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The aerodynamic characteristics of a family of related hovercraft shapes

- by -

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SUMMARY

The handling qualities of hovercraft indicate the need for a better understanding of the influence of the basic aerodynamic characteristics.

This report is the first of a series in which the aerodynamic characteristics of hovercraft shapes are studied with particular reference to current design variables starting with simple solid block models and progressing to more sophisticated hollow models having cushion efflux and air-induction.

This work was conducted under contract for the Ministry of Technology, Ref. Contract No. C1110.

Contents

List of symbols

$C_{D,\ Y,\ L}$	non-dimensional force coefficients along X, Y and Z wind axes $= \frac{\text{Force (lb)}}{\frac{1}{2}\rho V^2 \ell b}$
$C_{\ell,\ m,\ n}$	non-dimensional moment coefficients about X, Y and Z wind axes $= \frac{\text{Moment (lb ft)}}{\frac{1}{2}\rho V^2 \ell b^2}$
b	overall beam, feet
ℓ	overall length, feet
R	non-dimensional Reynolds number $= \frac{V\ell\rho}{\mu}$
V	flow velocity, feet/second
ρ	density, slugs/cu.ft.
μ	viscosity, lb seconds/sq.ft.

1. Introduction

Recent and rapid advances in hovercraft technology and development have made it abundantly clear that as yet a full understanding of the handling qualities of the amphibious hovercraft is far from complete.

These handling qualities encompassing all aspects of stability, control, manoeuvrability and performance depend upon the interaction of three effects; namely, aerodynamic, hydrodynamic and air-cushion effects. The last of these three effects is reasonably amenable to analytical treatment. The first two are at present heavily dependent on experimental techniques and results. In the case of aerodynamic effects, the problem concerns the bluff body at angles of yaw frequently as great as 180°; in the case of hydrodynamic effects, the problem concerns the continual or impulsive contact of a flexible structure with a liquid medium rather than the better-understood problem of the submersion of a rigid body.

The substance of this report is concerned solely with the aerodynamic effects in an attempt to evaluate their contribution to the following unfavourable handling qualities that have been experienced to date by amphibious hovercraft:

(a) plough-in, a vicious pitching-rolling motion accompanying a high yaw rate that on occasions has resulted in overturning;

(b) excessive changes of longitudinal trim between up-wind and down-wind operation, and between propulsive power-on and power-off conditions, which result in control difficulties leading to the plough-in problem;

(c) cross-wind effects which, if excessive, place unreasonable demands on lateral control devices, particularly so at low speeds if lateral drift is to be avoided; furthermore, excessive deviation from neutral weathercock stability, either in a positive or in a negative sense, and throughout a full 360° yaw range, giving rise to control difficulties;

(d) momentum interference between the mutually perpendicular lift and thrust systems which, if excessive, leads to a general loss of operating efficiency.

Such unfavourable qualities as those briefly mentioned above are influenced, undoubtedly to some extent not yet fully assessed, by the aerodynamic characteristics of the hovercraft. With this thought in mind it was decided to explore the aerodynamic characteristics of a family of related hovercraft shapes by wind-tunnel testing, in a systematic fashion, and by altering such variables as were known (ref. 1) or were thought to be of some significance. The test programme was developed in conjunction with the Royal Aircraft Establishment at Farnborough and Bedford, and with Hovercraft Development Limited.

2. Wind Tunnel Models

Bearing in mind that the aerodynamic characteristics of these hovercraft shapes would be significantly affected by the cushion efflux from beneath the skirt, and by the location of the air-induction system, it was decided that the overall programme should proceed in the following sequence.

(a) Solid models of basic shapes.

(b) Solid models with cushion efflux.

(c) Hollow models with air-induction and cushion efflux.

For the first series of tests in the above sequence, on account of tunnel availability, it was necessary to restrict the length of models to 12 inches and to employ the vortex-image technique using a 'live' model in the presence of an 'image' model to simulate the ground plane.

The R.A.E. tests (ref. 1) had shown the deck planform of the hovercraft to be of second-order aerodynamic effect. As a consequence, and in keeping with contemporary full-scale practice, the solid models were of invariant deck planform with a 2/1 length/beam ratio and a $1\frac{1}{2}/1$ skirt-depth/deck-thickness ratio.

The effects of the following variables on aerodynamic characteristics were the subject of test evaluation:

(a) shape of skirt panels;
(b) longitudinal edge radius of deck;
(c) foredeck length;
(d) height of superstructure above deck;
(e) inclination of sides of superstructure;
(f) edge radii of superstructure.

The related hovercraft shapes for the solid model tests are shown in Fig. 1 and typical building blocks for these models are shown in Fig. 2.

2.1 Configuration designations

All configurations are listed in Table 1. The configurations are described by subscripts, or in one instance by a superscript, to the basic designation KFSR, where K indicates skirt with subscripts S for straight panels, 45 for panels constructed from a radius intersecting the ground plane at 45°, and 60 for the similarly constructed panels intersecting at 60°.

F indicates foredeck length with subscripts L, M and S for long, medium and short respectively.

S indicates the superstructure, the inclination of whose sides are described by V, 15 and 30; for vertical, 15° and 30° respectively. Subscript position denotes a low superstructure, and superscript position denotes a high superstructure.

R indicates edge radii for both deck and superstructure. Subscripts of 0, $\frac{1}{2}$ and F indicate sharp edges (zero radius), half the full deck edge radius and the full (maximum obtainable deck edge radius respectively.

Hence configuration 13 would be designated $K_S F_M S^{30} R_{\frac{1}{2}}$ meaning -

Straight panelled skirt.
Medium length foredeck.
High superstructure with 30° side inclination.
Half full deck-edge radius on the longitudinal deck-edge and all superstructure edges.

The relationships between all configurations are indicated in Table 2.

3. Wind Tunnel

The wind tunnel employed in the solid model programme was the No. 2 subsonic tunnel of the Department of Aerodynamics at the College of Aeronautics. This tunnel has a 3ft. 6in. diameter open-jet with continuous return flow. With a contraction ratio of 4.3, the 37 HP AC motor gives a maximum test-section velocity of 130 ft/second corresponding to $R_e = 0.83 \times 10^5$ per foot.

3.1 Tunnel Balance

The tunnel is equipped with a 6 - component overhead Warden-type virtual-centre balance having four manually operated weigh-beams each referenced to a wind axis system.

In conventional operation, such as in the measurement of forces and moments of bodies in an airstream remote from ground effect, two modes of operation are provided. The first mode provides for direct measurement of lift, drag and yawing moment with indirect measurement of crosswind force. The second mode of operation provides direct measurement of pitching moment with indirect measurement of rolling moment. Changeover from one mode to the other is accomplished mechanically.

4. Test Installations

In all test installations the live model was attached to the balance by a small diameter strut of circular cross-section. The strut was unfaired since it was believed that the length of chord necessary for fairing, i.e. approaching the width of the superstructure, would act as a flow straightener in cross-flow conditions at large angles of yaw, and would influence the results obtained, particularly those pertaining to yawing and rolling moments. Strut corrections to results are discussed later.

For the measurement of drag, crosswind force, and yawing moment, the image model was rigidly attached to the live model, the balance was operated in the first mode and, after strut corrections had been applied, measured data were divided by two to give results pertinent to the live model in the presence of the image model.

For the measurement of pitching and rolling moments, the image model was mounted on a second strut (similar to the strut discussed above) that was grounded to the floor beneath the tunnel. Between the bases of live and image models, a seal of near-zero stiffness was used to prevent flow between the two models. For these tests the balance was operated in the second mode and, after corrections had been applied, results pertained to the live model in the presence of the image. See Fig. 3.

For the measurement of lift, the installation was exactly the same as that described in the paragraph above except that the balance was operated in the first mode.

The virtual centre of the balance, corresponding to the centre of gravity location of the model, was located symmetrically at mid-length and mid-width in the plane of the deck surface of the live model.

4.1 Strut Corrections

Using configurations $K_S F_S S_{15} R_{\frac{1}{2}}$ with live and image models rigidly attached together, and mounted to the grounded support strut, all six-component measurements were taken for the isolated support strut throughout the model yaw range of 0 to 180 degrees.

As expected, significant corrections were obtained for drag and pitching moment. Very small corrections were obtained for lift (due to a shoulder on the balance strut), and for crosswind force and rolling moment (both apparently due to malalignment of the balance with the tunnel flow axis). Yawing moment corrections for the strut were nil.

5. Test results

All tests were run at a tunnel speed of 120 ± 0.25 feet/second giving a Reynolds number of 0.77×10^6 based on the overall model length of one foot.

