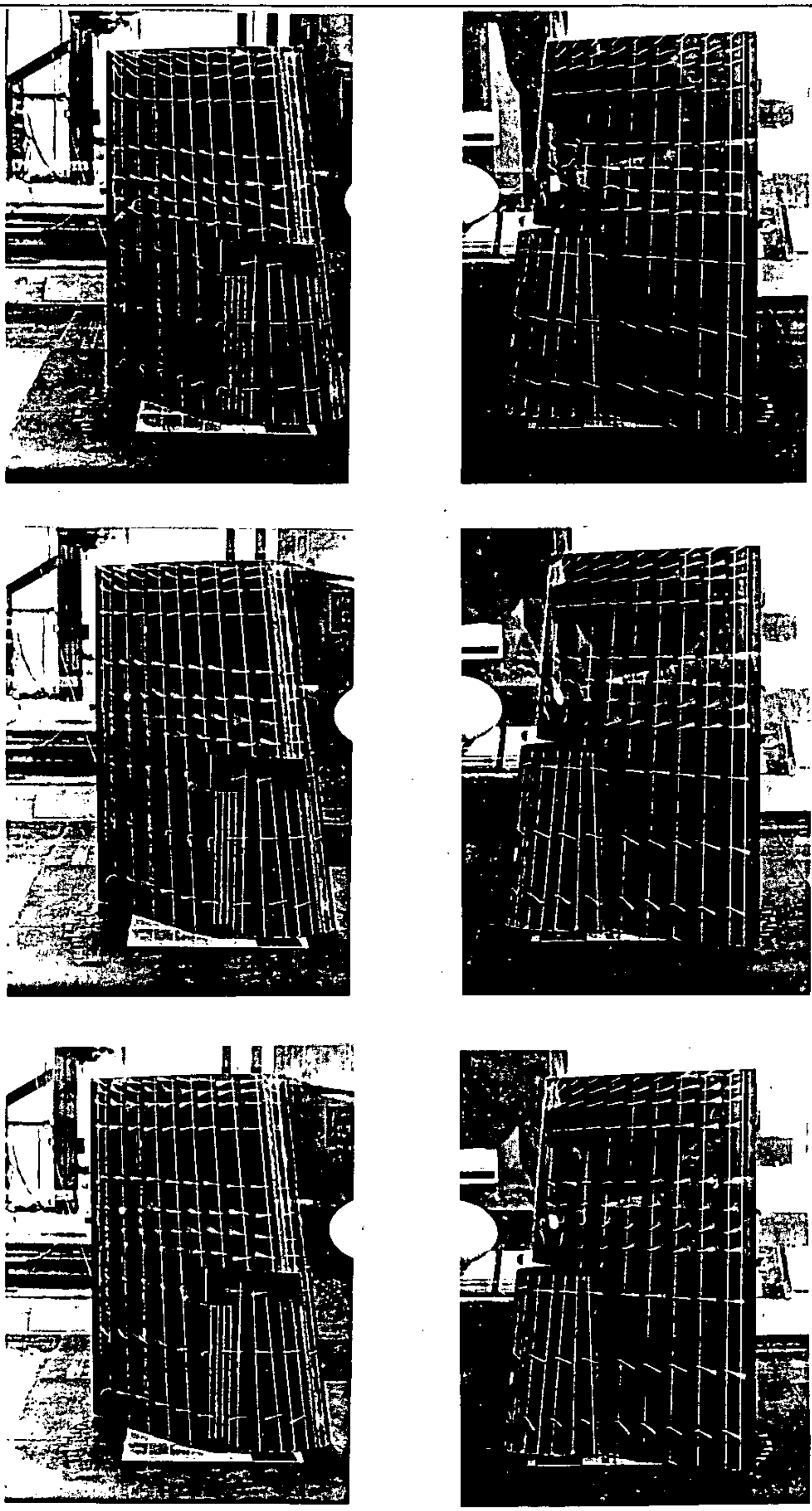


Figure 17 Influence of rudder angle on propeller torque for different advance ratio



