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A.F. Molland and S.R. Turnock

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SUMMARY

Performance tests were carried out on a semi-balanced skeg and an all-movable rudder model downstream of a propeller. The tests were carried out in a closed return wind tunnel with the wind tunnel fan stationary. The tests were not true zero speed as the model ship propeller circulated the air within the tunnel at a slow but measurable speed. This speed corresponded to a propeller advance ratio J of 0.17 and thrust loading K_T/J^2 of 12. Performance comparisons were made for several propeller rates of revolution. Surface pressure measurements were made at 200 locations distributed over the all-movable rudder. Measurements were made for seven rudder angles between -30° and +30° at two rates of revolution of 800 and 1460 rpm.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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 axis
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 ($L/0.5\rho cK_T n^2D^2$)
C_L'	Non-dimensional Lift (sideforce) ($L/0.5\rho AK_T n^2D^2$)
C_n'	Normal force per unit span ($N/0.5\rho cK_T n^2D^2$)
C_d'	Drag coefficient per unit span ($d/0.5\rho cK_T n^2D^2$)
C_D'	Non-Dimensional drag ($d/0.5\rho AK_T n^2D^2$)
CP_c	Chordwise centre of pressure, % chord from leading edge of rudder root
CP_s	Spanwise centre of pressure, % span from rudder root
C_{Mz}'	Non-dimensional Moment about rudder stock ($M_z/0.5\rho AcK_T n^2D^2$)
C_{Mx}'	Non-dimensional moment about rudder root chord ($M_x/0.5\rho ASK_T n^2D^2$)
C_{My}'	Non-dimensional moment about y axis ($M_y/0.5\rho ASK_T n^2D^2$)
C_p'	Non-Dimensional Pressure Coefficient ($p/0.5\rho K_T n^2D^2$)
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 (deg)
ρ	Air Density (kg/m3)

1.0 INTRODUCTION

As part of a wind tunnel research programme to investigate the interaction of a ship rudder and propeller this report describes a series of preliminary tests into the interaction at a nominal zero ship speed. The zero and low speed performance of vessels is especially important in the manoeuvring of vessels in and out of port. When ship speed is very low forces generated by the rudder-propeller arrangement will greatly effect the behaviour of the vessel. The tests described in this report attempt to quantify these forces.

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]. These particular tests were conducted with the wind tunnel fan stationary. The propeller caused a small but measurable flow around the wind tunnel. This was monitored using a Betz manometer.

Tests carried out on the semi-balanced skeg rudder and the all-movable rudder geometry (Rudder No. 2) for higher J values (lower thrust loadings) are reported in Molland and Turnock [3] and [4] respectively.

2.0 DESCRIPTION OF MODELS

2.1 Rudder

Two representative ship rudder models were used in this investigation: a semi-balanced skeg, and an all-movable type. Table I presents particulars of the rudders and Fig. 1 their overall dimensions.

The model skeg-rudder (Rudder No. 0), having a mean chord of 667mm, a span of 1000mm and NACA0020 section, was constructed from Jelutong using the method of manufacture described in Turnock [2]. The geometry of the rudder with its taper ratio of 0.8 is identical to that of the original Rudder No. 2 used by Goodrich and Molland [1], although for the current tests a larger mean chord of 667mm was used.

The model all-movable rudder (Rudder No. 2) has a constant chord of 667mm, span of 1000mm and a constant NACA0020 section. This rudder was manufactured from thin spanwise mahogany strips attached to ply formers (see Turnock[2]).

A roughness strip was applied to both sides of the two rudders, starting at 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 [5] 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 [6]. 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 were are given in Ref.[7].

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. A side view of the overall rig is shown in Fig. 2. 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 200 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 [8]. 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. [4].

3.5 Tests

The results described were obtained during a two-week testing period carried out in August 1990. The rudder and propeller models were mounted on the tunnel centre-line. For the semi-balanced skeg Rudder No. 0 a longitudinal separation $X/D = 0.34$ was used where X is the distance between the propeller plane of rotation and the rudder leading edge at the height of the propeller axis (see Fig. 2). A longitudinal separations of $X/D = 0.39$ was used for all-movable Rudder No. 2 at this position the stock position was the same distnace form the propeller plane (Y) for both rudders.

The steady-state wind speed imparted by the propeller to the air in the tunnel was measured using a Betz manometer connected to the tunnel pitot-static tube upstream of the rudder-propeller rig. It should be noted that velocities induced by the propeller at the higher revs. led to effective Reynolds Numbers of up to 0.75×10^6 over much of the rudder. Results presented in [9] indicate that tests at these conditions should preclude any significant scale effect.

Measurements were made for Rudder No. 0 at propeller revolutions of 800, 1450, and 2100 rpm, and for Rudder No. 2 at 800 and 1460 rpm. The wind speed imparted by the propeller was not sensitive to rudder incidence and was proportional to the rate of revolution of the propeller. The actual advance ratio J for each value of revs. was found to be 0.17 corresponding to an open-water thrust loading (K_T/J^2) of 12.

Rudder and propeller force measurements were carried out over a range of incidences between -35° and 40° to include stall were possible. Pressure measurements were made for Rudder No. 2 at X/D=0.39 for 800 rpm and 1460 at rudder incidences of -30.4°, -20.4°, -10.4°, -0.4°, 9.6°, 19.6° and 29.6°.

All force and moment measurements on the skeg rudder were carrie dout for the movable rudder plus skeg combination. In all cases the skeg was maintained at zero incidence to the flow.

4.0 DATA REDUCTION AND CORRECTIONS

A computer programme Ref. [4] 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° 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' for each span position.

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 and pressure coefficients were non-dimensionalised using a nominal velocity of $n.D.(K_T)^{0.5}$ and actual rudder area (S.c). In the case of the skeg rudder the area includes the movable rudder and skeg.

The data are presented in terms of propeller rate of revolution values.

6.0 DISCUSSION OF RESULTS

6.1 Effect of propeller rate of revolution on rudder performance

Performance comparisons are made for Rudder No.'s 0 and 2 in Figure 4 and 5 respectively. For Rudder No. 0 the performance at 1460 and 2100 rpm is similar whereas at 800 rpm there is a sideforce generated at zero rudder incidence. This effect is also seen for Rudder No. 2. The rudder drag decreases with increasing propeller rpm for both rudders. Also shown in Figure 5 for Rudder No. 2 is the integration of surface pressures for both 800 and 1460 rpm. These agree quite closely with the force measurement at 1460 rpm but not those at 800 rpm. This suggests that because of the low forces at 800 rpm that the results are not reliable.

6.2 Comparison of rudder performance

In Figure 6 the performance of the all-movable and semi-balanced rudder is compared. Overall there are only small differences in performance.

6.3 Influence of rudder on propeller performance

Figures 7 and 8 show the influence of rudder incidence on propeller thrust and torque respectively for semi-balanced skeg Rudder No. 0 for three diferent rates of revolution. For both thrust and torque the lowest speed of 800 rpm shows considerable scatter which reflects the low values of force measurements introducing uncertainty. However, for both 1460 and 2100 rpm there appears to be very little change in thrust or torque with change in rudder incidence.

The influence of rudder-propeller separation on propeller thrust and torque is shown in Figures 9 and 10 respectively. Again both thrust and torque are not noticeably altered by rudder incidence. The separation does appear to alter the operating point of the propeller. The propeller thrust seeming to increase with decreasing separation although at high positive incidence this trend is not so marked. The different Rudder No. 0 at X/D=0.34 has a larger increase in K_T and K_Q. It is interesting to note that the minimum separation (X/D=0.30) has the least effect on propeller torque.

6.4 Spanwise load distribution over rudder

Figures 11 and 12 present the spanwise distribution of load over Rudder No.2 at propeller revolutions of 800 and 1460 rpm respectively. The two sets of curves are broadly similar in shape although there are local differences in the value of Cn. An interesting feature is the behaviour of Cn in the region between the tunnel floor (Span=0.0) and the start of the propeller coverage (Span=0.2). For positive incidences there is almost no load in this region whereas especially at negative incidence there is quite a considerable spill over. Overall the shape of the curves is similar to that reported in Ref.[4] for flow over Rudder No. 2 at J=0.35 with the propeller induced loading dominating.

6.5 Chordwise pressure distributions

Figure 13 and 14 show the chordwise distribution of pressures for all eight spans and seven rudder angles for 800 and 1460 rpm respectively. Again, the shape of the individual pressure distributions is very similar between the two rates of revolution.

7.0 CONCLUSION

A limited set of force measurements have been obtained. These showed that for a rate of revolution of at least 1460 rpm the rudder performance was independent of rate of revolution.

The tests were carried out in a nominal bollard pull condition. The wind tunnel flow was driven by the model propeller and for the range of propeller revolutions tested the rate of wind tunnel flow was proportional to revolutions. The actual advance ratio for the tests was therfore a J of 0.17. This corresponds to a high propeller thrust loading and corresponding low-speed condition and therefore the results should be indicative of the zero speed (bollard pull) case.

The load distribution over the rudder is dominated by the propeller.

The rudder surface pressure measurements provide a useful set of data both for the validation of theoretical methods and for carrying out rudder stress analysis at high propeller thrust loading.

8.0 ACKNOWLEDGMENTS

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APPENDIX A RUDDER DYNAMOMETER

RUDDER DYNAMOMETER epbz111.rud 800 rpm 0m/s Rudder No. 0 X/D=0.34

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-30.40	6.45	807.95	-0.7280	-0.770	0.280	0.046	-0.3920	-0.0270	29.391	24.583
-20.40	6.45	808.94	-0.5870	-0.601	0.146	0.046	-0.2520	-0.0190	27.691	20.716
-10.40	6.45	808.38	-0.2620	-0.263	0.027	0.021	-0.1270	-0.0200	27.354	28.753
-0.40	6.45	808.72	0.1180	0.118	0.063	0.015	0.1120	0.0200	47.943	77.750
9.60	6.45	808.24	0.3410	0.352	0.097	-0.014	0.2300	0.0230	31.522	47.944
19.60	6.45	808.01	0.6620	0.674	0.149	-0.045	0.4410	0.0480	28.678	46.499
29.60	6.45	808.20	0.8600	0.891	0.289	-0.044	0.5830	0.0920	30.419	44.551

RUDDER DYNAMOMETER epbz211.rud 1460 rpm 0m/s Rudder No. 0 X/D=0.34

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-30.40	11.63	1463.30	-0.8300	-0.862	0.289	0.063	-0.5080	0.1290	28.123	40.894
-20.40	11.62	1463.25	-0.5890	-0.596	0.126	0.056	-0.3300	0.0570	25.912	37.750
-10.40	11.63	1463.30	-0.3120	-0.310	0.019	0.036	-0.1600	0.0070	23.704	33.487
-0.40	11.63	1464.62	-0.0640	-0.064	-0.023	0.005	0.0380	0.0030	28.252	-76.885
9.60	11.63	1463.66	0.3000	0.304	0.054	-0.009	0.2800	0.0340	32.461	74.993
19.60	11.63	1463.71	0.6230	0.643	0.167	-0.020	0.5030	0.0990	32.310	61.288
29.60	11.63	1463.59	0.8450	0.890	0.315	-0.026	0.6770	0.1970	32.474	59.500

RUDDER DYNAMOMETER epbz311.rud 2100 rpm 0m/s Rudder No. 0 X/D=0.34

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-30.40	17.35	2184.11	-0.8630	-0.881	0.271	0.061	-0.5520	0.1750	28.453	46.567
-20.40	17.35	2183.74	-0.5750	-0.580	0.117	0.058	-0.3640	0.0770	25.332	46.016
-10.40	17.35	2184.01	-0.3230	-0.324	0.033	0.042	-0.1650	0.0150	22.385	33.608
9.60	17.35	2184.13	0.3040	0.310	0.064	-0.002	0.2830	0.0440	34.644	74.857
19.60	17.35	2184.48	0.6040	0.626	0.170	-0.013	0.5200	0.1200	33.265	67.100
29.60	17.35	2184.38	0.8900	0.941	0.338	-0.013	0.7320	0.2370	33.962	62.558