The results presented refer to the wind-axis system pertinent to the balance, and conversion to a model body-axis system has not been attempted.

Hence at 90° angle of yaw, a drag force in wind axes corresponds to a lateral force in body axes, and a crosswind force in wind axes corresponds to a longitudinal force in body axes.

A similar interplay between rolling and pitching moments exists. At 90° angle of yaw a pitching moment in a wind-axis system correspond to a rolling moment in a body axis system and vice versa.

The sign convention adopted for the presentation of results is shown in Fig. 4 It follows that of positive measurement on the balance weigh-beams.

Test results are presented in figures 5 through 18.

6. Discussion

The absence of pitching and rolling moment data will be noted. It was determined for all configurations that the magnitude of these moments was too small for any confidence to be placed in the magnitude of the results.

In the case of pitching moment for example, the equivalent moment coefficient for balance sensitivity was ± 0.02; the strut moment correction was - 0.47; and the maximum measured model moment (configuration $K_S F_M S^{15} R_{\frac{1}{2}}$) was + 0.10.

In the case of rolling moment, the equivalent coefficnent for balance sensitivity was ± 0.04 compared with measured maximum rolling moment coefficient of approximately ± 0.08.

While to some minor extent being handicapped by similar lack of balance sensitivity, test results obtained for yawing moment and crosswind force are considered reasonable.

Lift results, except around zero angle of yaw, are considered to be reasonably reliable. As was anticipated it was found that lift results were critically dependent on the effectiveness of the foam rubber seal between the image and live models. Any untoward gaps caused a spurious cushion pressure which invalidated balance measurements.

A few tests were made to explore the effect of misalignment in yaw of the live and image models. Differences of up to ± 2° had no effect on lift, pitching moment and rolling moment results.

6.1 Effect of Edge Radius

The effect of increasing edge radius as shown by Figures 5, 8, 12 and 13 are as follows:

(1) A substantial reduction in drag throughout the yaw range.

(2) A general reduction in crosswind force throughout the yaw range. With the higher superstructure there is evidence of a separation effect with the sharp edge which does not exist for the radiused edges.

(3) Yawing moments tend toward positive stability at $\beta = 0°$ but there is little or no effect on the unstable moment at $\beta = 180°$. There is a significant reduction in β for zero yawing moment.

(4) With beam winds, increased edge radius increases the lift of the higher superstructure whereas the reverse is true for the lower superstructure.

6.2 Effect of Side Inclination

The effect of increasing the side inclination of the superstructure is shown in Figures 6, 9, 14 and 15, and is as follows:-

(1) Some reduction in drag throughout the yaw range.

(2) A decrease of crosswind force throughout the yaw range most pronounced when $\beta = 30°$. With the higher superstructure there is evidence of a separation effect.

(3) Yawing moments tend toward positive stability when $\beta = 0$ and again there is a substantial reduction in β for zero yawing moment.

(4) In marked contrast to the effect of edge radius which shows lift effects which reverse with superstructure height, increasing the superstructure height decreases the lift for all side inclinations.

6.3 Effect of Foredeck Length

The effect of decreasing the foredeck length is shown in figures 7, 10, 16 and 17 and is as follows:

(1) At low angles of yaw there is a small reduction in drag, whereas over the remainder of the yaw range there is a general increase in drag.

(2) An increase in crosswind force throughout the yaw range.

(3) Yawing moments become more unstable at $\beta = 0$ but less unstable at $\beta = 180°$. There is an increase in β for zero yawing moment.

(4) With the low superstructure, lift is slightly increased at low angles of yaw whereas, with beam winds, lift is substantially decreased. However, the reverse is true for the high superstructure.

6.4 Effect of Superstructure Height

The effect of increasing superstructure height on drag, crosswind force and yawing moment is one of a general increase in magnitude. Albeit, a separation effect is apparent for the high superstructure with zero edge-radius and vertical sides. This separation decreases crosswind forces and yawing moments.

In the case of lift, Figures 13, 15 and 17 show that, with increasing superstructure height, lift is increased with large edge radii and the short foredeck, whereas with zero edge radius and the longer foredeck the lift is decreased. However, regardless of the side inclination of the superstructure, lift is decreased by increasing the superstructure height.

6.5 Effect of Skirt

The effect of different skirts is shown in figures 11 and 18.

The radiused type of skirt differs but little from the straight-sided type as far as crosswind force and yawing moments are concerned. The general drag level throughout the yaw range is about the same although higher peak drags occur with the radiused type of skirt.

Lift values at $\beta = 0°$ and $180°$ are significantly higher with the radiused type of skirt although beam wind values remain on the same order.

6.6 Qualitative Tests

Aural tests by means of a stethoscope were made to check whether at these rather low Reynolds numbers the boundary layers were laminar or turbulent. Characteristic noise clearly indicated that the latter was applicable.

Tests with tufts showed intense separation and flow reversal behind sharp edges, particularly those at the bow and stern of the deck and, when applicable, from the sharp edges of the superstructure. At approximately $35°$ and $145°$ yaw the separation from the leading edge of the deck wrapped up into a vortex causing a considerable downwash component of velocity across the leeward longitudinal edge of the deck.

It was of interest to note that with the straight skirt configurations even at zero angle of yaw all flow in the longitudinal V between the skirt panels of the live and image models was completely separated over the length of the model. It will be noted that the drag level at zero angle of yaw does not change appreciably with skirt type, in spite of the considerably smaller frontal area of the straight panelled type.

All configurations showed extremely turbulent wakes, their cross-sectional areas being essentially the same as the projected frontal areas of the models. The wakes extended downstream about one and one-half model lengths.

7. Conclusions

In the light of the unfavourable handling qualities mentioned in Section 1 of this report, the following conclusions may be drawn from the test results obtained.

(i) While the differing basic shapes certainly have unique aerodynamic characteristics, pitching and rolling moment characteristics in themselves are insignificantly small so far as overturning is concerned. It must be remembered, however, that the results pertain to no-efflux and no-induction conditions.

In spite of the above, however, what well might be significant is the tenfold increase in lift from head-on to beam-wind conditions. In a rapid yaw rate situation, should the leading longitudinal edge dig-in hydrodynamically, then the lift force moment about this edge will be additive to the inertial overturning moment.

(ii) Crosswind forces, as would be expected, are primarily dependent on the pertinent projected area in the vertical plane. Forces causing lateral drift can be lessened, however, by the introduction of large radii and by inclination of the sides of the superstructure.

Ideally, the amphibious hovercraft should possess positive directional stability in head-wind conditions (normal cruising operation) and near-neutral directional stability in beam- and tail-wind conditions (low speed manoeuvering, docking, etc.). These requirements are in mutual aerodynamic conflict - particularly so if a fixed vertical fin is required for positive cruising stability. However, it would appear that in conjunction with vectored thrust or with a retractable vertical fin, the basic hull and superstructure configuration could be designed to exhibit only small yawing moments throughout the yaw range.

(iii) Straight panelled skirts of 45° inclination do not appear to have any particular aerodynamic merit over the curved type of skirts. This characteristic is undoubtedly due to the severe separation in the longitudinal- V formed by the skirt.

(iv) The results obtained do not lead to any conclusive comments on longitudinal trim. This subject, however, is part of the suggested follow-up programme described in the next section of the present report. Comments on this topic would be more pertinent after the completion of the second part of the overall study.

8. Future Developments

The following discussion considers in some detail the follow-up programme believed necessary to ensure a logical continuation of the initial programme forming the substance of the first half of this report.

8.1 Solid Models

It is felt that some study should be made of the effects of attitude on the aerodynamic characteristics of the solid models prior to introducing the more sophisticated effects of cushion efflux and air-induction.

With this thought in mind it is proposed to retest configuration $K_S F_M S_{15} R_F$ over the range ± 4° of pitch attitude followed by ± 4° of roll attitude.

The tunnel support fixtures used in the initial programme have provision for ± 5° deviation from a 'deck-horizontal' attitude; only simple modifications to the skirt components of the models would be necessary. The tests would be run in the same $3\frac{1}{2}$ ft. diameter tunnel and the test procedure would be identical to that of the initial tests.

It is also considered desirable that a configuration should be modified to resemble the BHC SRN series of hovercraft-especially in regard to the foredeck planform. The test results from such would provide a valuable link between all results discussed previously and full scale measurements obtained from a current programme at RAE, Bedford.