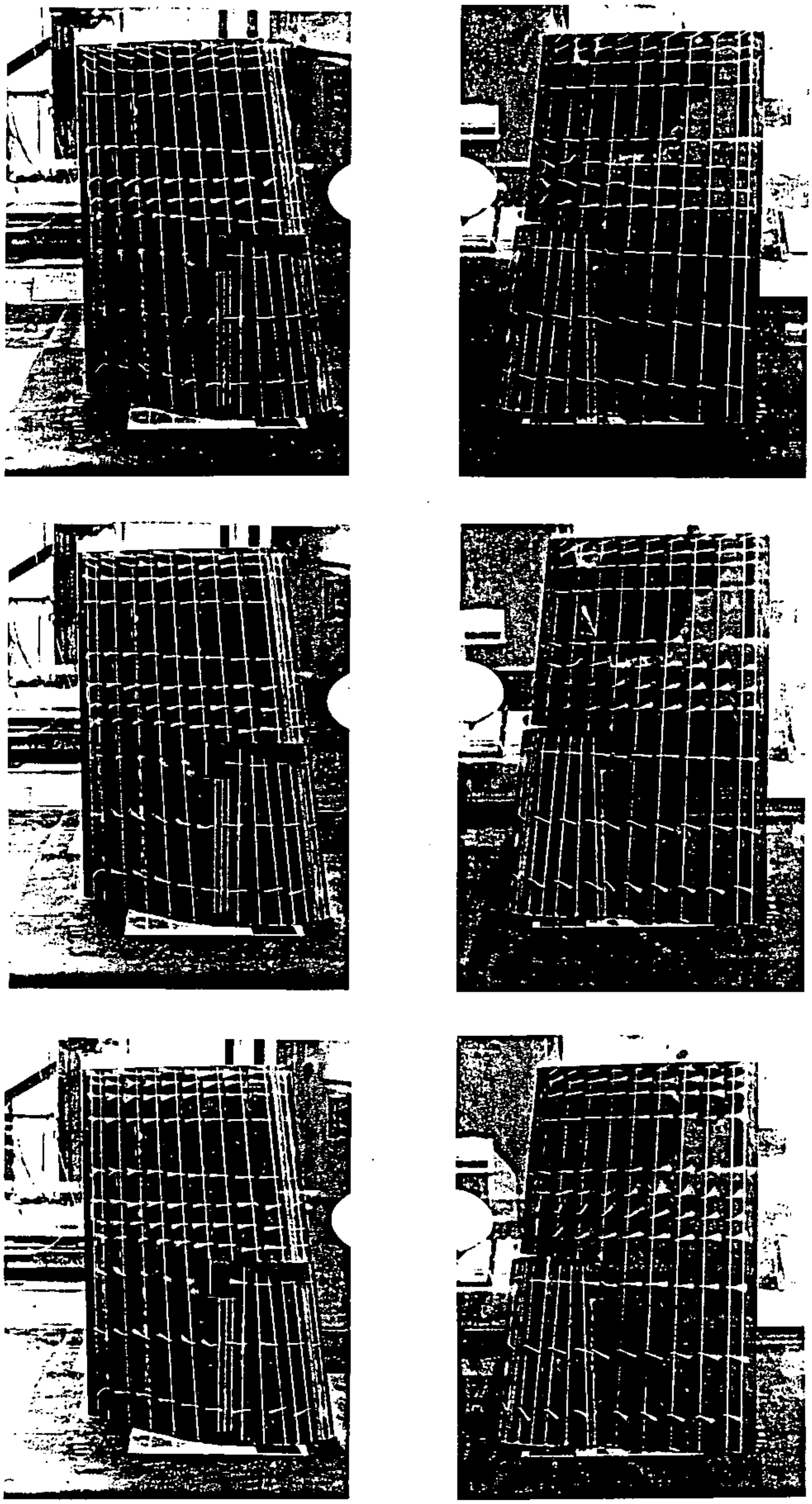
J=0.94

J=0.51

J=0.36

Rudder Incidence: -30^{o}

Figure 18 Views from flow visualisation showing main features