RUDDER DYNAMOMETER epbx2z1.rud 800 rpm 0m/s Rudder No. 2 X/D=0.39

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-30.40	6.54	819.98	-0.7780	-0.909	0.470	0.080	-0.5765	0.0805	21.129	41.799
-20.40	6.53	818.80	-0.4240	-0.499	0.293	0.083	-0.3630	0.0440	13.019	54.227
-10.40	6.54	819.12	-0.1940	-0.227	0.204	0.043	-0.1500	-0.0330	11.045	44.663
-0.40	6.54	819.49	0.2910	0.290	0.135	0.020	0.1200	0.0420	36.788	23.566
9.60	6.53	819.10	0.4865	0.510	0.185	-0.008	0.2935	0.0545	28.489	41.018
19.60	6.54	819.99	0.8125	0.857	0.272	-0.039	0.5540	0.1015	25.509	47.320
29.60	6.52	817.58	1.0890	1.173	0.456	-0.053	0.7630	0.1430	25.522	45.123

RUDDER DYNAMOMETER epbx2z2.rud 1460 rpm 0m/s Rudder No. 2 X/D=0.39

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-30.40	11.72	1475.65	-0.9950	-1.014	0.309	0.072	-0.6330	0.1600	22.833	44.379
-20.40	11.74	1477.17	-0.5860	-0.611	0.178	0.073	-0.3870	0.0735	18.030	46.045
-10.40	11.73	1476.10	-0.2665	-0.274	0.068	0.046	-0.1625	0.0130	13.356	42.073
-0.40	11.72	1475.68	0.0125	0.008	0.001	0.000	0.1315	-0.0040	52.856	-367.472
9.60	11.74	1477.60	0.3570	0.367	0.086	-0.036	0.3000	0.0370	20.253	65.122
19.60	11.73	1476.54	0.6440	0.666	0.176	-0.067	0.5250	0.0990	19.793	61.817
29.60	11.73	1476.44	0.9730	1.016	0.344	-0.086	0.7805	0.2050	21.580	59.261

APPENDIX B Propeller Dynamometer

epbz111.pro 800 rpm 0m/s Rudder No. 0 X/D=0.34

Angle	V	RPM	J	Kt	Kq	n	Kt/J2	Kq/J2
-30.40	0.00	807.95	0.0000	0.374	0.061	0.000	-1.0000	-1.0000
-20.40	0.00	808.94	0.0000	0.393	0.063	0.000	-1.0000	-1.0000
-10.40	0.00	808.38	0.0000	0.372	0.058	0.000	-1.0000	-1.0000
-0.40	0.00	808.72	0.0000	0.459	0.063	0.000	-1.0000	-1.0000
9.60	0.00	808.24	0.0000	0.334	0.058	0.000	-1.0000	-1.0000
19.60	0.00	808.01	0.0000	0.349	0.058	0.000	-1.0000	-1.0000
29.60	0.00	808.20	0.0000	0.331	0.056	0.000	-1.0000	-1.0000

epbz211.pro 1460 rpm 0m/s Rudder No. 0 X/D=0.34

Angle	V	RPM	J	Kt	Kq	n	Kt/J2	Kq/J2
-30.40	0.00	1463.30	0.0000	0.396	0.059	0.000	-1.0000	-1.0000
-20.40	0.00	1463.25	0.0000	0.393	0.060	0.000	-1.0000	-1.0000
-10.40	0.00	1463.30	0.0000	0.398	0.059	0.000	-1.0000	-1.0000
-0.40	0.00	1464.62	0.0000	0.392	0.060	0.000	-1.0000	-1.0000
9.60	0.00	1463.66	0.0000	0.399	0.059	0.000	-1.0000	-1.0000
19.60	0.00	1463.71	0.0000	0.388	0.061	0.000	-1.0000	-1.0000
29.60	0.00	1463.59	0.0000	0.395	0.059	0.000	-1.0000	-1.0000

epbz311.pro 2100 rpm 0m/s Rudder No. 0 X/D=0.34

Angle	V	RPM	J	Kt	Kq	n	Kt/J2	Kq/J2
-30.40	0.00	2184.11	0.0000	0.392	0.056	0.000	-1.0000	-1.0000
-20.40	0.00	2183.74	0.0000	0.377	0.056	0.000	-1.0000	-1.0000
-10.40	0.00	2184.01	0.0000	0.394	0.057	0.000	-1.0000	-1.0000
9.60	0.00	2184.13	0.0000	0.388	0.057	0.000	-1.0000	-1.0000
19.60	0.00	2184.48	0.0000	0.385	0.058	0.000	-1.0000	-1.0000
29.60	0.00	2184.38	0.0000	0.392	0.057	0.000	-1.0000	-1.0000

epbx1z135.pro 800 rpm 0m/s Rudder No. 2 X/D=0.30

Angle	V	RPM	J	Kt	Kq	n	Kt/J2	Kq/J2
-30.40	0.00	822.53	0.0000	0.396	0.056	0.000	-1.0000	-1.0000
-20.40	0.00	822.53	0.0000	0.396	0.057	0.000	-1.0000	-1.0000
-10.40	0.00	822.53	0.0000	0.412	0.057	0.000	-1.0000	-1.0000
-0.40	0.00	822.53	0.0000	0.432	0.059	0.000	-1.0000	-1.0000
9.60	0.00	822.53	0.0000	0.394	0.057	0.000	-1.0000	-1.0000
19.60	0.00	822.53	0.0000	0.368	0.051	0.000	-1.0000	-1.0000
29.60	0.00	822.53	0.0000	0.393	0.057	0.000	-1.0000	-1.0000

pbx2z1.pro 800 rpm 0m/s Rudder No. 2 X/D=0.39

Angle	V	RPM	J	Kt	Kq	n	Kt/J2	Kq/J2
-30.40	0.00	819.98	0.0000	0.345	0.057	0.000	-1.0000	-1.0000
-20.40	0.00	818.80	0.0000	0.316	0.055	0.000	-1.0000	-1.0000
-10.40	0.00	819.12	0.0000	0.321	0.058	0.000	-1.0000	-1.0000
-0.40	0.00	818.47	0.0000	0.354	0.059	0.000	-1.0000	-1.0000
9.60	0.00	819.10	0.0000	0.332	0.053	0.000	-1.0000	-1.0000
19.60	0.00	819.99	0.0000	0.364	0.055	0.000	-1.0000	-1.0000
29.60	0.00	817.58	0.0000	0.344	0.055	0.000	-1.0000	-1.0000

epbx3z130.pro 800 rpm 0m/s Rudder No. 2 X/D=0.52

Angle	V	RPM	J	Kt	Kq	n	Kt/J2	Kq/J2
-30.40	0.00	818.90	0.0000	0.335	0.053	0.000	-1.0000	-1.0000
-20.40	0.00	818.90	0.0000	0.345	0.055	0.000	-1.0000	-1.0000
-10.40	0.00	818.90	0.0000	0.369	0.057	0.000	-1.0000	-1.0000
-0.40	0.00	818.90	0.0000	0.353	0.053	0.000	-1.0000	-1.0000
9.60	0.00	818.90	0.0000	0.322	0.053	0.000	-1.0000	-1.0000
19.60	0.00	818.90	0.0000	0.338	0.055	0.000	-1.0000	-1.0000
29.60	0.00	818.90	0.0000	0.342	0.056	0.000	-1.0000	-1.0000

epbx1z235.pro 1460 rpm 0m/s Rudder No. 2 X/D=0.30

Angle	V	RPM	J	Kt	Kq	n	Kt/J2	Kq/J2
-30.40	0.00	1479.16	0.0000	0.392	0.054	0.000	-1.0000	-1.0000
-20.40	0.00	1479.16	0.0000	0.391	0.054	0.000	-1.0000	-1.0000
-10.40	0.00	1479.16	0.0000	0.395	0.055	0.000	-1.0000	-1.0000
-0.40	0.00	1479.16	0.0000	0.384	0.052	0.000	-1.0000	-1.0000
9.60	0.00	1479.16	0.0000	0.384	0.054	0.000	-1.0000	-1.0000
19.60	0.00	1479.16	0.0000	0.372	0.054	0.000	-1.0000	-1.0000
29.60	0.00	1479.16	0.0000	0.383	0.053	0.000	-1.0000	-1.0000

epbx2z2.pro 1460 rpm 0m/s Rudder No. 2 X/D=0.39

Angle	V	RPM	J	Kt	Kq	n	Kt/J2	Kq/J2
-30.40	0.00	1475.65	0.0000	0.372	0.057	0.000	-1.0000	-1.0000
-20.40	0.00	1477.17	0.0000	0.372	0.055	0.000	-1.0000	-1.0000
-10.40	0.00	1476.10	0.0000	0.370	0.056	0.000	-1.0000	-1.0000
-0.40	0.00	1475.68	0.0000	0.360	0.056	0.000	-1.0000	-1.0000
9.60	0.00	1477.60	0.0000	0.389	0.057	0.000	-1.0000	-1.0000
19.60	0.00	1476.54	0.0000	0.372	0.056	0.000	-1.0000	-1.0000
29.60	0.00	1476.44	0.0000	0.387	0.058	0.000	-1.0000	-1.0000

epbx3z230.pro 1460 rpm 0m/s Rudder No. 2 X/D=0.52

Angle	V	RPM	J	Kt	Kq	n	Kt/J2	Kq/J2
-30.40	0.00	1475.91	0.0000	0.364	0.055	0.000	-1.0000	-1.0000
-20.40	0.00	1475.91	0.0000	0.377	0.055	0.000	-1.0000	-1.0000
-10.40	0.00	1475.91	0.0000	0.376	0.055	0.000	-1.0000	-1.0000
-0.40	0.00	1475.91	0.0000	0.368	0.054	0.000	-1.0000	-1.0000
9.60	0.00	1475.91	0.0000	0.358	0.055	0.000	-1.0000	-1.0000
19.60	0.00	1475.91	0.0000	0.369	0.054	0.000	-1.0000	-1.0000
29.60	0.00	1475.91	0.0000	0.381	0.055	0.000	-1.0000	-1.0000

APPENDIX C LOCAL Cn DISTRIBUTION

Local Distribution

1sn.d 800 rpm 0m/s -30 Rudder No. 2 X/D=0.39

Angle	V	RPM	Span	Cn	Cmz	Cmx	Cpc
-30.40	0.00	800.00	0.0000	-0.568	-0.070	-0.0397	48.442
-30.40	0.00	800.00	0.0700	-0.568	-0.070	-0.0397	48.442
-30.40	0.00	800.00	0.2300	-0.640	0.044	-0.1473	19.603
-30.40	0.00	800.00	0.4000	-1.556	0.100	-0.6224	20.339
-30.40	0.00	800.00	0.5300	-0.998	0.053	-0.5289	22.064
-30.40	0.00	800.00	0.7000	-0.779	0.077	-0.5456	15.125
-30.40	0.00	800.00	0.8300	-0.616	0.046	-0.5113	18.696
-30.40	0.00	800.00	0.9400	-0.104	0.034	-0.0974	-19.322
-30.40	0.00	800.00	0.9700	-0.012	0.015	-0.0115	-164.354
-30.40	0.00	800.00	1.0000	0.000	0.000	0.0000	0.000

Local Distribution

2sn.d 800 rpm 0m/s -20 Rudder No. 2 X/D=0.39

Angle	V	RPM	Span	Cn	Cmz	Cmx	Cpc
-20.40	0.00	800.00	0.0000	-0.253	-0.042	-0.0177	54.591
-20.40	0.00	800.00	0.0700	-0.253	-0.042	-0.0177	54.591
-20.40	0.00	800.00	0.2300	-0.382	0.043	-0.0879	13.136
-20.40	0.00	800.00	0.4000	-1.284	0.107	-0.5137	17.454
-20.40	0.00	800.00	0.5300	-0.728	0.065	-0.3857	16.613
-20.40	0.00	800.00	0.7000	-0.405	0.028	-0.2836	19.782
-20.40	0.00	800.00	0.8300	-0.264	0.004	-0.2194	27.555
-20.40	0.00	800.00	0.9400	-0.037	-0.001	-0.0352	34.932
-20.40	0.00	800.00	0.9700	0.063	0.012	0.0611	59.446
-20.40	0.00	800.00	1.0000	0.000	0.000	0.0000	0.000

Local Distribution

3sn.d 800 rpm 0m/s -10 Rudder No. 2 X/D=0.39

Angle	V	RPM	Span	Cn	Cmz	Cmx	Cpc
-10.40	0.00	800.00	0.0000	-0.055	-0.012	-0.0039	63.529
-10.40	0.00	800.00	0.0700	-0.055	-0.012	-0.0039	63.529
-10.40	0.00	800.00	0.2300	-0.232	0.043	-0.0533	2.177
-10.40	0.00	800.00	0.4000	-0.859	0.093	-0.3438	13.727
-10.40	0.00	800.00	0.5300	-0.579	0.060	-0.3069	14.518
-10.40	0.00	800.00	0.7000	-0.014	-0.033	-0.0096	395.100
-10.40	0.00	800.00	0.8300	0.082	-0.027	0.0679	-19.756
-10.40	0.00	800.00	0.9400	0.092	-0.010	0.0869	14.023
-10.40	0.00	800.00	0.9700	0.014	-0.009	0.0139	-68.321
-10.40	0.00	800.00	1.0000	0.000	0.000	0.0000	0.000