8.2 Solid Models with Cushion Efflux

The method of test for the remainder of the overall programme has been given careful consideration. First it was considered undesirable to utilize the vortex-image technique with cushion efflux models, and impractical to use this technique with subsequent air-induction models. Hence, thinking in terms of one 'live' model, there lay a choice between fixed ground-board reflection or moving ground reflection. Discussions with BAC Warton, who are experienced in moving-ground techniques, revealed that the prime reason for their utilization of the moving ground in VTOL transition tests at low forward speeds, was to avoid interaction between the high velocity/small mass flow of the lifting jet (engine) and the boundary layer of the tunnel floor. This interaction would cause boundary layer separation - a situation not arising full scale because of the effective absence of boundary layer. In the case of the hovercraft application, the low velocity/high mass flow of a peripheral efflux from beneath the skirt would predominate regardless of boundary layer thickness, and that as a consequence a moving ground was unnecessary and that a ground-board reflector would be all that would be required.

The tests on a model hovercraft at the University of Toronto (ref. 2) indicate the effect of ground-board boundary layer to be unimportant and the unpublished tests at RAE on the HD II configuration (ref. 1) show that fixed-ground results differ little from moving-ground results, provided that free-stream dynamic pressures do not exceed equivalent cushion pressures.

Finding no conclusive reason why a moving ground should be used, it was decided to propose the use of the fixed ground-board technique for the remainder of the programme.

For the efflux tests it is proposed that configuration $K_S F_M S_{15} R_F$ should be modified further to provide a plenum chamber in the base of the skirt.

Tests on this configuration would be made in the same tunnel as those discussed previously. A single 'live' model mounted over a fixed ground-board would be strut-mounted to the overhead balance. Compressed air from a source external to the tunnel would be piped from beneath through the ground board into the plenum chamber of the model from which it would escape as a peripheral efflux from beneath the skirt.

The main object of these tests would be to study the effect of the efflux on the overall aerodynamic characteristics. It is believed that the efflux will interact on the separated flow under the longitudinal sides of the skirt at low angles of yaw.

In addition to examining the effects of mass flow it is proposed to study the effects of efflux location and the effects on differing skirt configurations.

8.3 Hollow Models with Air-Induction and Cushion

This degree of sophistication absolutely precludes further use of the small solid models and it becomes necessary to consider larger models.

Although inlet velocity distribution is a function of the shape of a hovercraft, of its forward speed, and its fan characteristics, it is believed to be highly desirable that some basic understanding is obtained on the effect of inlet location on aerodynamic characteristics.

Accordingly, it is proposed that a representative model, i.e. an available $\frac{1}{12}$ scale model of the HD II, be tested with a range of inlet locations on the superstructure roof, sides and rear. Intakes will be represented by circular discs of porous material giving a high pressure drop under design flow conditions thus ensuring uniformity of inlet velocity.

The model would be tested with a ground-board in the 8ft. x 6ft. subsonic tunnel at The College of Aeronautics. This tunnel with a contraction ratio of 7 and its 500 H.P. variable pitch propellor provides a maximum speed of 275ft. per second, or a Reynolds number of 1.7×10^6 per foot. Thus with the proposed HD II model which is $2\frac{1}{2}$ feet long, the test Reynolds number would be in the order of 4×10^6.

The existing tunnel balance, on overhead automated six-component Warden-type, has been modified for blowing air from models. Further modifications of simple type would be required for providing the suction necessary for the air-induction system of the HD II model. The vacuum pumps and tanks of an adjacent intermittent supersonic tunnel might be used as a source for this suction.

It is believed that some preliminary tests would be required to assess suction requirements and to check the general feasibility of the proposed air-induction tests. These preliminary tests would be made in the $3\frac{1}{2}$ ft. diameter tunnel using a simple flat-plate model.

8.4 Schedule

It is anticipated that the solid model tests described in para. 8.1 will have been started during the current contract period terminating September 30, 1967.

Provided the continuation of the programme is authorized to proceed without interruption it is expected that the cushion efflux tests of para. 8.2., and the air-induction tests of para. 8.3., could be completed by the end of 1968.

The level of funding required to support the continuation of the programme will be comparable to that of the current programme.

References

1. An unpublished report of tests on the aerodynamics of hovercraft shapes made at RAE on behalf of Hovercraft Development Ltd.

2. Effect of ground board boundary layer on air cushion vehicle wind tunnel tests, by E.K. Garay, UTIAS Technical Note No. 100.

TABLE 1 HOVERCRAFT CONFIGURATIONS

CONFIGURATION	DESIGNATION
1	$K_S F_S S_{15} R_{\frac{1}{2}}$
2	$K_S F_M S_{15} R_{\frac{1}{2}}$
3	$K_S F_L S_{15} R_{\frac{1}{2}}$
4	$K_S F_M S_{15} R_0$
5	$K_S F_M S_{15} R_F$
6	$K_S F_M S_V R_{\frac{1}{2}}$
7	$K_S F_M S_{30} R_{\frac{1}{2}}$
8	$K_S F_S S^{15} R_{\frac{1}{2}}$
9	$K_S F_M S^{15} R_{\frac{1}{2}}$
10	$K_S F_M S^{15} R_0$
11	$K_S F_M S^{15} R_F$
12	$K_S F_M S^V R_{\frac{1}{2}}$
13	$K_S F_M S^{30} R_{\frac{1}{2}}$
14	$K_{45} F_M S_{15} R_{\frac{1}{2}}$
15	$K_{60} F_M S_{15} R_{\frac{1}{2}}$

TABLE 2 CONFIGURATION RELATIONSHIPS

<table>
<tr><th>SUPERSTRUCTURE</th><th>LOW</th><th>HIGH</th></tr>
<tr><td>VERTICAL SIDES</td><td>FOREDECK LENGTH
L
M 6
S
Edge Radius
0 ½ F</td><td>L
M 12
S
0 ½ F</td></tr>
<tr><td>15° SIDES</td><td>L 3
M 4 2 5
S 1
0 ½ F</td><td>L
M 10 9 11
S 8
0 ½ F</td></tr>
<tr><td>30° SIDES</td><td>L
M 7
S
0 ½ F</td><td>L
M 13
S
0 ½ F</td></tr>
<tr><td></td><td colspan="2">ALL ABOVE HAVE STRAIGHT SKIRT PANELS</td></tr>
<tr><td>15° SIDES AND
½ EDGE RADIUS</td><td>L
M 1 14 15
S
Skirt Type
S 45 60</td><td></td></tr>
</table>

APPENDIX

1. Introduction

Subsequent to the completion of the tests exploring the effects of configuration variables on aerodynamic characteristics (Sections 5,6 and 7 of the main report), additional tests have been conducted in accordance with the supplementary programme presented in Section 8.1 of that report. These additional tests relate to the effects of pitch and roll attitude on the crosswind forces, yawing moments and drag forces experienced by configuration $K_S F_M S_{15} R_F$.

2. Test Installation

By suitably removing wedge-shaped slices from the skirt components of the live/image model combination, attitudes about the model centre of gravity of ± 4° pitch from deck horizontal and of + 4° roll from deck horizontal could be independently provided. The resulting cavities between the skirt components were filled and appropriately faired with plasticine.

The model combination was mounted in the tunnel as described in Section 4 of the main report and the same tunnel operating procedure was followed except that, in the case of + 4° roll attitude, the model was yawed through 360° to obtain data for ± 4° roll attitude through 180° yaw. In all other tests the model had been yawed from o° to 180°.

3. Test Results

As in the main report, all results relate to a wind-axis system of measurement.

Test results are presented in Figures 1A and 2A.

4. Discussion

It will be seen from Figure 1A that the effect of pitch attitude on crosswind force is considerable. Over the range ± 4° the maximum crosswind forces, occurring at approximately 30° and 150° yaw angle, are virtually doubled by the attitude change. Also the yaw angle for zero crosswind force is changed by more than 40°, clearly due to asymmetric separation around the differing Vs beneath the bow and stern skirt-elements when considered in beam-wind perspective.

In general, yawing moments follow a similar trend; depressing the bow lessens the inherent directional instability, and raising the bow increases the instability. There is a sizeable change in the angle for zero yawing moment. The effect of pitch attitude on drag is that, at small angles of yaw, raising the bow decreases the drag, and depressing the bow increases the drag. In beam-wind conditions, changes in drag levels are relatively minor.

The general effects of roll attitude while measurable are not of major consequence. It will be seen from Figure 2A that maximum cross-wind forces, yawing moments and drag forces are not significantly changed over the $\pm 4°$ of roll attitude covered by these tests.