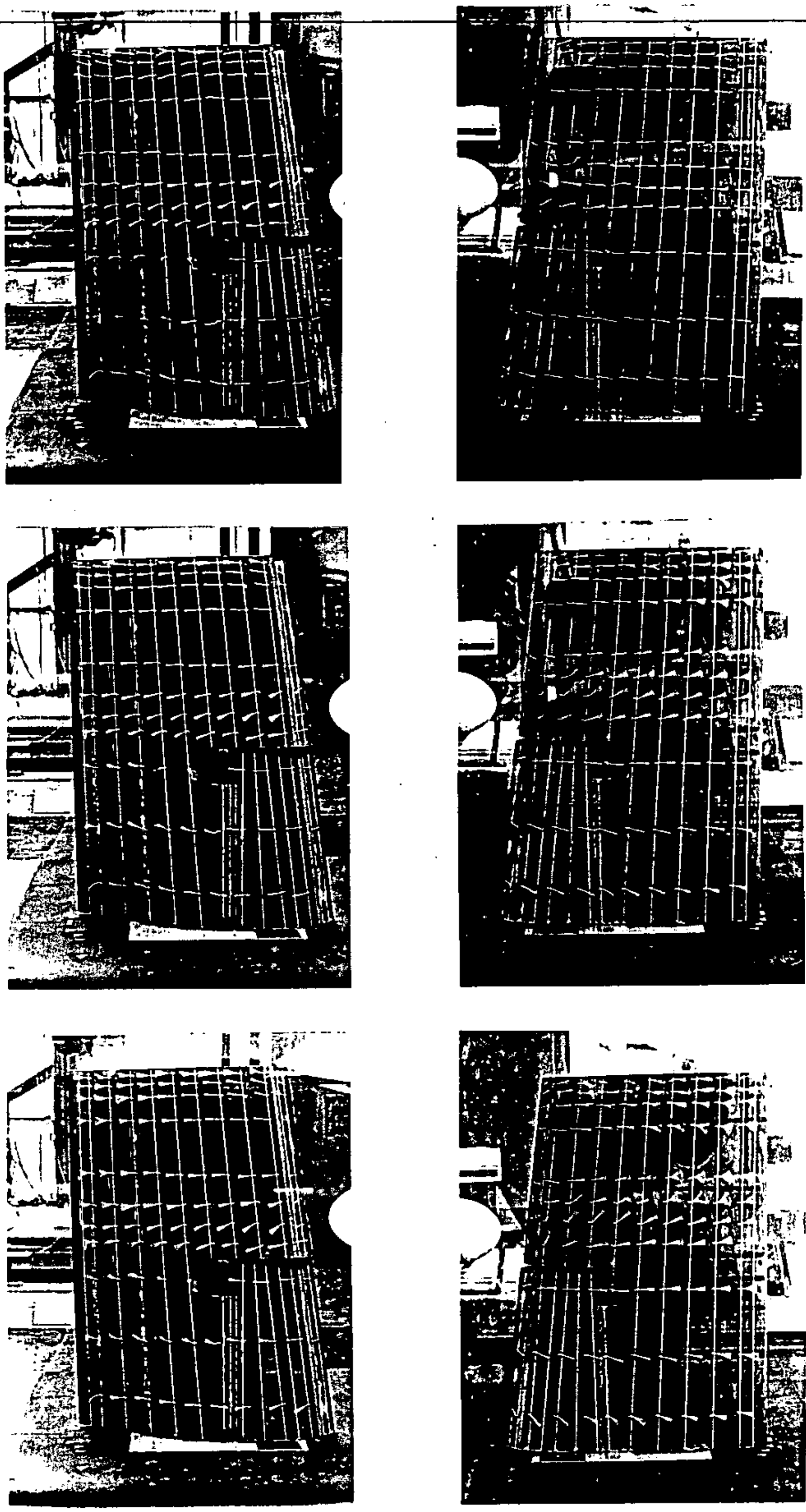
J=0.94

J=0.51

J=0.36

Rudder Incidence: -20°

Figure 18 Views from flow visualisation showing main features



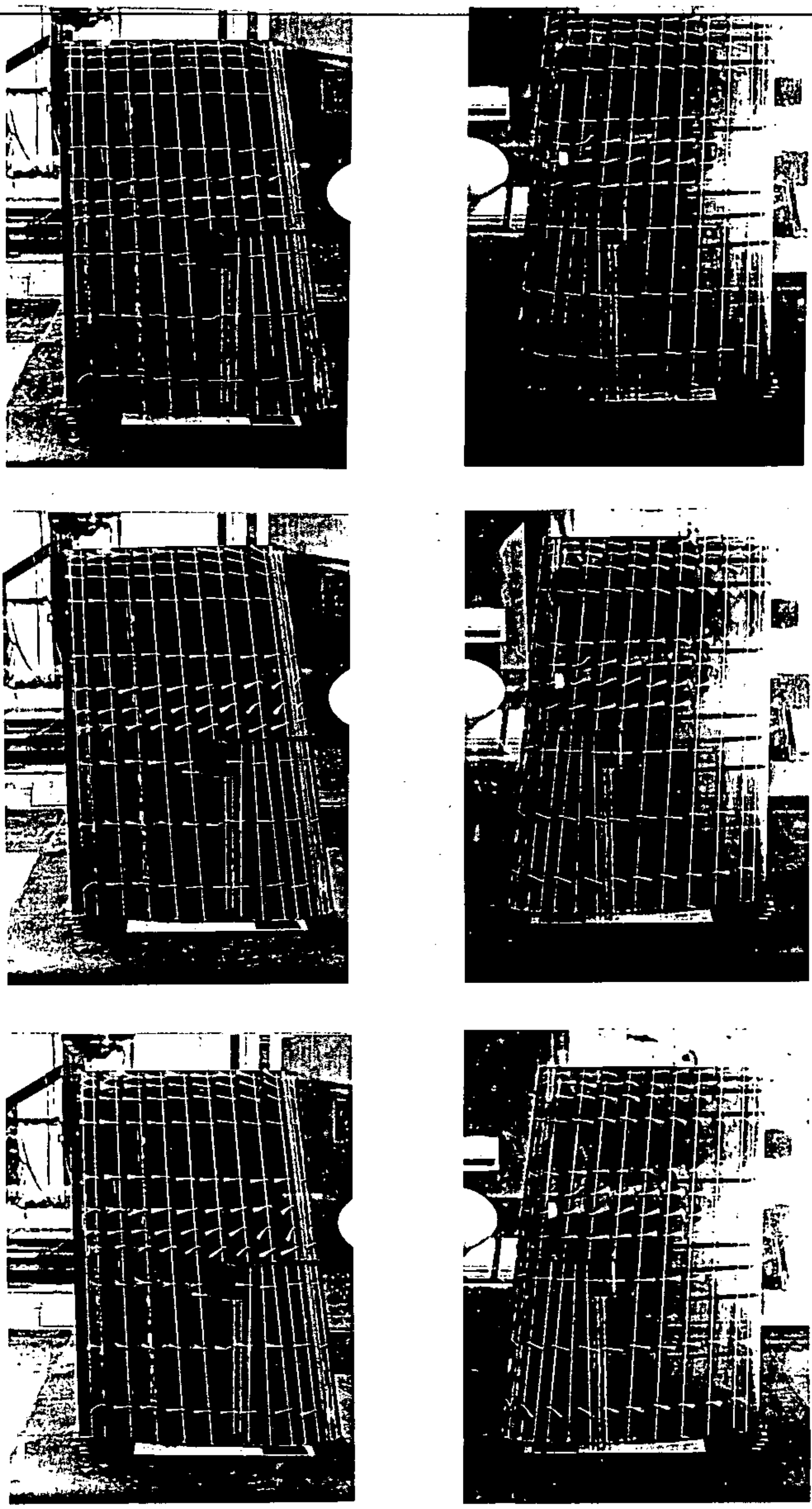