Local Distribution

4sn.d 800 rpm 0m/s 0 Rudder No. 2 X/D=0.39

Angle	V	RPM	Span	Cn	Cmz	Cmx	Cpc
-0.40	0.00	800.00	0.0000	-0.023	0.005	-0.0016	-4.656
-0.40	0.00	800.00	0.0700	-0.023	0.005	-0.0016	-4.656
-0.40	0.00	800.00	0.2300	-0.105	0.032	-0.0242	-15.587
-0.40	0.00	800.00	0.4000	-0.644	0.075	-0.2574	12.521
-0.40	0.00	800.00	0.5300	-0.450	0.026	-0.2386	21.443
-0.40	0.00	800.00	0.7000	0.359	-0.087	0.2512	-6.546
-0.40	0.00	800.00	0.8300	0.417	-0.054	0.3464	10.701
-0.40	0.00	800.00	0.9400	0.146	-0.035	0.1369	-5.556
-0.40	0.00	800.00	0.9700	0.025	-0.026	0.0246	-122.385
-0.40	0.00	800.00	1.0000	0.000	0.000	0.0000	0.000

Local Distribution

5sn.d 800 rpm 0m/s +10 Rudder No. 2 X/D=0.39

Angle	V	RPM	Span	Cn	Cmz	Cmx	Cpc
9.60	0.00	800.00	0.0000	0.022	0.001	0.0016	38.251
9.60	0.00	800.00	0.0700	0.022	0.001	0.0016	38.251
9.60	0.00	800.00	0.2300	-0.005	0.018	-0.0013	-472.131
9.60	0.00	800.00	0.4000	-0.199	0.002	-0.0798	28.371
9.60	0.00	800.00	0.5300	-0.197	-0.012	-0.1045	38.970
9.60	0.00	800.00	0.7000	0.831	-0.060	0.5819	19.153
9.60	0.00	800.00	0.8300	0.810	-0.097	0.6726	11.952
9.60	0.00	800.00	0.9400	0.273	-0.041	0.2563	7.648
9.60	0.00	800.00	0.9700	0.124	-0.024	0.1207	0.950
9.60	0.00	800.00	1.0000	0.000	0.000	0.0000	0.000

Local Distribution

6sn.d 800 rpm 0m/s +20 Rudder No. 2 X/D=0.39

Angle	V	RPM	Span	Cn	Cmz	Cmx	Cpc
19.60	0.00	800.00	0.0000	0.006	-0.003	0.0005	-36.616
19.60	0.00	800.00	0.0700	0.006	-0.003	0.0005	-36.616
19.60	0.00	800.00	0.2300	0.156	-0.004	0.0358	26.541
19.60	0.00	800.00	0.4000	0.245	-0.042	0.0981	4.403
19.60	0.00	800.00	0.5300	0.075	-0.066	0.0398	-101.928
19.60	0.00	800.00	0.7000	1.134	-0.058	0.7937	22.363
19.60	0.00	800.00	0.8300	1.243	-0.108	1.0314	16.966
19.60	0.00	800.00	0.9400	0.444	-0.046	0.4178	14.459
19.60	0.00	800.00	0.9700	0.238	-0.026	0.2312	13.760
19.60	0.00	800.00	1.0000	0.000	0.000	0.0000	0.000

Local Distribution

7sn.d 800 rpm 0m/s +30 Rudder No. 2 X/D=0.39

Angle	V	RPM	Span	Cn	Cmz	Cmx	Cpc
29.60	0.00	800.00	0.0000	0.057	0.015	0.0040	70.316
29.60	0.00	800.00	0.0700	0.057	0.015	0.0040	70.316
29.60	0.00	800.00	0.2300	0.226	-0.013	0.0520	21.142
29.60	0.00	800.00	0.4000	0.462	-0.103	0.1847	-3.493
29.60	0.00	800.00	0.5300	0.325	-0.095	0.1723	-13.937
29.60	0.00	800.00	0.7000	1.360	-0.055	0.9518	23.915
29.60	0.00	800.00	0.8300	1.440	-0.089	1.1955	20.675
29.60	0.00	800.00	0.9400	0.663	-0.032	0.6229	22.835
29.60	0.00	800.00	0.9700	0.410	-0.010	0.3977	26.239
29.60	0.00	800.00	1.0000	0.000	0.000	0.0000	0.000

Local Distribution

1tn.d 1460 rpm 0m/s -30 Rudder No. 2 X/D=0.39

Angle	V	RPM	Span	Cn	Cmz	Cmx	Cpc
-30.40	0.00	1460.00	0.0000	-0.488	-0.067	-0.0342	50.540
-30.40	0.00	1460.00	0.0700	-0.488	-0.067	-0.0342	50.540
-30.40	0.00	1460.00	0.2300	-0.610	0.036	-0.1402	21.187
-30.40	0.00	1460.00	0.4000	-1.416	0.095	-0.5666	19.973
-30.40	0.00	1460.00	0.5300	-0.960	0.055	-0.5088	21.362
-30.40	0.00	1460.00	0.7000	-0.696	0.076	-0.4873	13.640
-30.40	0.00	1460.00	0.8300	-0.625	0.043	-0.5191	19.749
-30.40	0.00	1460.00	0.9400	-0.121	0.034	-0.1139	-12.398
-30.40	0.00	1460.00	0.9700	-0.001	0.021	-0.0013	-2233.721
-30.40	0.00	1460.00	1.0000	0.000	0.000	0.0000	0.000

Local Distribution

2tn.d 1460 rpm 0m/s -20 Rudder No. 2 X/D=0.39

Angle	V	RPM	Span	Cn	Cmz	Cmx	Cpc
-20.40	0.00	1460.00	0.0000	-0.237	-0.039	-0.0166	54.806
-20.40	0.00	1460.00	0.0700	-0.237	-0.039	-0.0166	54.806
-20.40	0.00	1460.00	0.2300	-0.402	0.040	-0.0925	14.950
-20.40	0.00	1460.00	0.4000	-1.192	0.097	-0.4768	17.742
-20.40	0.00	1460.00	0.5300	-0.788	0.059	-0.4178	18.808
-20.40	0.00	1460.00	0.7000	-0.326	0.043	-0.2282	10.351
-20.40	0.00	1460.00	0.8300	-0.262	0.012	-0.2178	23.030
-20.40	0.00	1460.00	0.9400	-0.047	0.001	-0.0446	28.289
-20.40	0.00	1460.00	0.9700	0.025	0.003	0.0240	46.594
-20.40	0.00	1460.00	1.0000	0.000	0.000	0.0000	0.000

Local Distribution

3tn.d 1460 rpm 0m/s -10 Rudder No. 2 X/D=0.39

Angle	V	RPM	Span	Cn	Cmz	Cmx	Cpc
-10.40	0.00	1460.00	0.0000	-0.085	-0.012	-0.0059	50.913
-10.40	0.00	1460.00	0.0700	-0.085	-0.012	-0.0059	50.913
-10.40	0.00	1460.00	0.2300	-0.238	0.043	-0.0548	2.616
-10.40	0.00	1460.00	0.4000	-0.871	0.086	-0.3482	15.094
-10.40	0.00	1460.00	0.5300	-0.556	0.059	-0.2947	14.037
-10.40	0.00	1460.00	0.7000	-0.031	-0.029	-0.0219	169.602
-10.40	0.00	1460.00	0.8300	0.041	-0.035	0.0338	-99.021
-10.40	0.00	1460.00	0.9400	0.054	-0.006	0.0505	12.137
-10.40	0.00	1460.00	0.9700	0.003	-0.011	0.0034	-445.346
-10.40	0.00	1460.00	1.0000	0.000	0.000	0.0000	0.000

Local Distribution

4tn.d 1460 rpm 0m/s 0 Rudder No. 2 X/D=0.39

Angle	V	RPM	Span	Cn	Cmz	Cmx	Cpc
-0.40	0.00	1460.00	0.0000	-0.011	0.001	-0.0008	17.254
-0.40	0.00	1460.00	0.0700	-0.011	0.001	-0.0008	17.254
-0.40	0.00	1460.00	0.2300	-0.088	0.034	-0.0202	-27.876
-0.40	0.00	1460.00	0.4000	-0.489	0.068	-0.1955	9.141
-0.40	0.00	1460.00	0.5300	-0.409	0.029	-0.2168	19.224
-0.40	0.00	1460.00	0.7000	0.306	-0.075	0.2139	-6.925
-0.40	0.00	1460.00	0.8300	0.459	-0.048	0.3807	14.398
-0.40	0.00	1460.00	0.9400	0.105	-0.035	0.0991	-20.260
-0.40	0.00	1460.00	0.9700	0.027	-0.019	0.0265	-73.780
-0.40	0.00	1460.00	1.0000	0.000	0.000	0.0000	0.000

Local Distribution

5tn.d 1460 rpm 0m/s +10 Rudder No. 2 X/D=0.39

Angle	V	RPM	Span	Cn	Cmz	Cmx	Cpc
9.60	0.00	1460.00	0.0000	0.012	0.005	0.0008	94.759
9.60	0.00	1460.00	0.0700	0.012	0.005	0.0008	94.759
9.60	0.00	1460.00	0.2300	0.011	0.004	0.0025	87.063
9.60	0.00	1460.00	0.4000	-0.168	0.007	-0.0671	23.568
9.60	0.00	1460.00	0.5300	-0.196	-0.009	-0.1037	36.820
9.60	0.00	1460.00	0.7000	0.794	-0.061	0.5556	18.547
9.60	0.00	1460.00	0.8300	0.786	-0.090	0.6521	12.722
9.60	0.00	1460.00	0.9400	0.262	-0.044	0.2458	4.714
9.60	0.00	1460.00	0.9700	0.108	-0.023	0.1048	-2.475
9.60	0.00	1460.00	1.0000	0.000	0.000	0.0000	0.000

Local Distribution

6tn.d 1460 rpm 0m/s +20 Rudder No. 2 X/D=0.39

Angle	V	RPM	Span	Cn	Cmz	Cmx	Cpc
19.60	0.00	1460.00	0.0000	-0.002	0.004	-0.0001	-360.391
19.60	0.00	1460.00	0.0700	-0.002	0.004	-0.0001	-360.391
19.60	0.00	1460.00	0.2300	0.106	-0.008	0.0243	18.066
19.60	0.00	1460.00	0.4000	0.180	-0.048	0.0718	-10.065
19.60	0.00	1460.00	0.5300	0.033	-0.052	0.0175	-206.071
19.60	0.00	1460.00	0.7000	1.141	-0.060	0.7989	22.143
19.60	0.00	1460.00	0.8300	1.095	-0.091	0.9086	17.557
19.60	0.00	1460.00	0.9400	0.463	-0.045	0.4355	15.280
19.60	0.00	1460.00	0.9700	0.226	-0.020	0.2195	16.881
19.60	0.00	1460.00	1.0000	0.000	0.000	0.0000	0.000

Local Distribution

7tn.d 1460 rpm 0m/s +30 Rudder No. 2 X/D=0.39

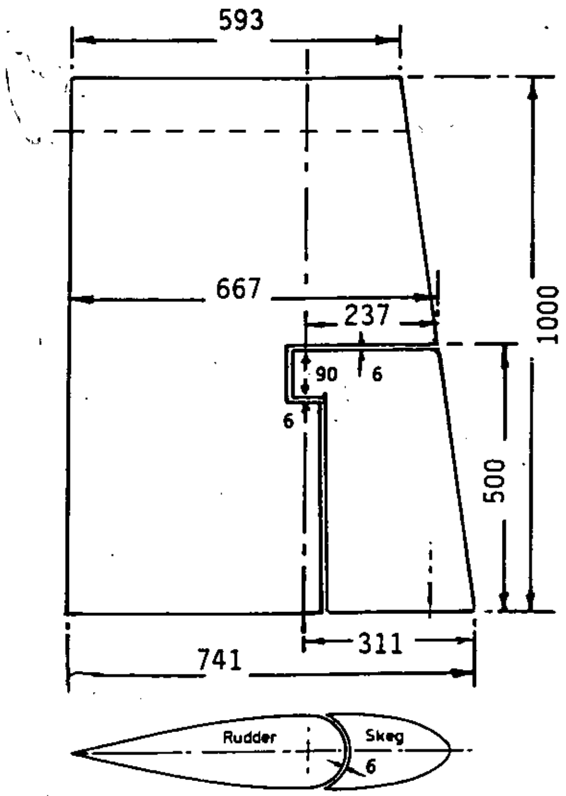
Angle	V	RPM	Span	Cn	Cmz	Cmx	Cpc
29.60	0.00	1460.00	0.0000	0.086	0.018	0.0060	60.940
29.60	0.00	1460.00	0.0700	0.086	0.018	0.0060	60.940
29.60	0.00	1460.00	0.2300	0.254	-0.016	0.0583	20.570
29.60	0.00	1460.00	0.4000	0.506	-0.107	0.2024	-1.862
29.60	0.00	1460.00	0.5300	0.342	-0.090	0.1810	-9.620
29.60	0.00	1460.00	0.7000	1.445	-0.049	1.0117	24.902
29.60	0.00	1460.00	0.8300	1.482	-0.085	1.2303	21.399
29.60	0.00	1460.00	0.9400	0.711	-0.037	0.6680	22.241
29.60	0.00	1460.00	0.9700	0.418	-0.011	0.4053	26.057
29.60	0.00	1460.00	1.0000	0.000	0.000	0.0000	0.000