5. Conclusions

(i) Pitch attitude appears to have a significant effect on crosswind forces and yawing moments. These, in turn, influence handling qualities and it is strongly recommended that tests be made on the effects of pitch attitude on the pitching and rolling moments and lift forces of configuration $K_S F_M S_{15} R_F$

(ii) From the performance viewpoint, the attitude for longitudinal trim seems to be consequential. In high speed cruising conditions a nose-down trimmed attitude cound reflect adversely on drag levels.

(iii) The effects of roll attitude on crosswind forces, yawing moments and drag forces appear to be relatively innocuous and the desirability of examining the effects of roll attitude on the pitching and rolling moments and lift forces of configuration $K_S F_M S_{15} R_F$ should be given further consideration.

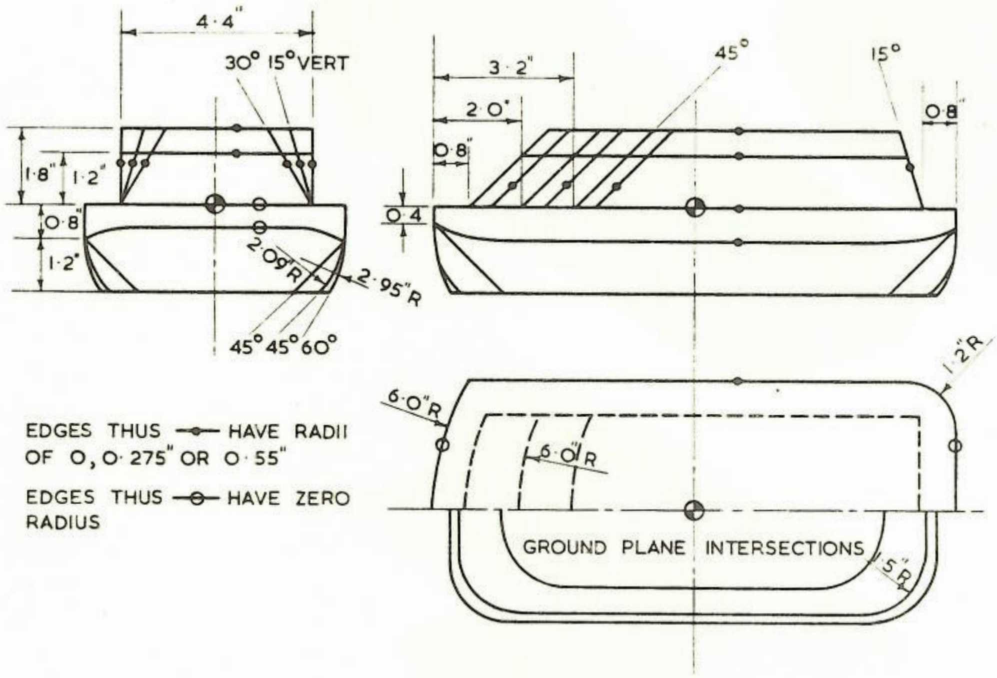

FIG.1. RELATED HOVERCRAFT SHAPES.

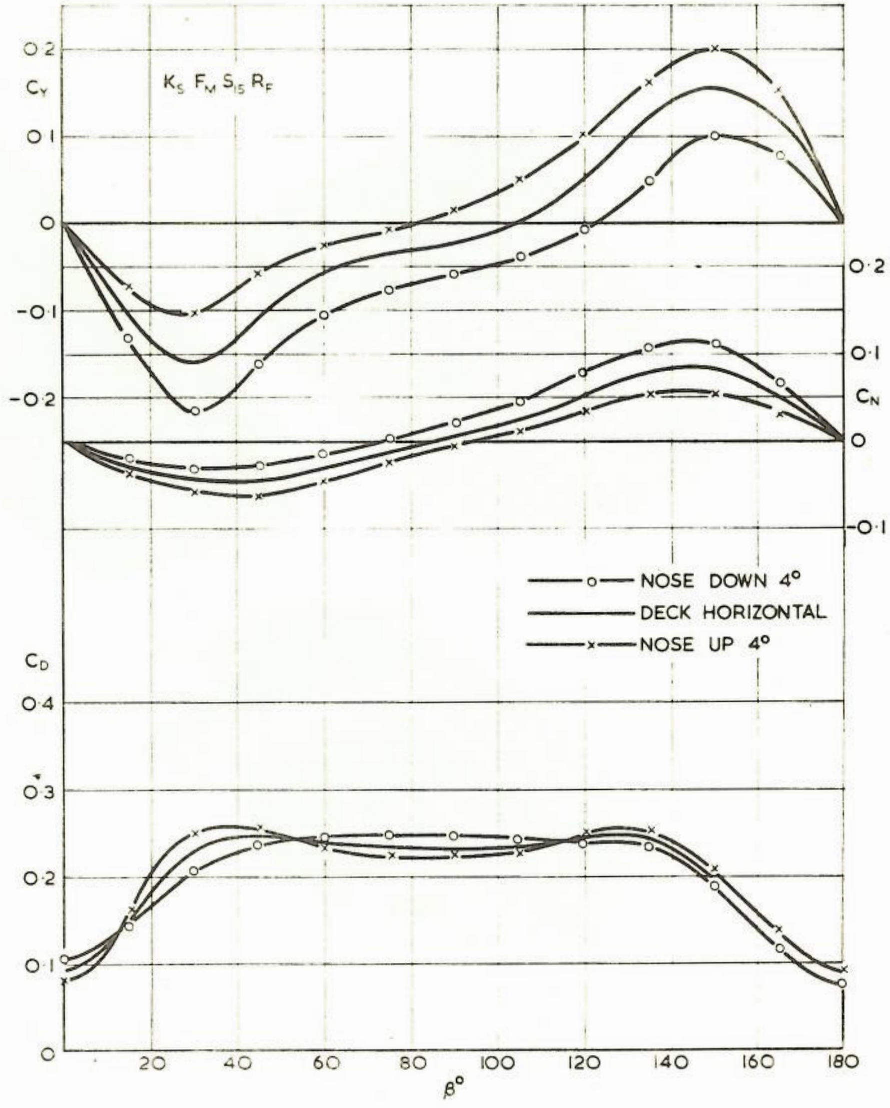

FIG.1a. EFFECT OF PITCH ATTITUDE ON C_Y, C_N AND C_D (LOW SUPER-STRUCTURE.)