J=0.94

J=0.51

J=0.36

Rudder Incidence: -10^{0}

Figure 18 Views from flow visualisation showing main features



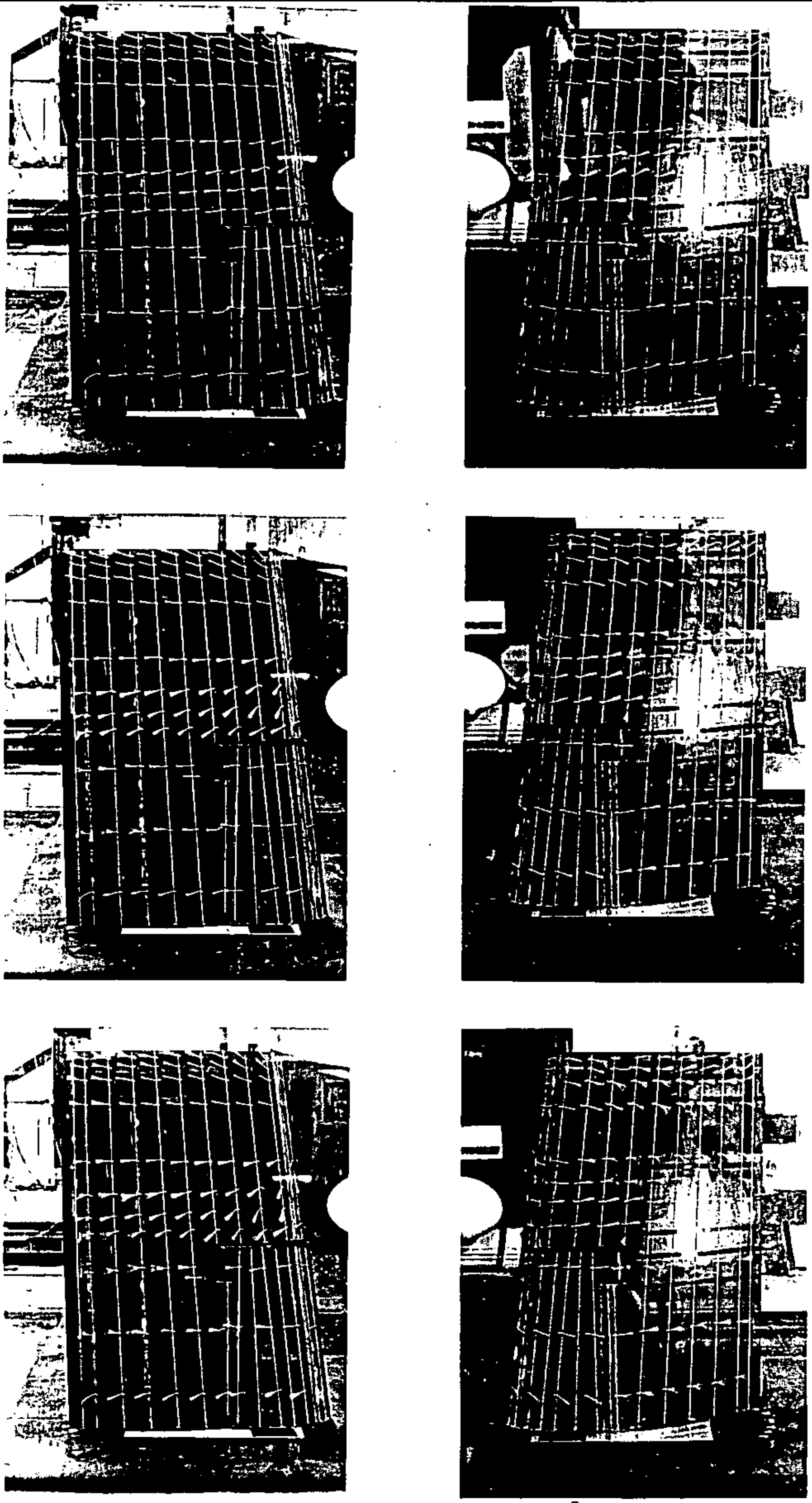
J=0.94

J=0.51