Table I Rudder Particulars

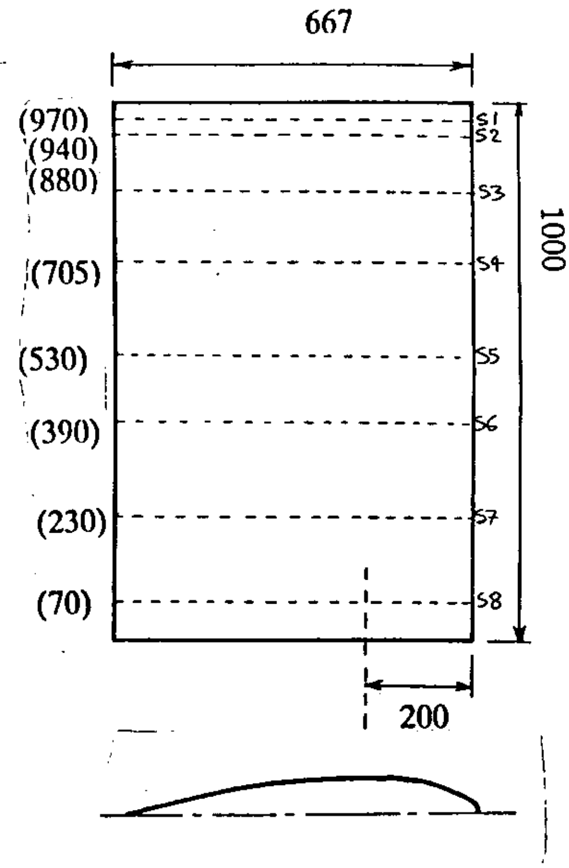
Type	:	Semi-balanced	All-Movable
Rudder Number	:	0	2
Mean Chord c mm	:	667	667
Span S mm	:	1000	1000
Geometric Aspect Ratio AR_G	:	3.0	3.0
Taper Ratio C_T/C_R	:	0.80	1.0
Thickness/Chord ratio t/c	:	0.20	0.20
Section	:	NACA0020 Root and Tip with square ends	

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



RUDDER No.0
(Skeg Rudder)



SECTION: NACA 0020

Chordwise position of tappings (%c from L.E.):
0, 2.5, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95