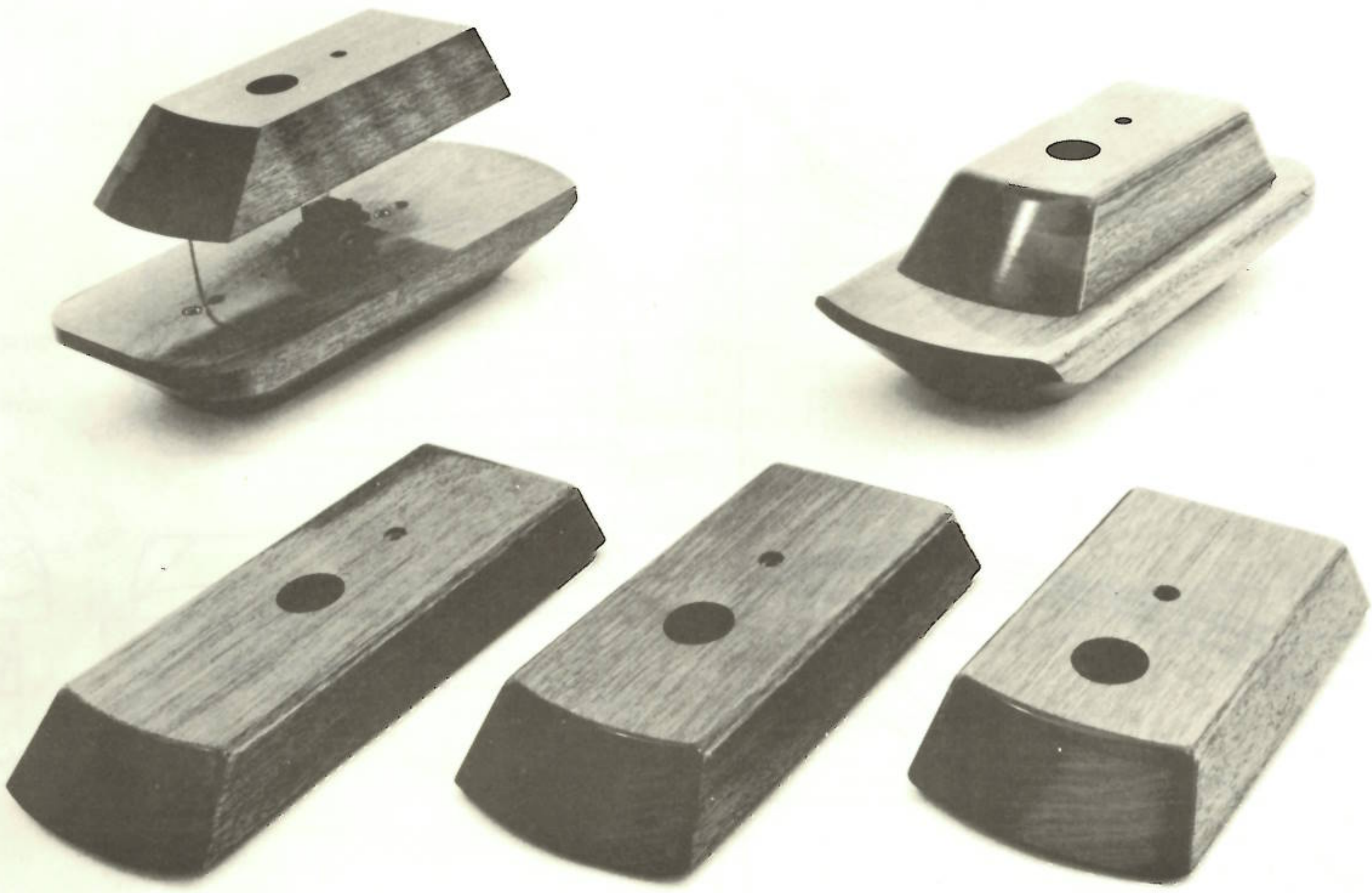

FIG. 2 CONFIGURATION BUILDING BLOCKS

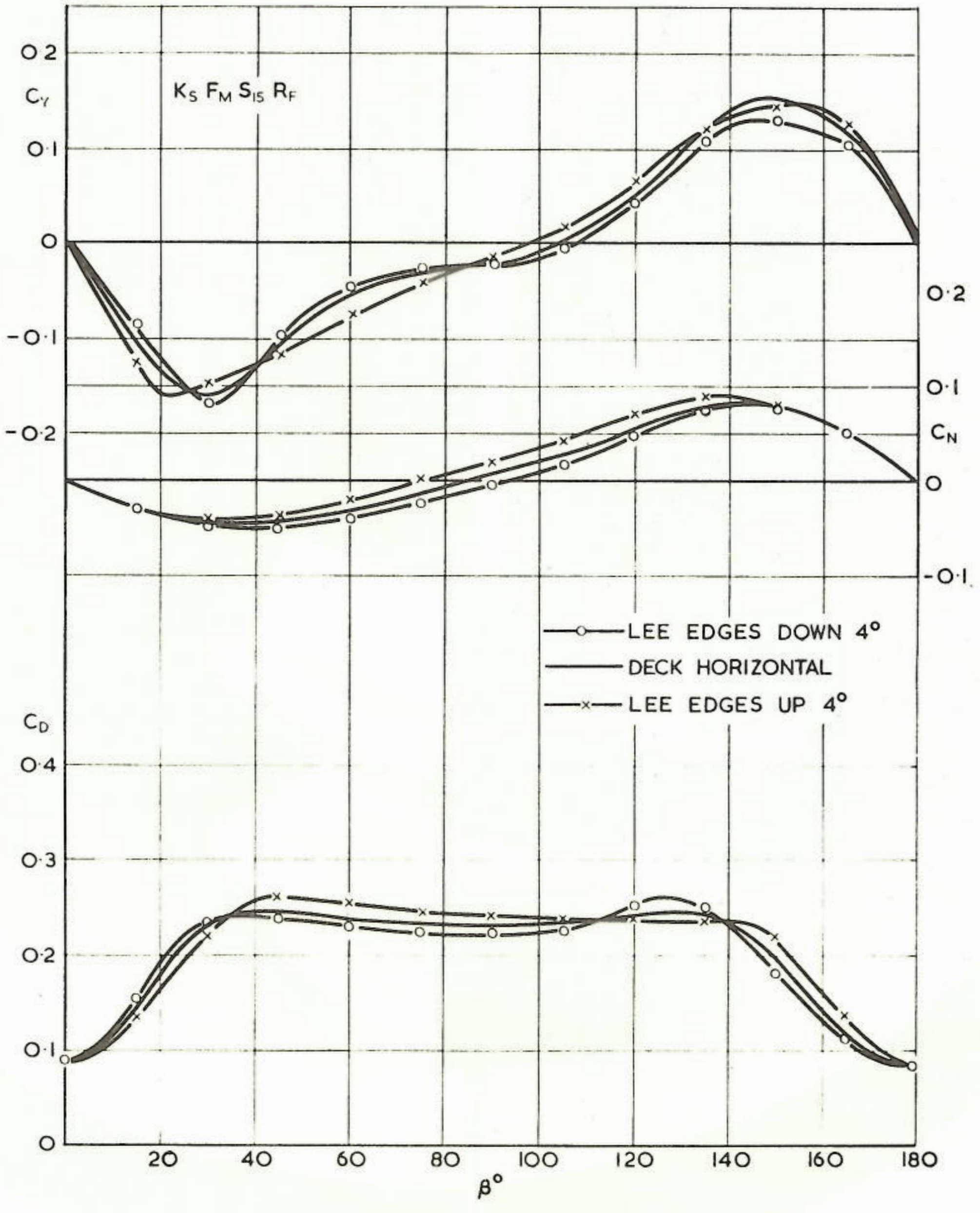

FIG. 2a. EFFECT OF ROLL ATTITUDE ON C_Y, C_N AND C_D (LOW SUPER-STRUCTURE)