J=0.36

Rudder Incidence: 0^o

Figure 18 Views from flow visualisation showing main features



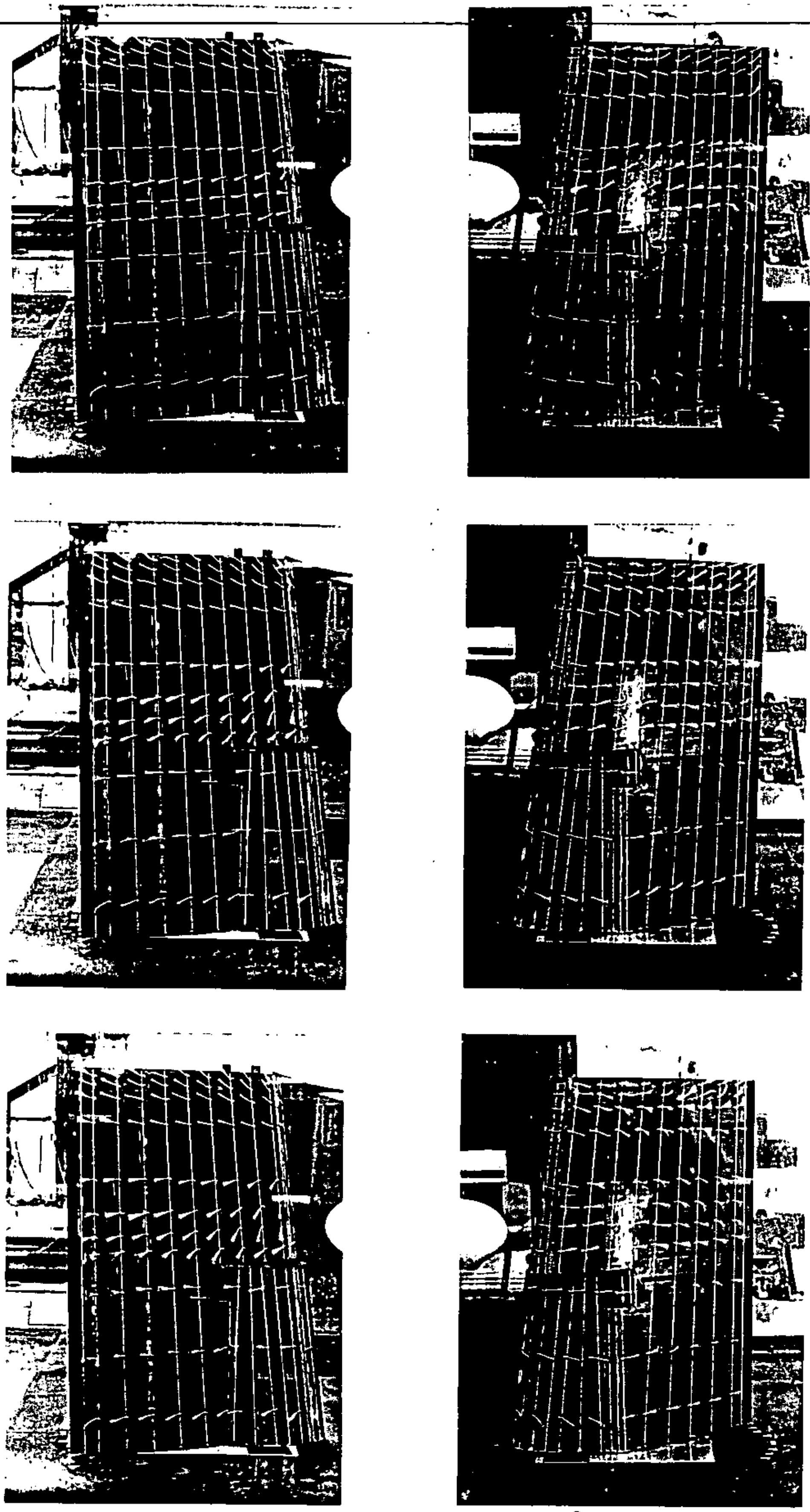
J=0.94

J=0.51

J=0.36