Figure 1 Overall dimensions of rudder models

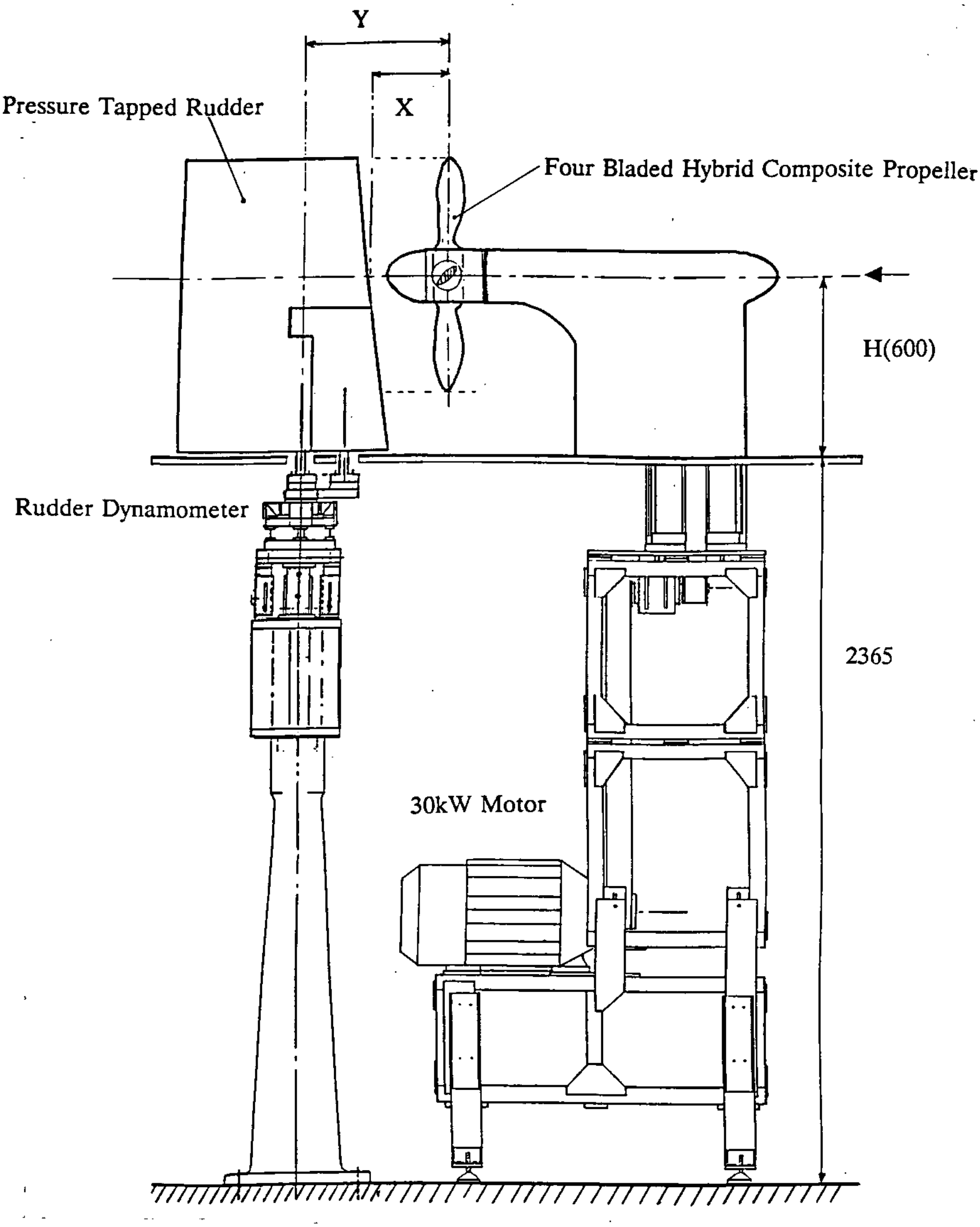


Figure 2 Side view of overall rudder and propeller rigs

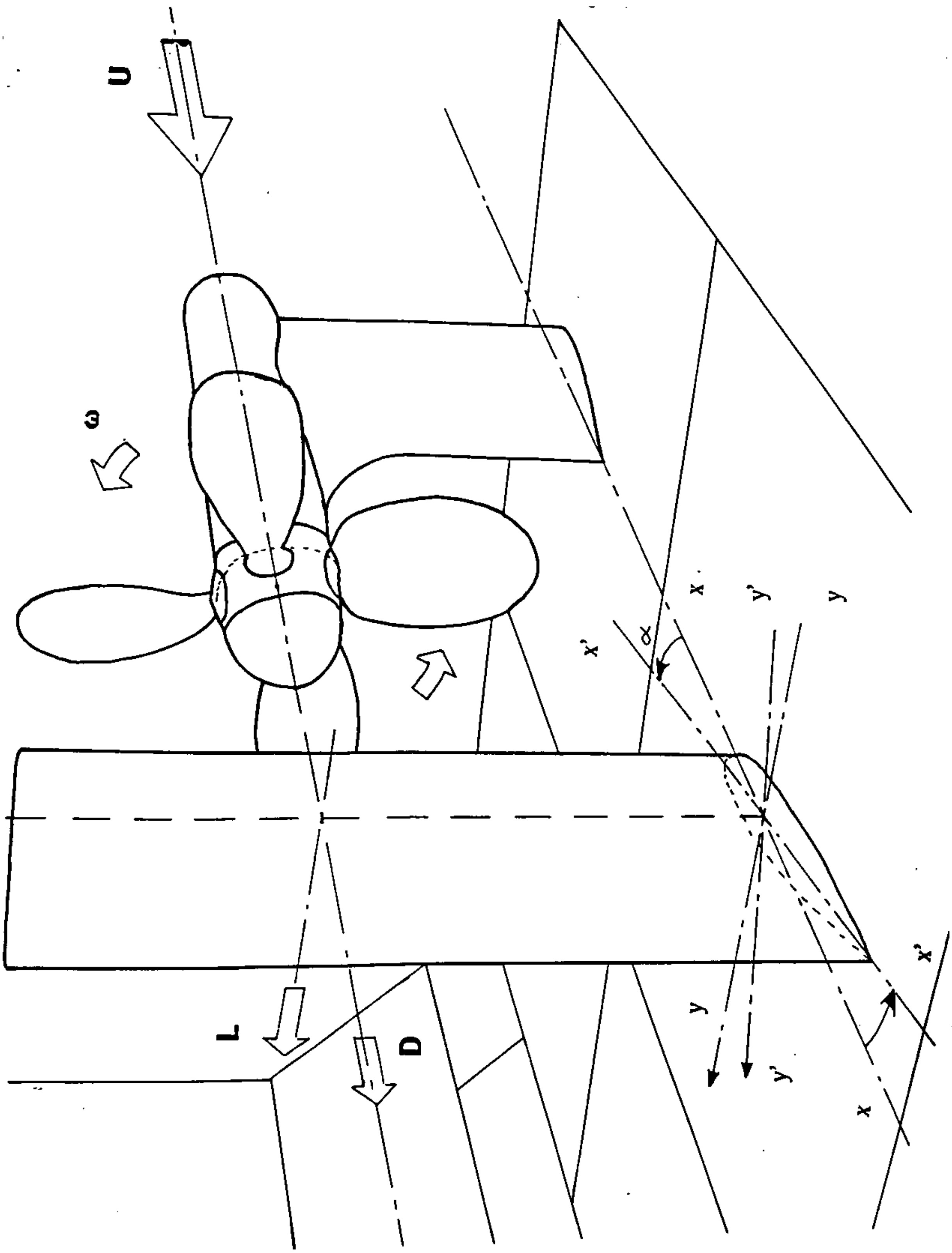


Figure 3 Schematic view of rudder-propeller models

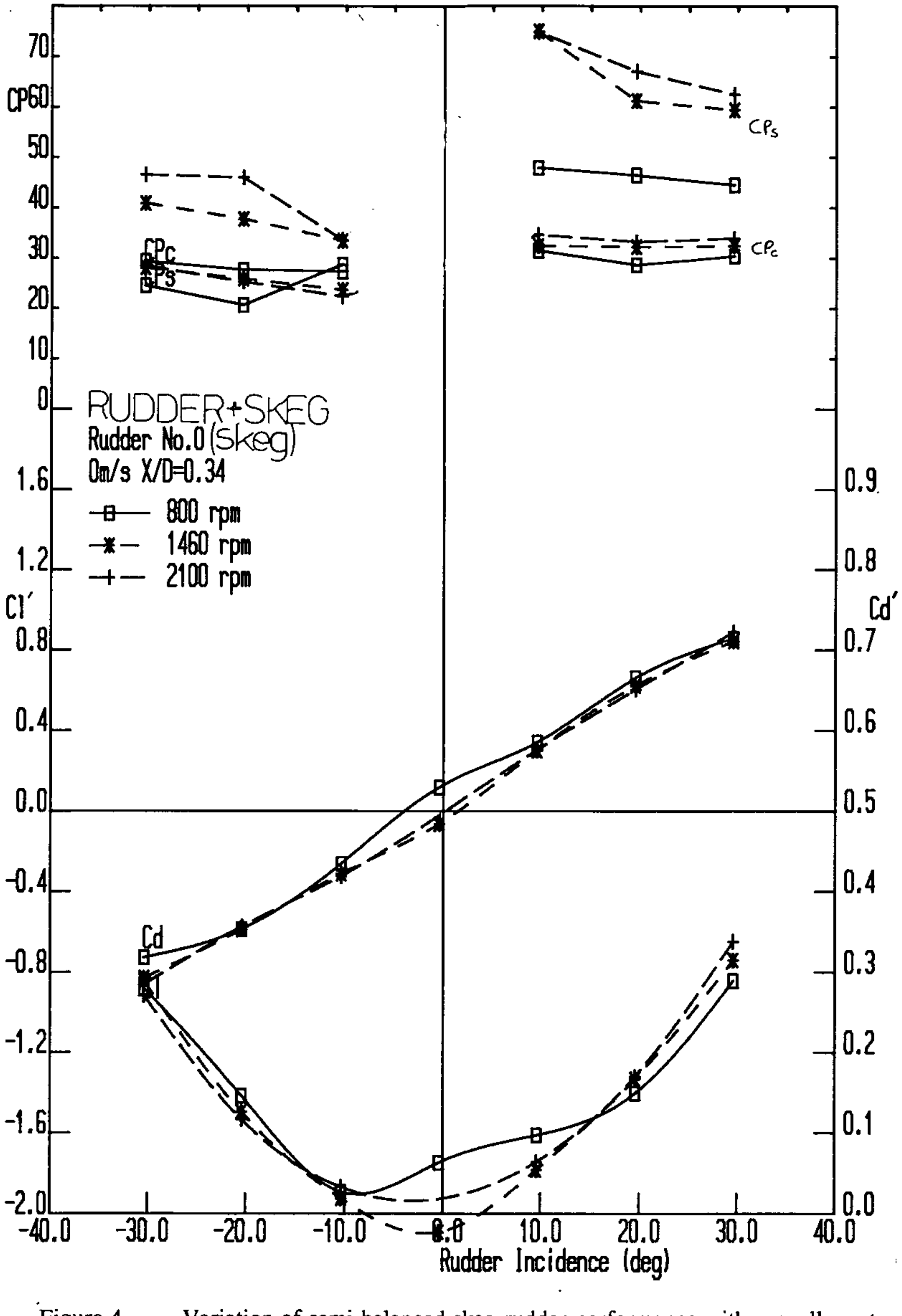


Figure 4 Variation of semi-balanced skeg rudder performance with propeller rate of revolution

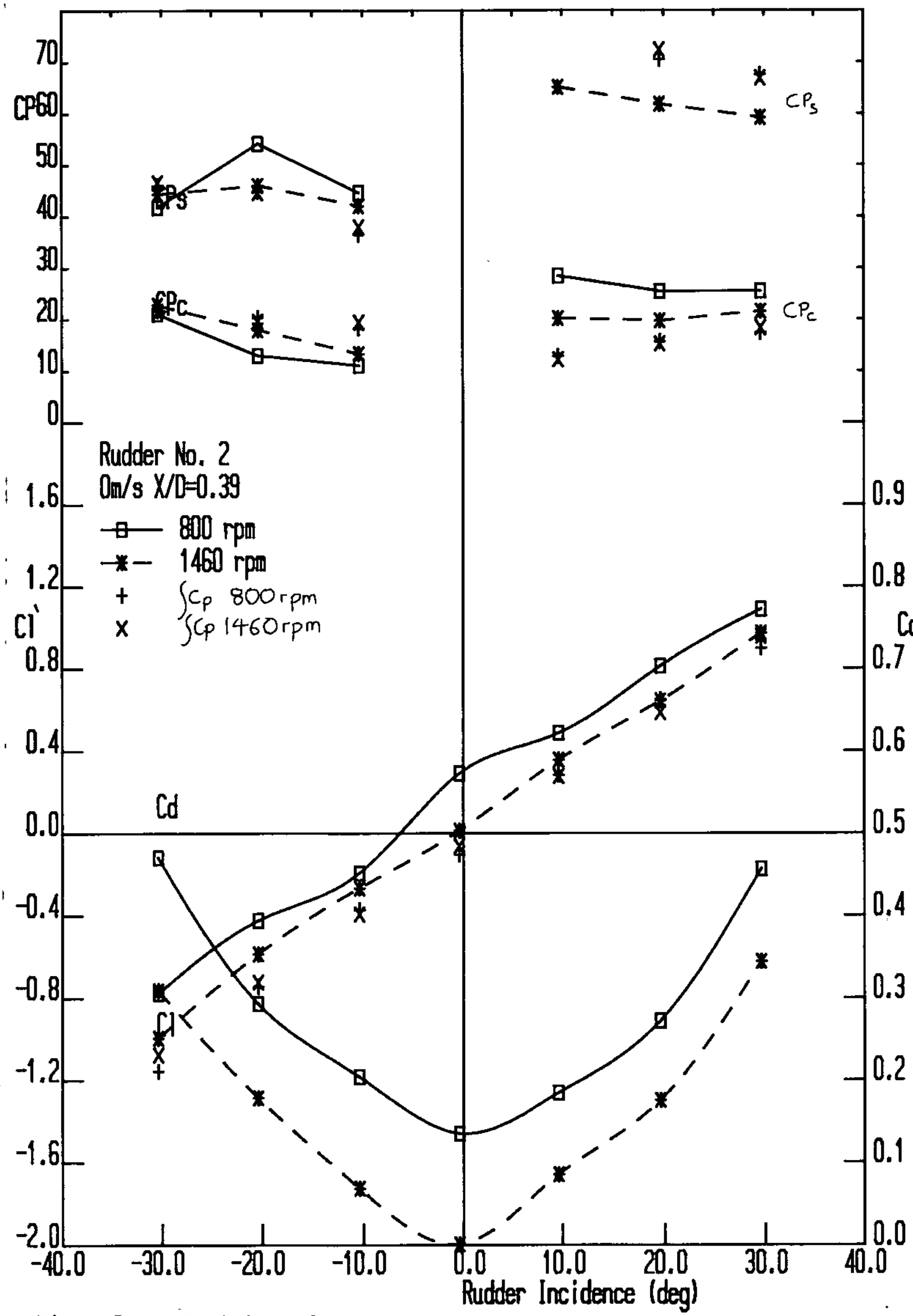


Figure 5 Variation of all-movable rudder performance with propeller rate of revolution

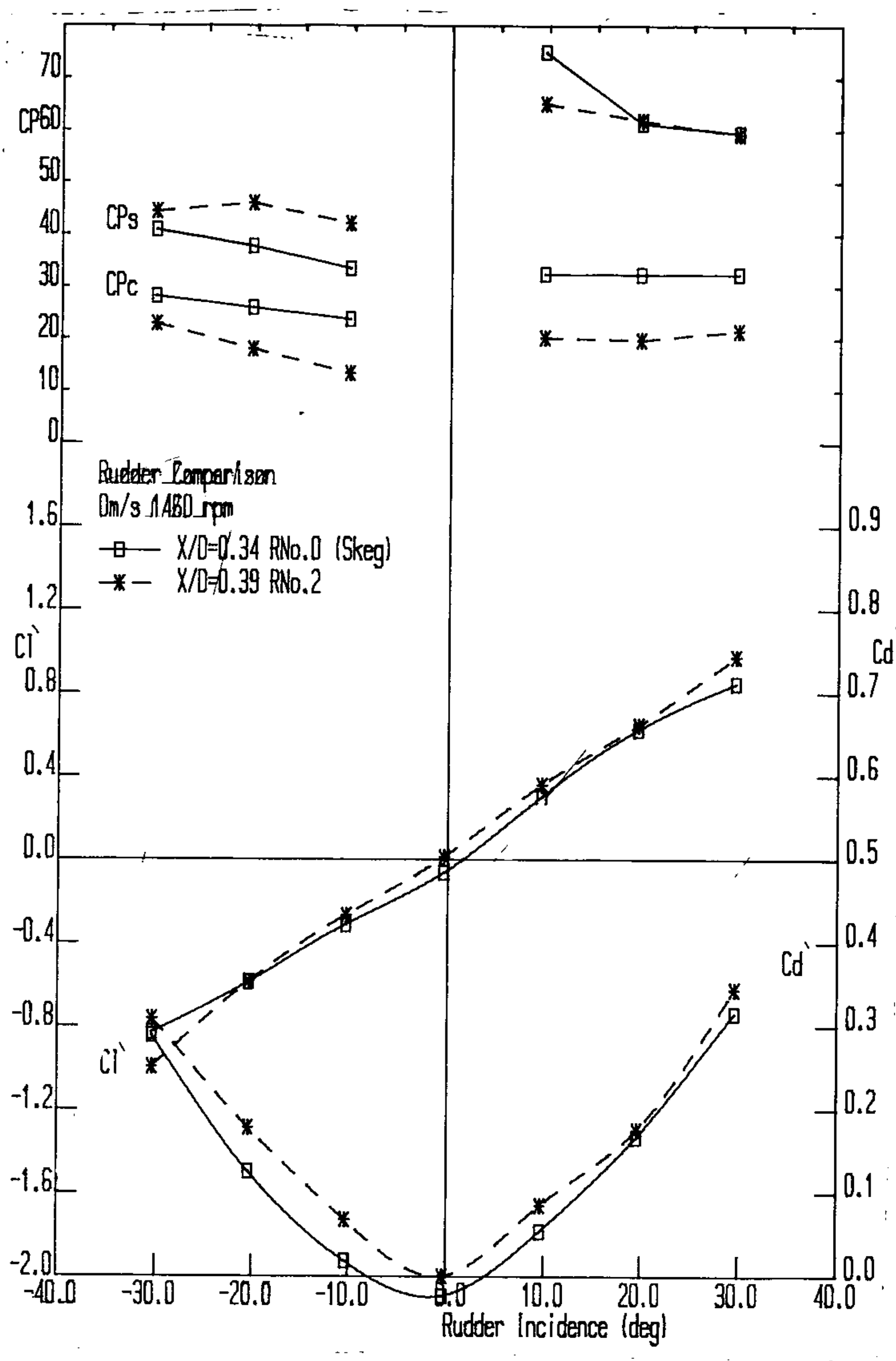


Figure 6 Comparison of rudder performance between all-movable Rudder No.2 and semi-balanced skeg Rudder No.0. at a rotation speed of 1460rpm

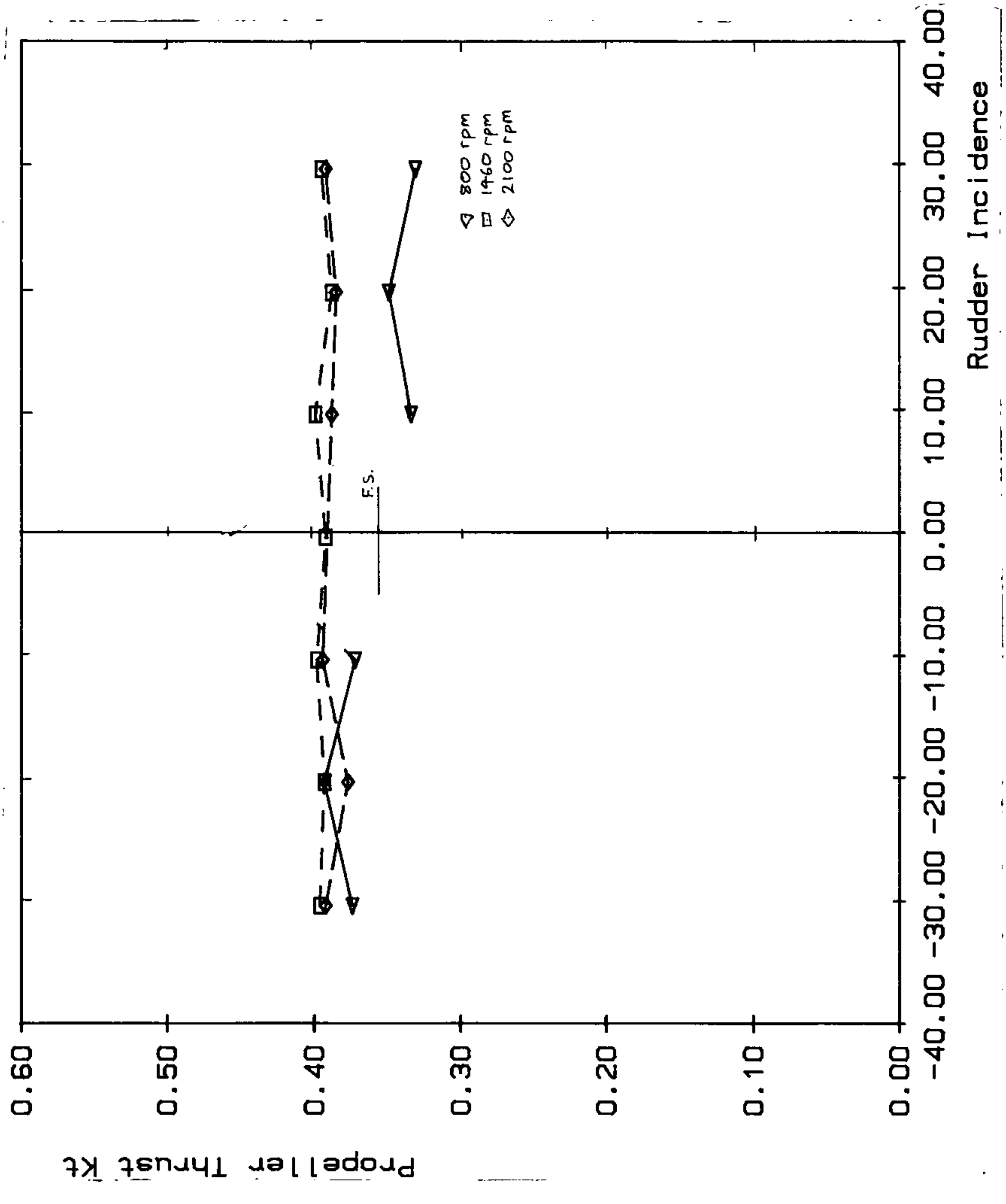


Figure 7 Influence of semi-balance skeg rudder incidence on propeller thrust for different rotational speeds