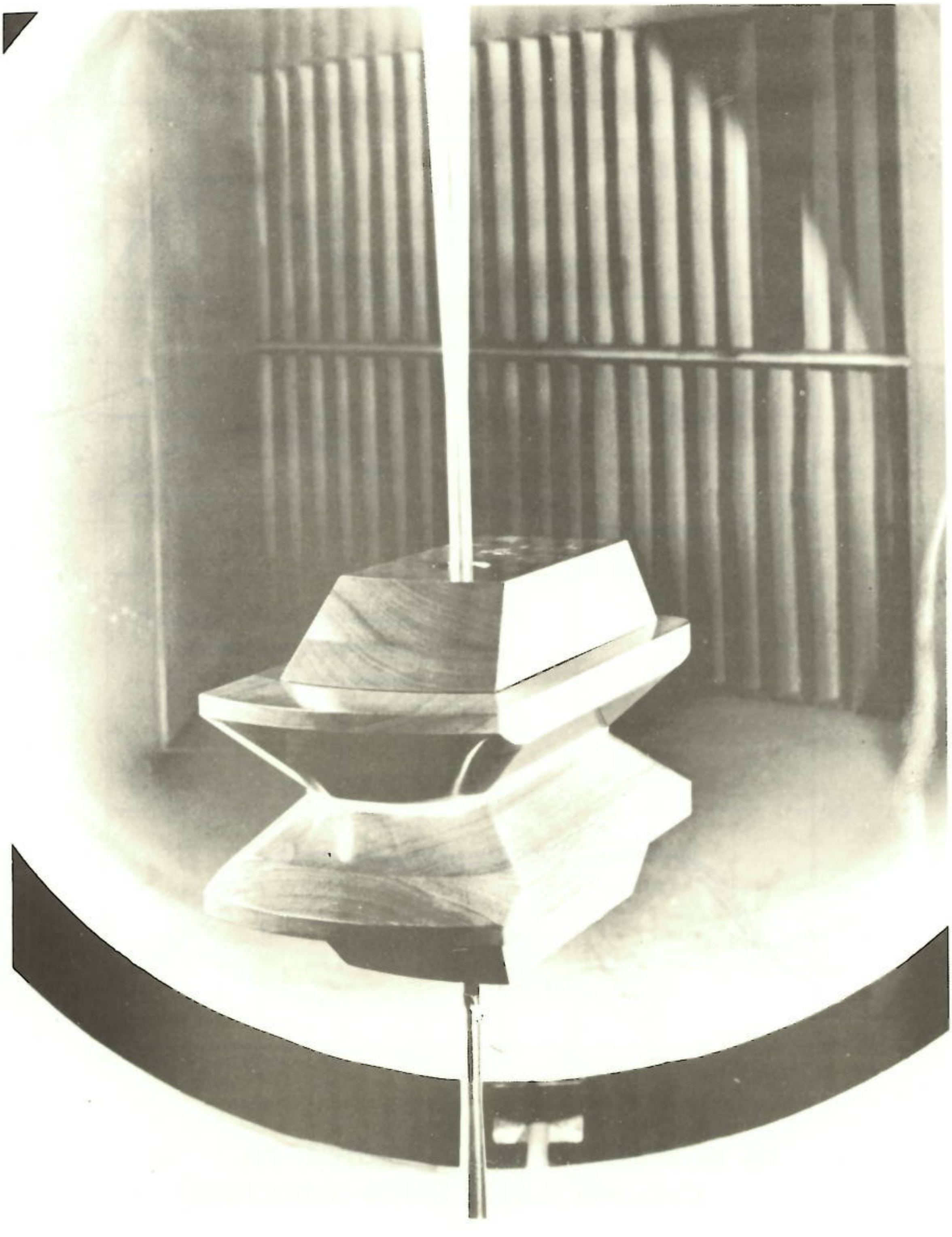

FIG. 3   MODEL INSTALLATION FOR LIFT, PITCH AND ROLL

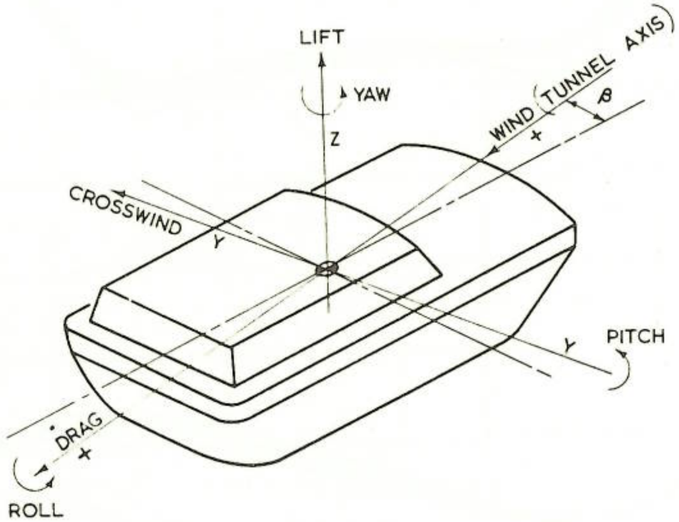

FIG. 4. POSITIVE FORCES AND MOMENTS (AS MEASURED BY BALANCE).

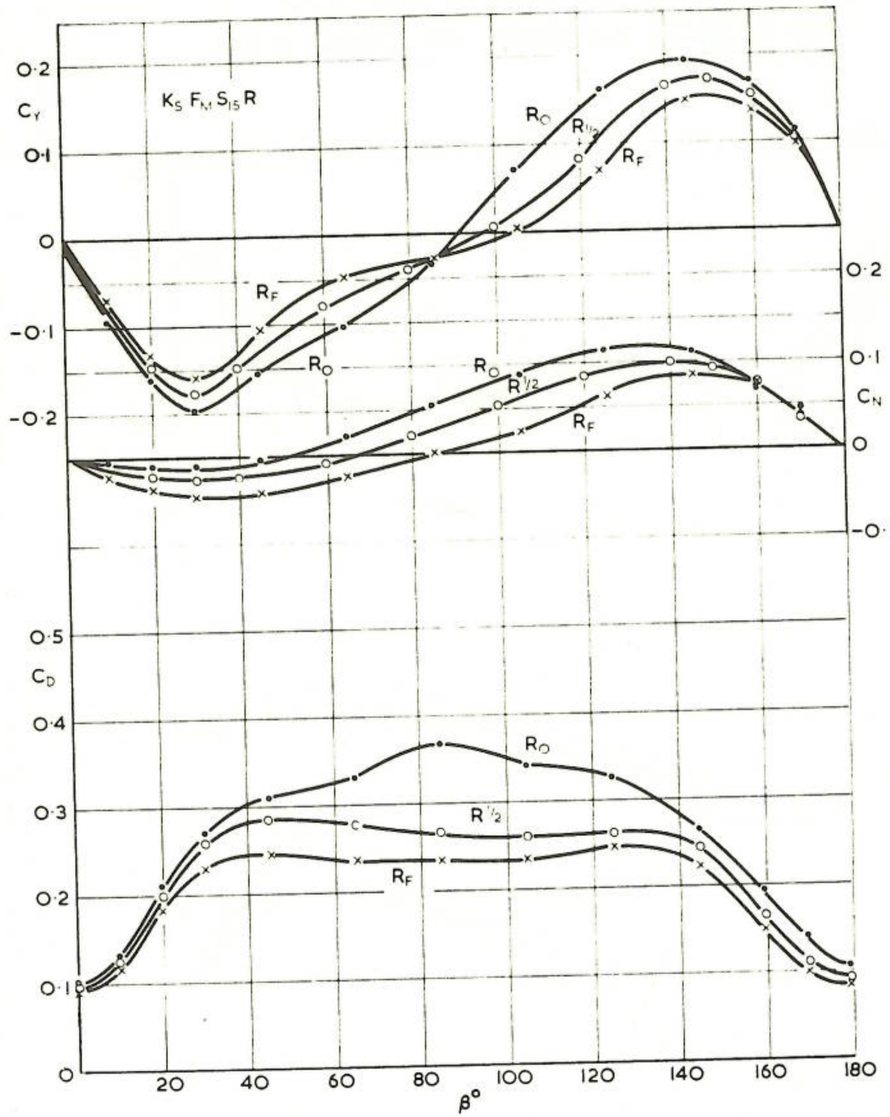

FIG. 5. EFFECT OF EDGE RADII ON C_Y, C_N AND C_D (LOW SUPER-STRUCTURE).

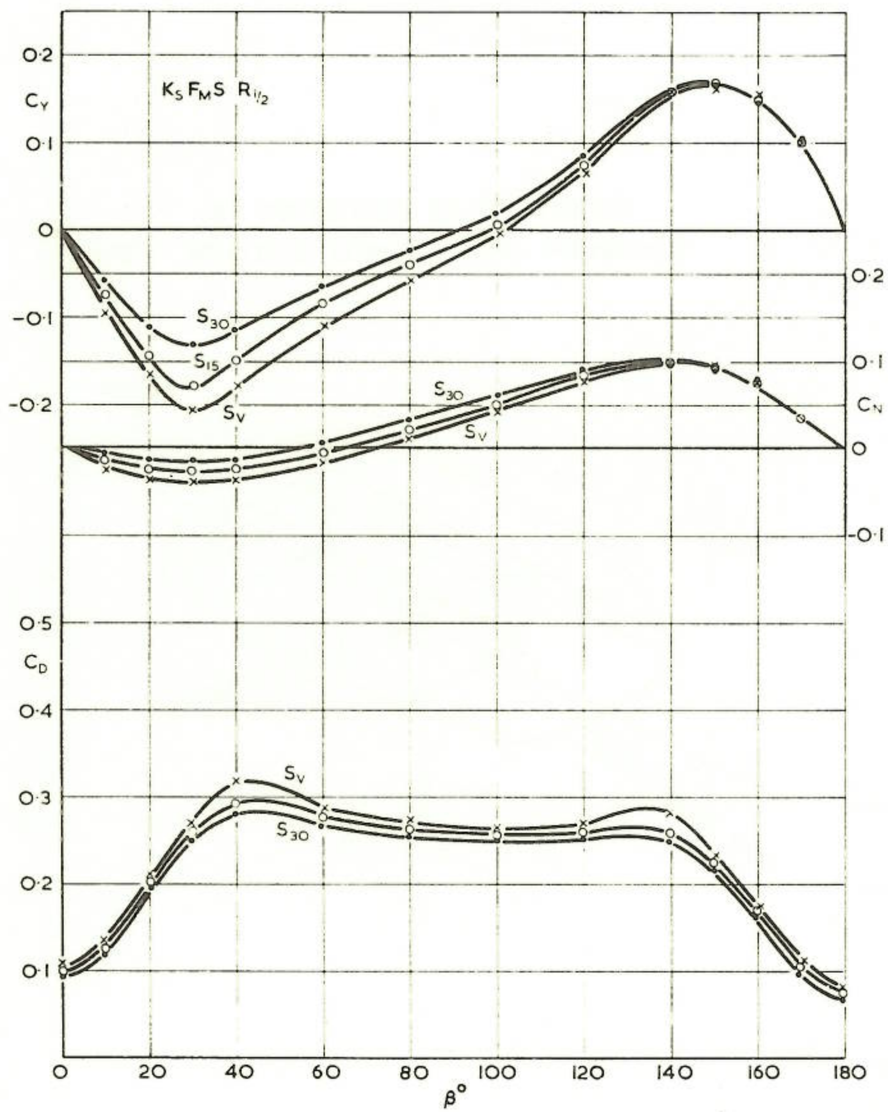

FIG. 6. EFFECT OF SIDE INCLINATION ON C_Y, C_N AND C_D (LOW SUPER-STRUCTURE.)