Rudder Incidence: $+10^{\circ}$

Figure 18 Views from flow visualisation showing main features



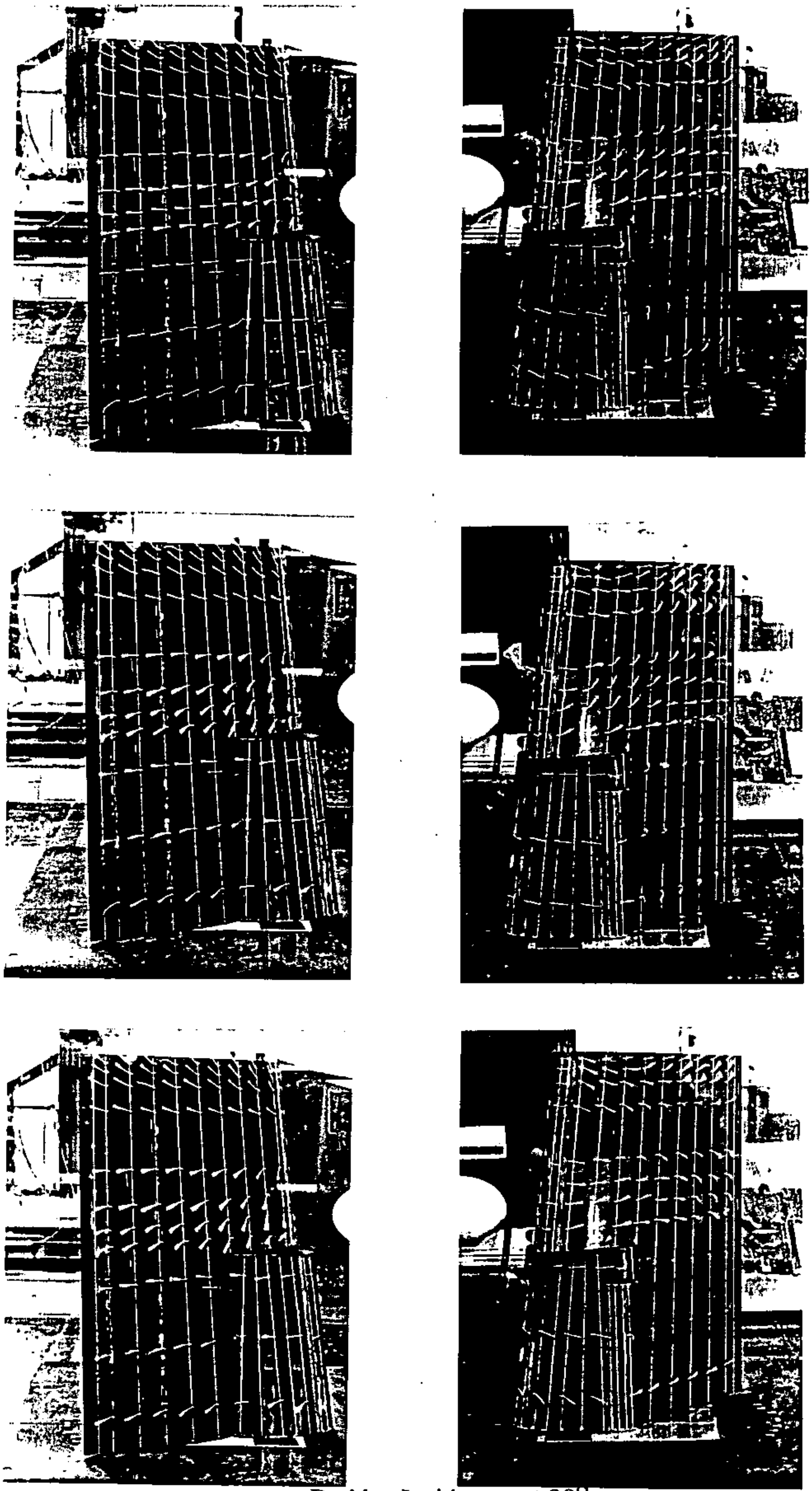
J=0.94

J=0.51

J=0.36

Rudder Incidence: $+20^{o}$

Figure 18 Views from flow visualisation showing main features



J=0.94

J=0.51

J=0.36

Rudder Incidence: +30°

Figure 18 Views from flow visualisation showing main features