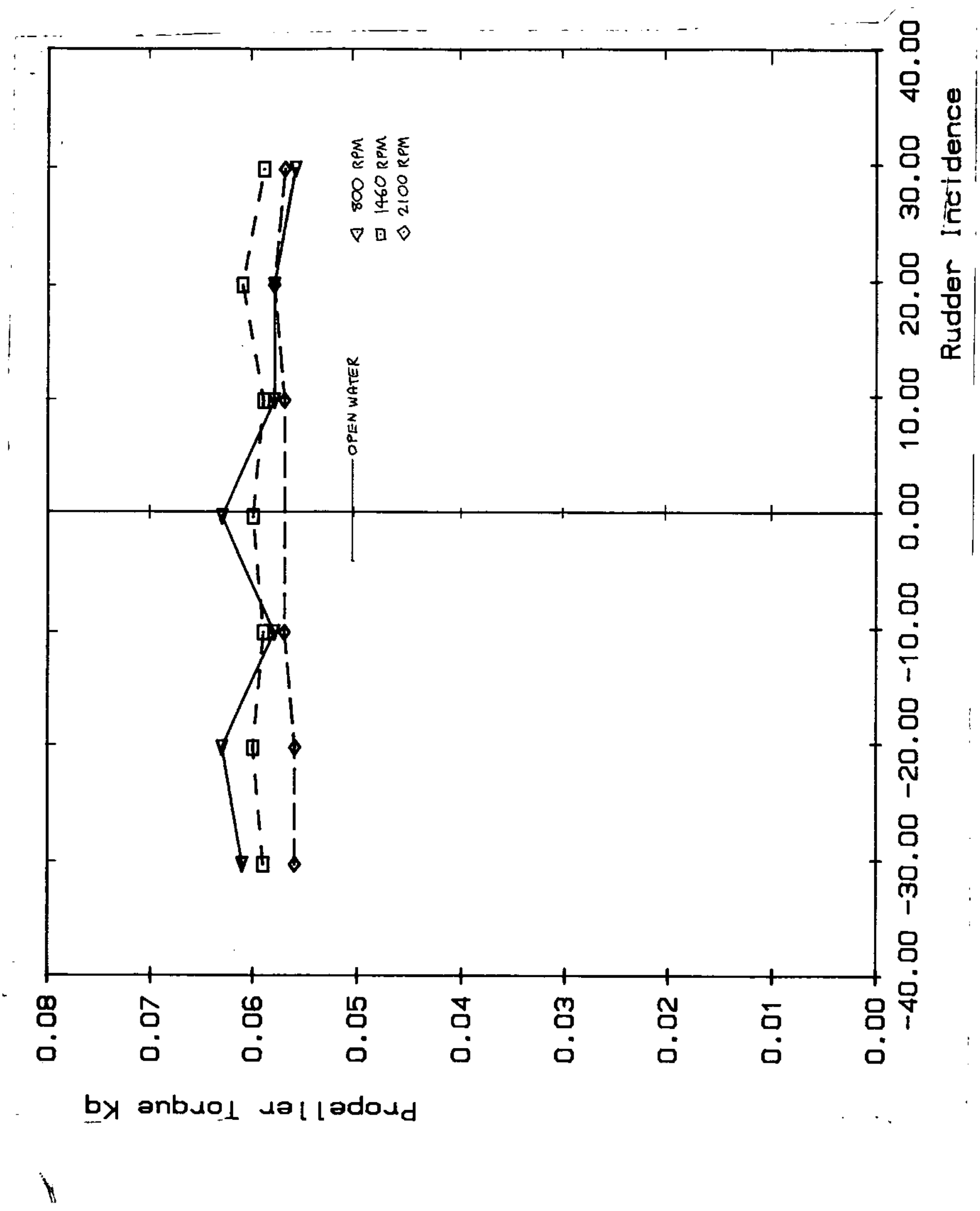


Figure 8 Influence of semi-balanced skeg rudder incidence on propeller torque for different rotational speeds

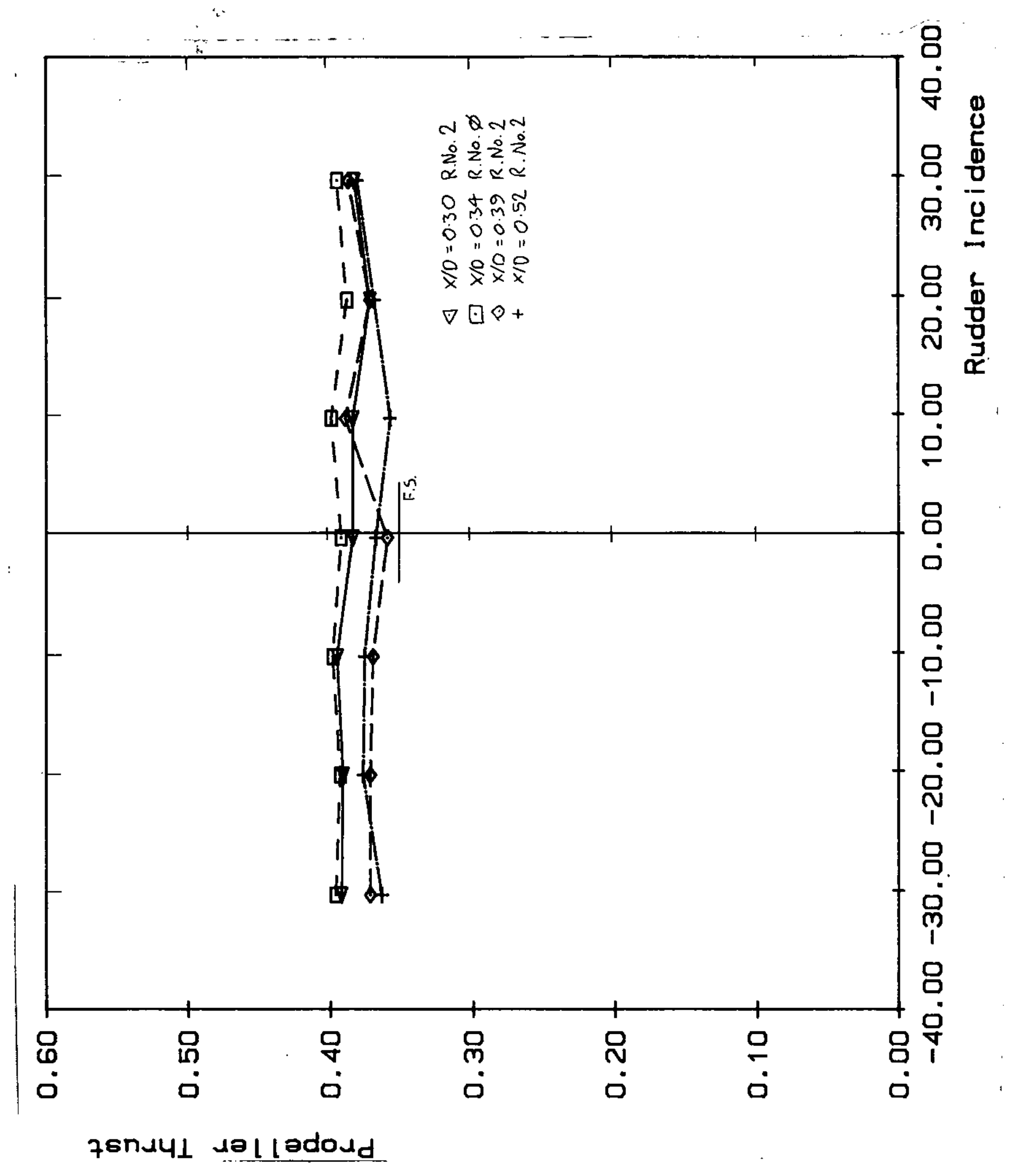


Figure 9 Influence of all-movable rudder incidence on propeller thrust for different longitudinal separations of rudder and propeller

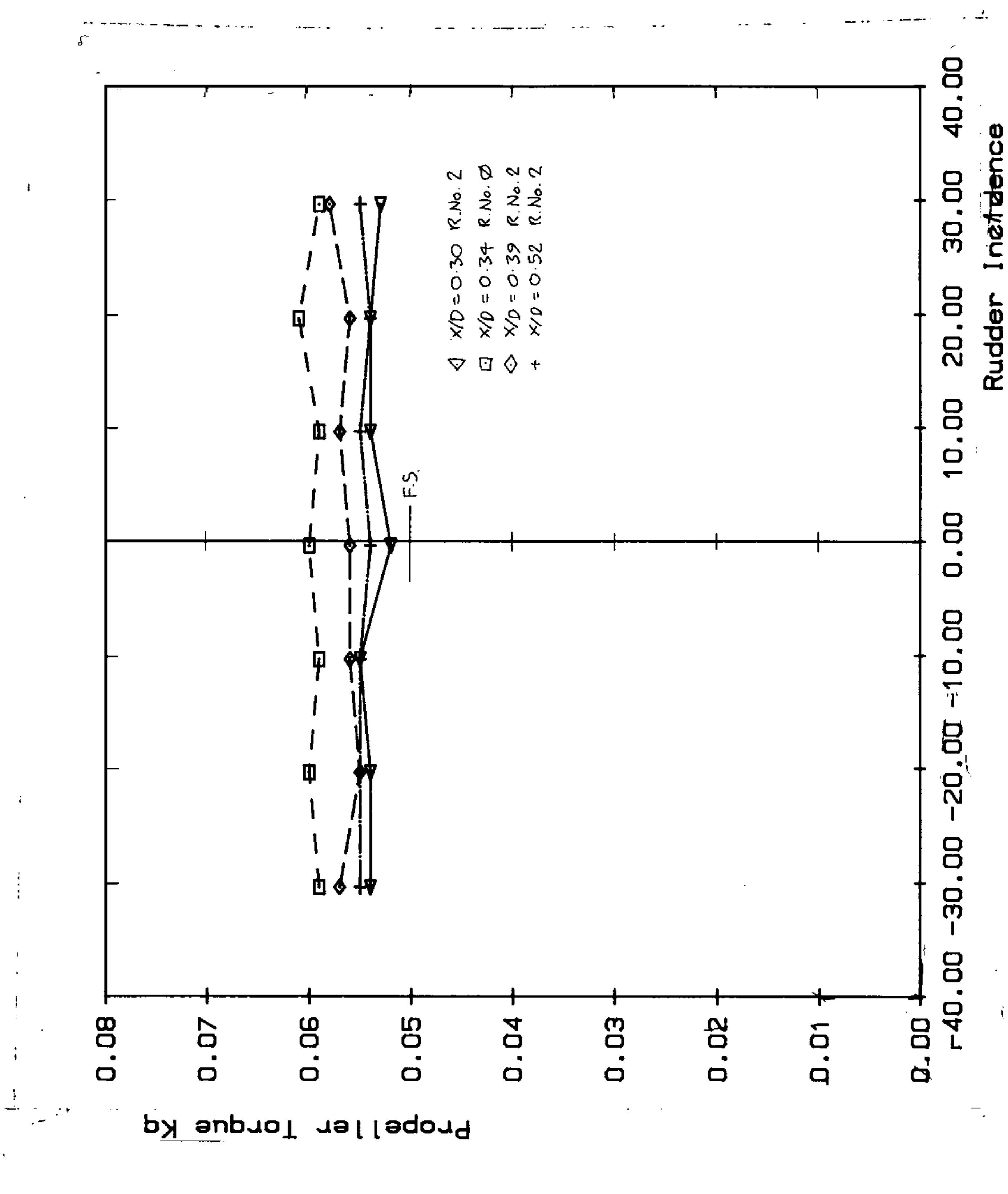


Figure 10 Influence of all-movable rudder incidence on propeller torque for different longitudinal separations of rudder and propeller