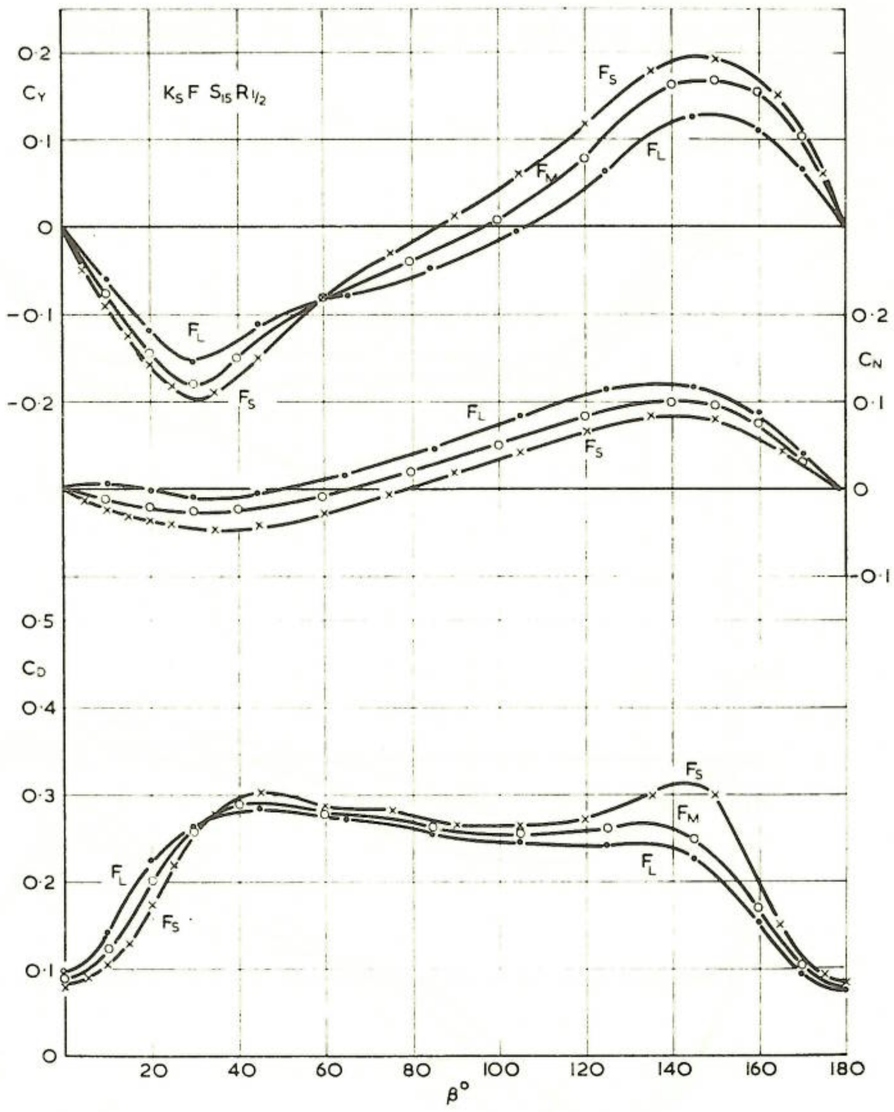

FIG. 7. EFFECT OF FOREDECK LENGTH ON C_Y, C_N AND C_D (LOW SUPER-STRUCTURE)

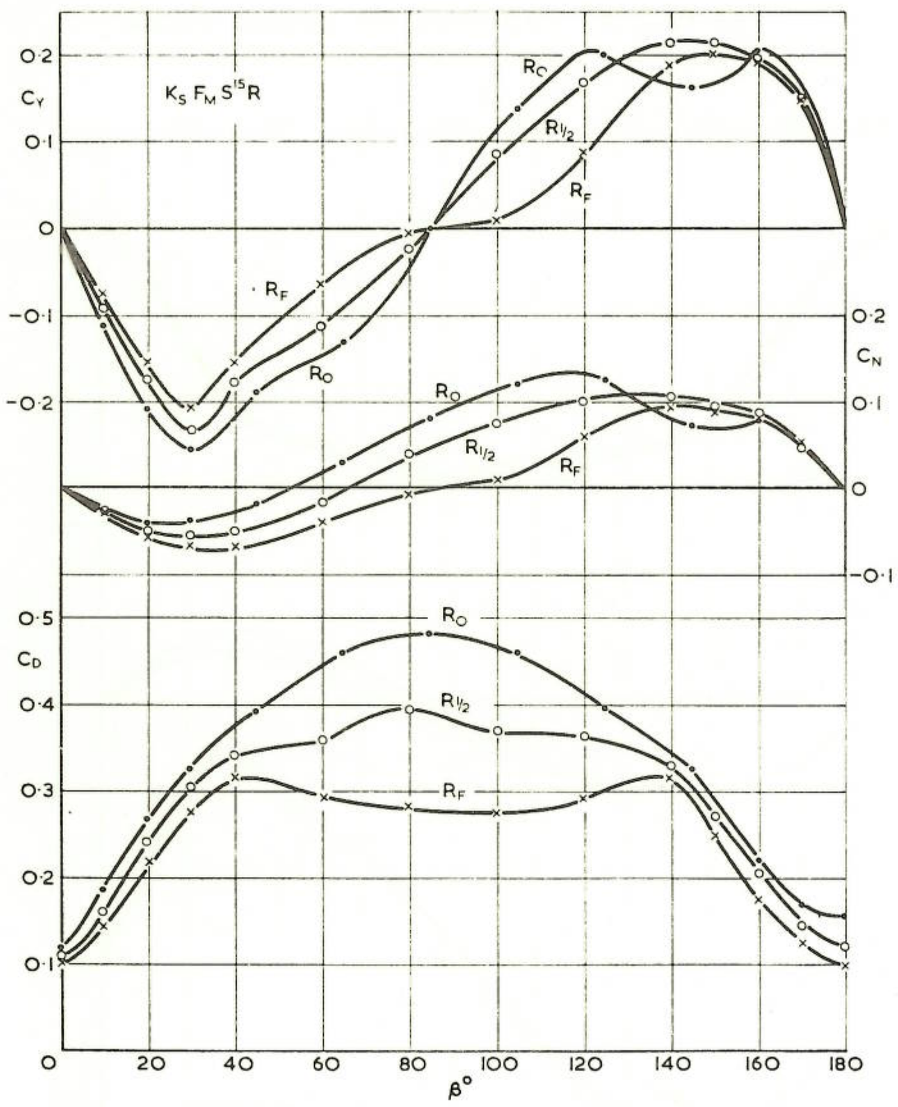

FIG. 8. EFFECT OF EDGE RADII ON C_Y, C_N AND C_D (HIGH SUPER-STRUCTURE.)