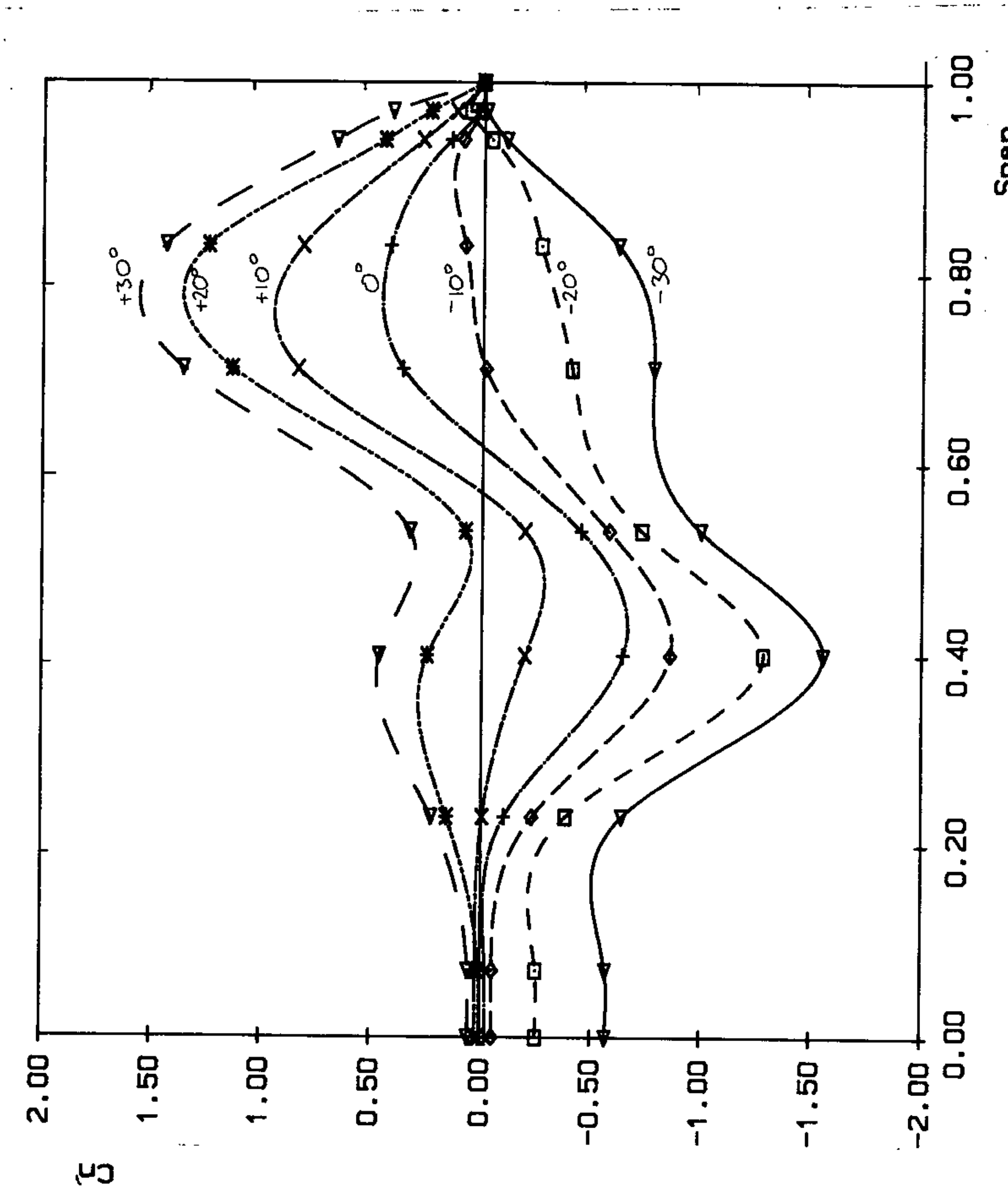


Figure 11 Variation with rudder incidence of the spanwise distribution of local section Cn' of all-movable Rudder No. 2 at a propeller rate of rotation of 800 rpm

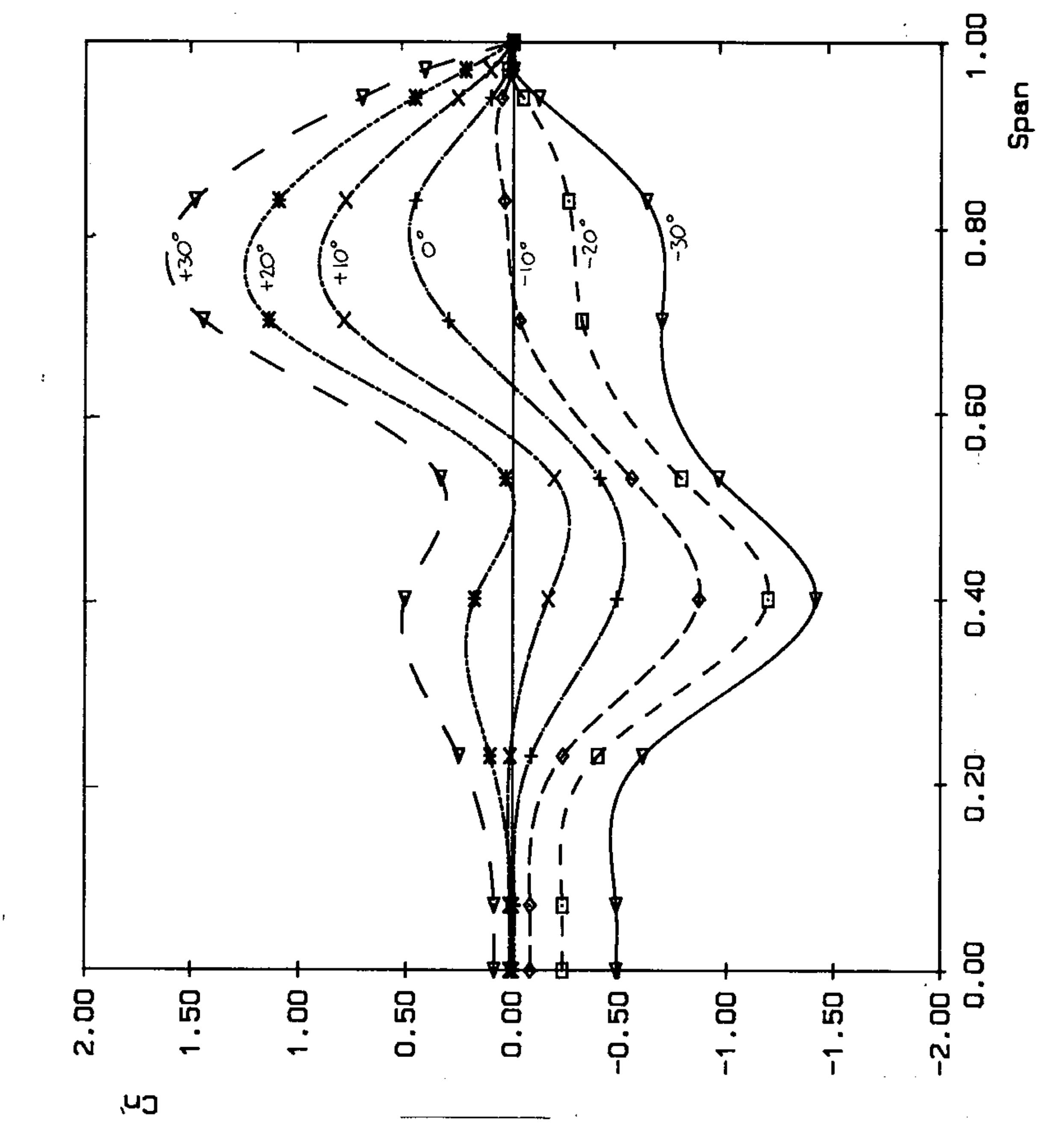


Figure 12 Variation with rudder incidence of the spanwise distribution of local section Cn'of all-movable Rudder No. 2 at a propeller rate of rotation of 1460 rpm

ΔCp'=5, Max Cp=5, Min Cp=-10

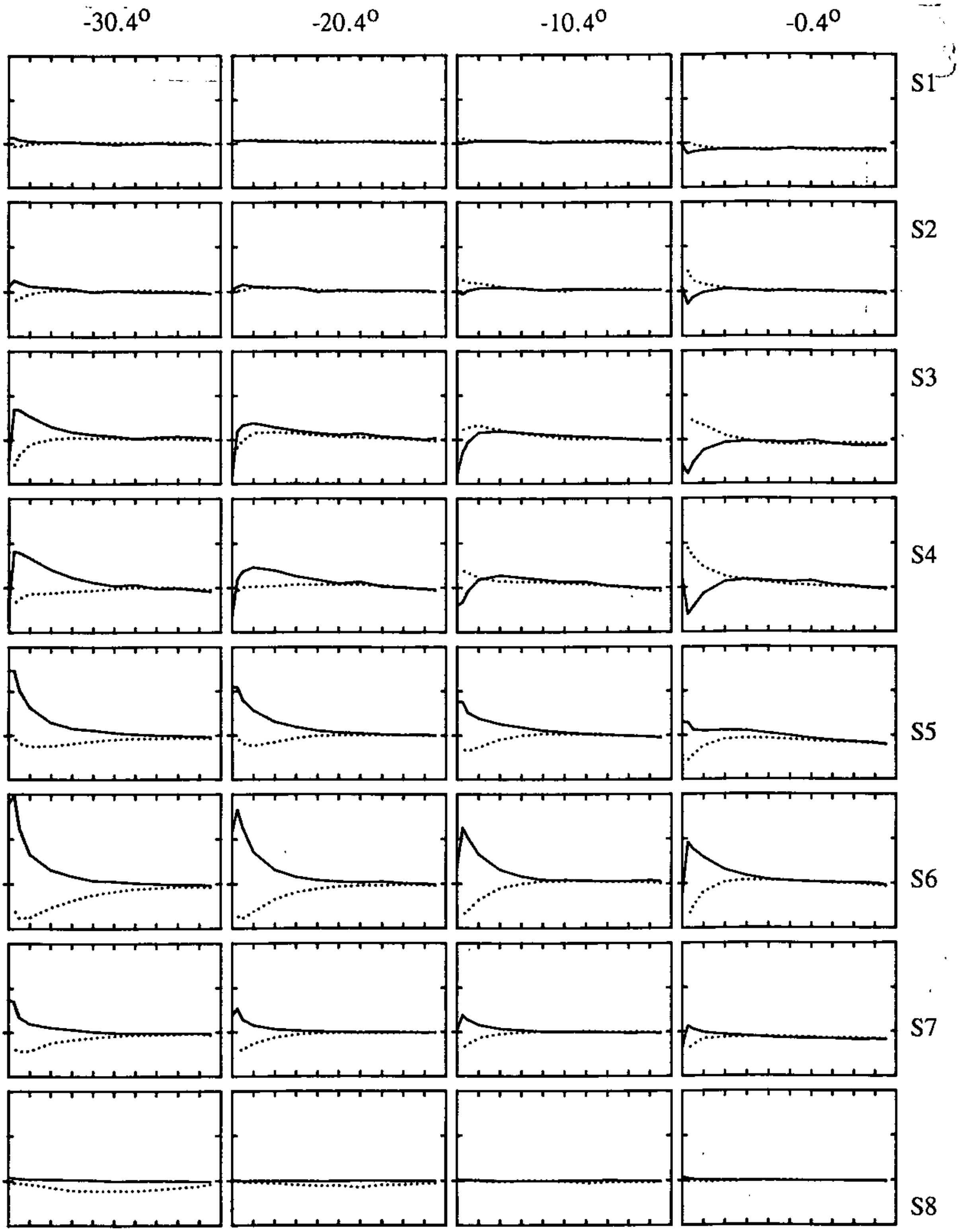


Figure 13 Chordwise pressure distributions at 8 spanwise positions for all-movable Rudder No. 2 at 800 rpm for rudder incidences between -30.4° and 29.6°

ΔCp'=5, Max Cp=5, Min Cp=-10

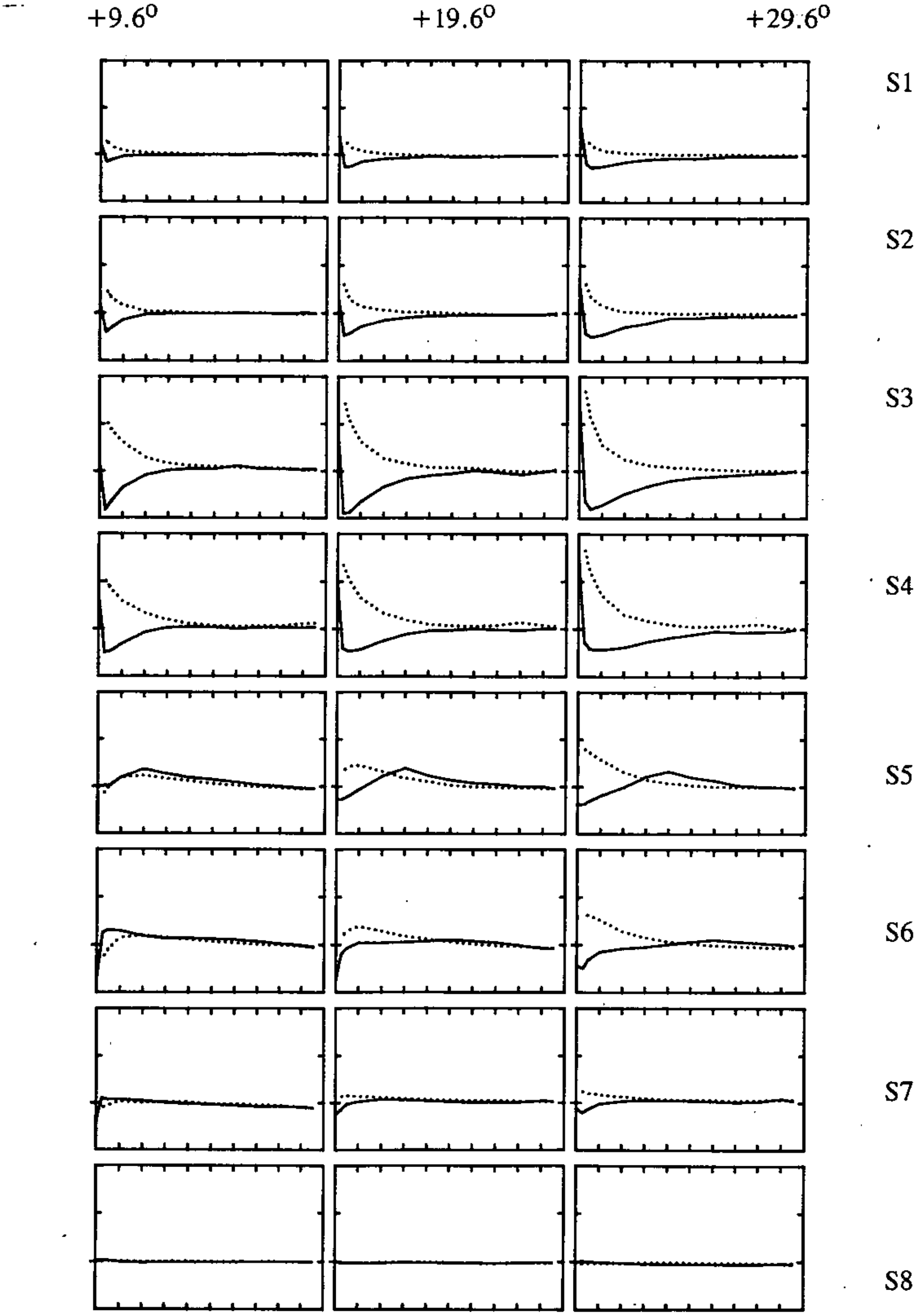


Figure 13 Chordwise pressure distributions at 8 spanwise positions for all-movable Rudder No. 2 at 800 rpm for rudder incidences between -30.4° and 29.6°

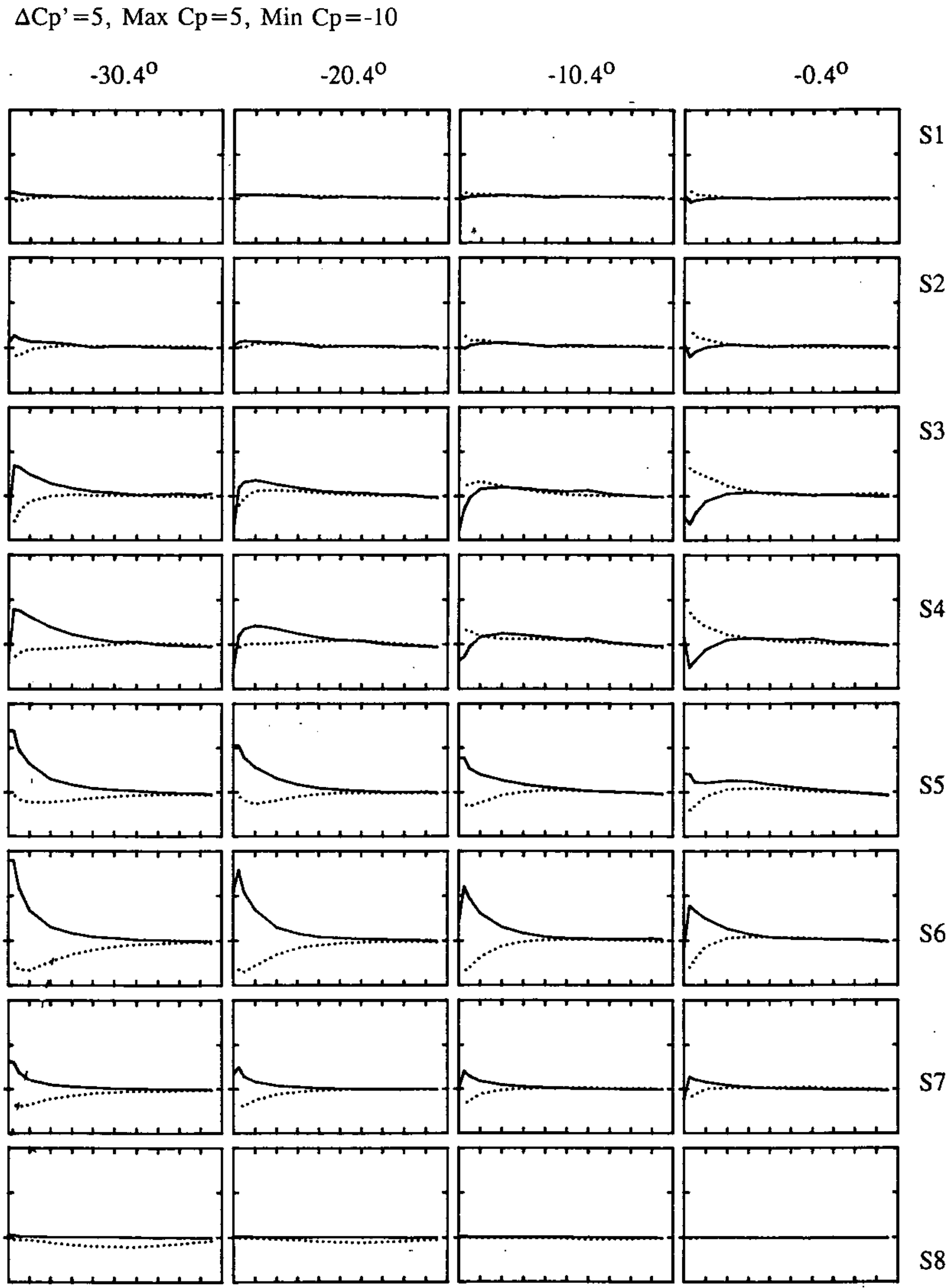


Figure 14 Chordwise pressure distributions at 8 spanwise positions for all-movable Rudder No. 2 at 1460 rpm for rudder incidences between -30.4° and 29.6°

ΔCp'=5, Max Cp=5, Min Cp=-10

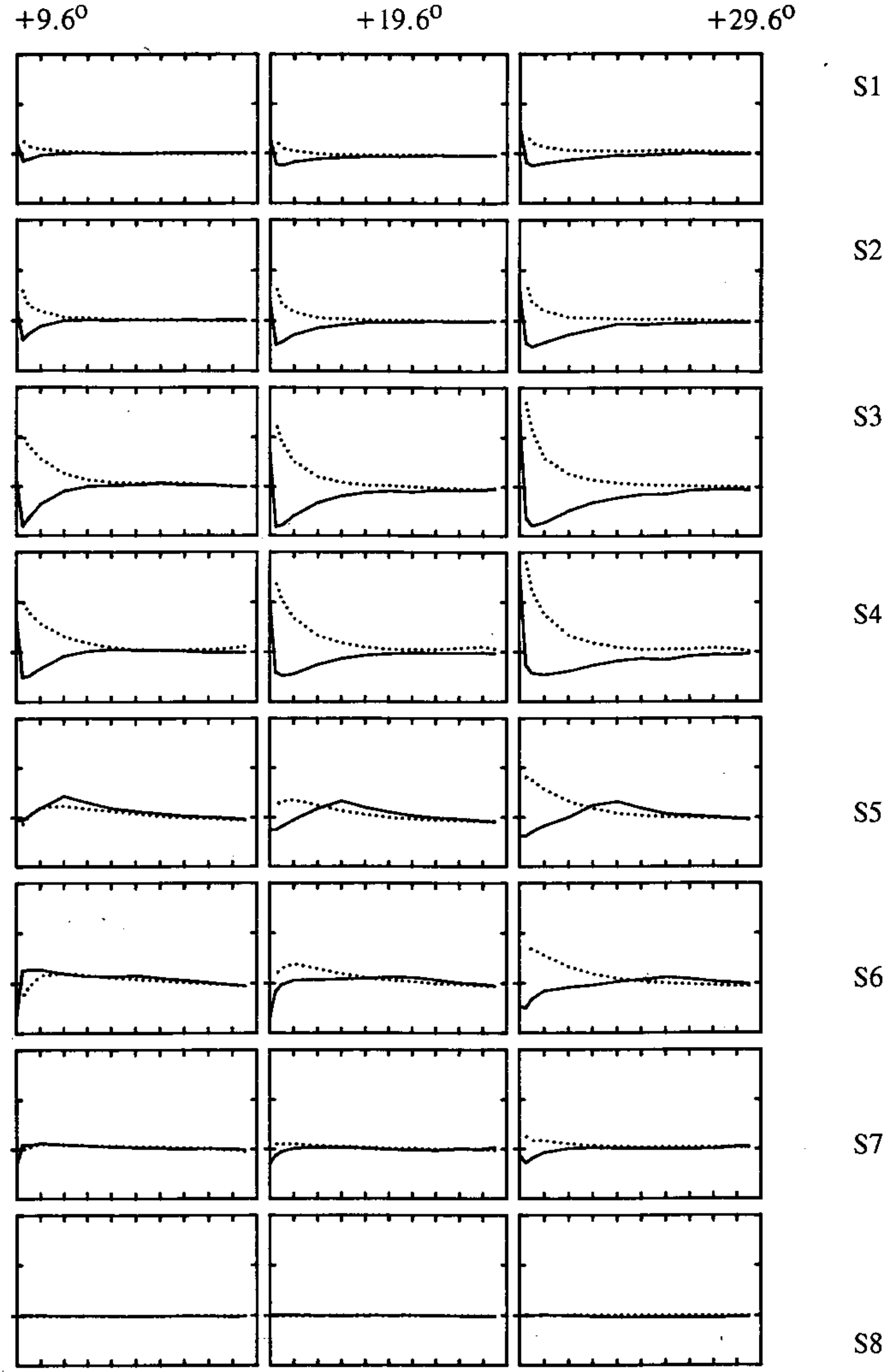


Figure 14 Chordwise pressure distributions at 8 spanwise positions for all-movable Rudder No. 2 at 1460 rpm for rudder incidences between -30.4° and 29.6°