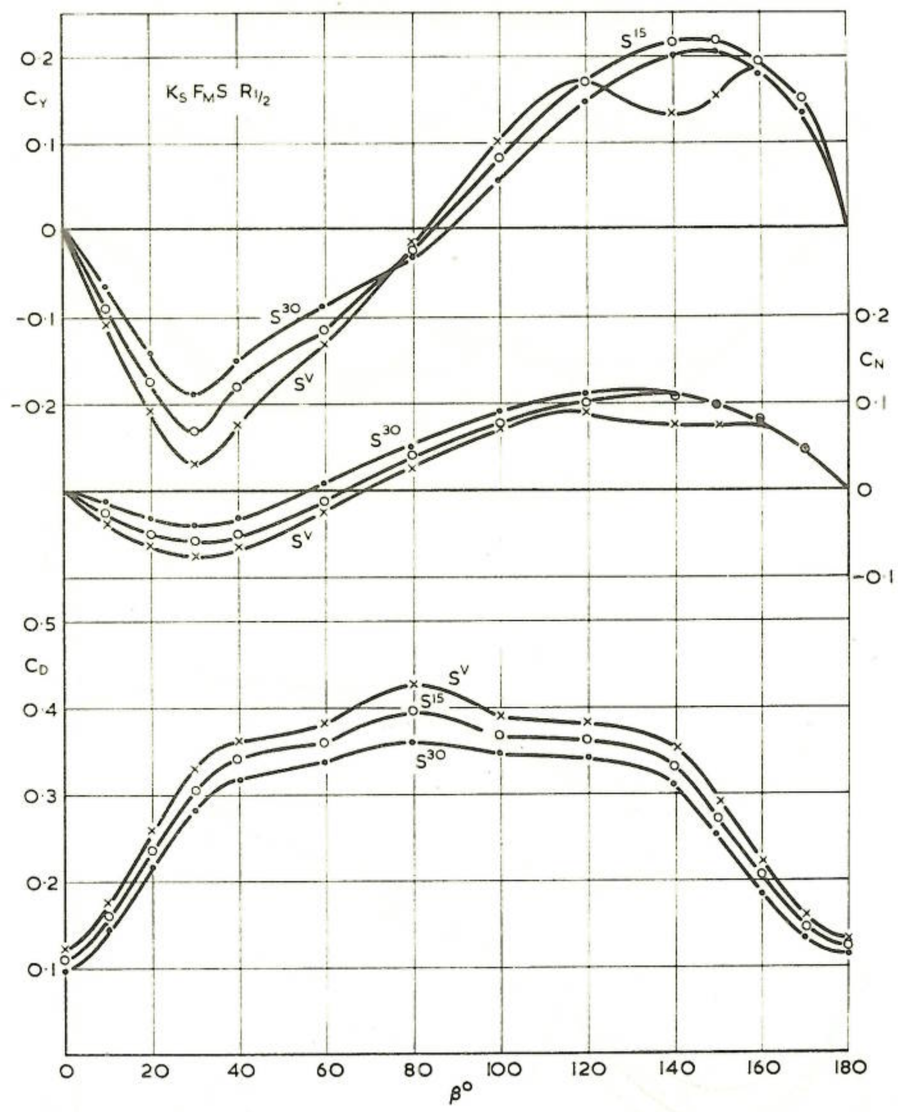

FIG. 9. EFFECT OF SIDE INCLINATION ON C_Y, C_N AND C_D (HIGH SUPER-STRUCTURE.)

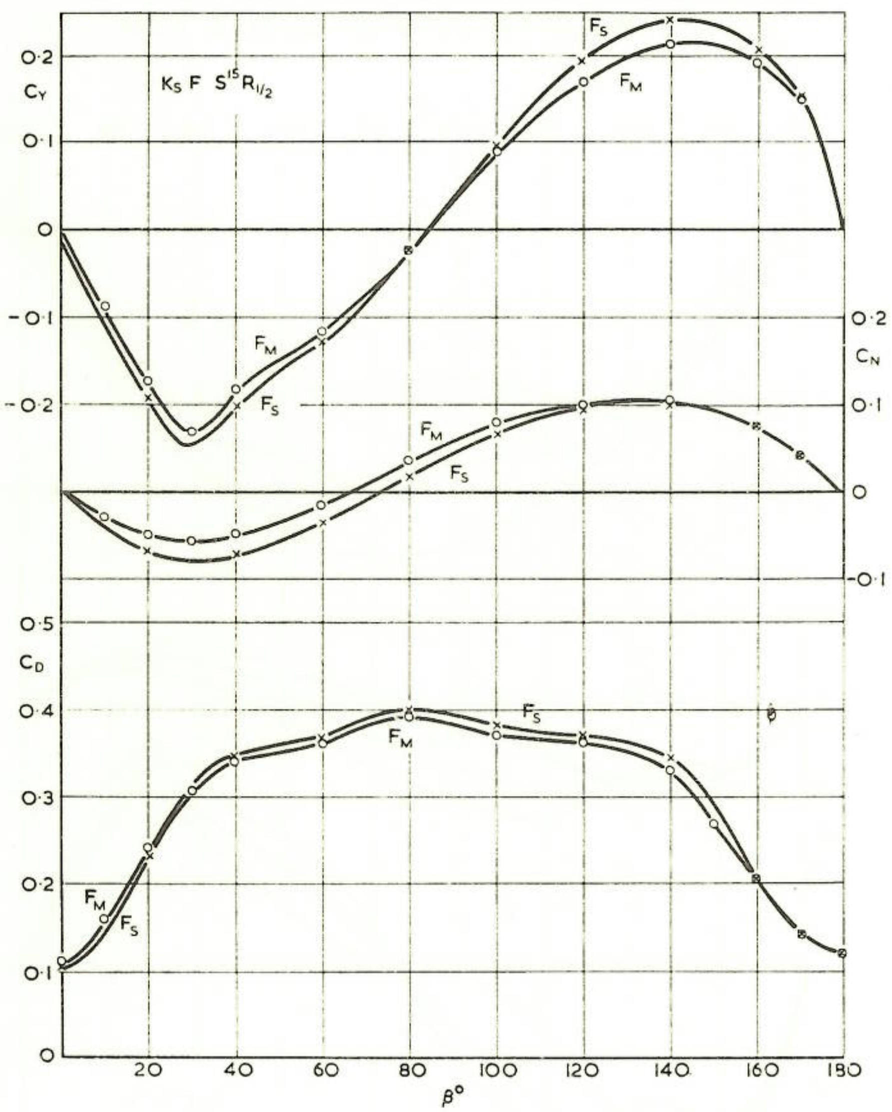

FIG. 10. EFFECT OF FOREDECK LENGTH ON C_Y, C_N AND C_D (HIGH SUPER-STRUCTURE.)

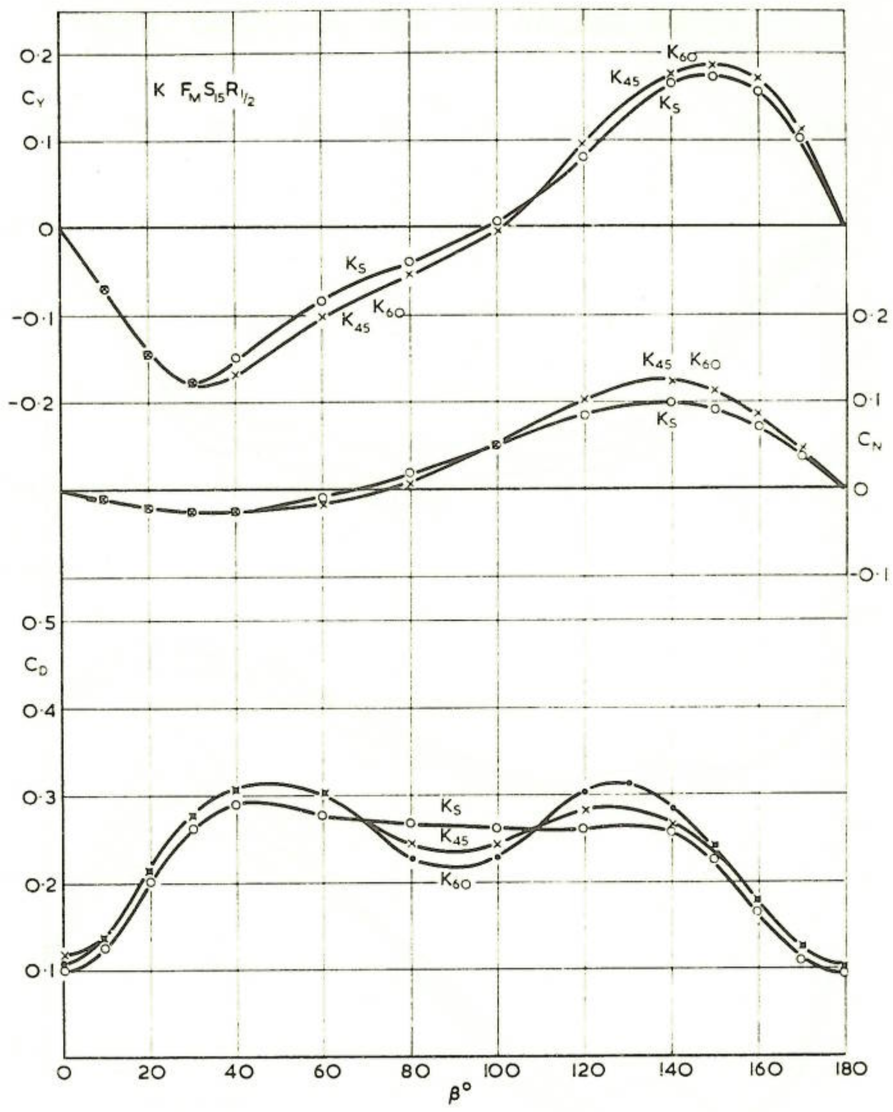

FIG. 11. EFFECT OF SKIRT ON C_Y C_N AND C_D (LOW SUPER-STRUCTURE.)

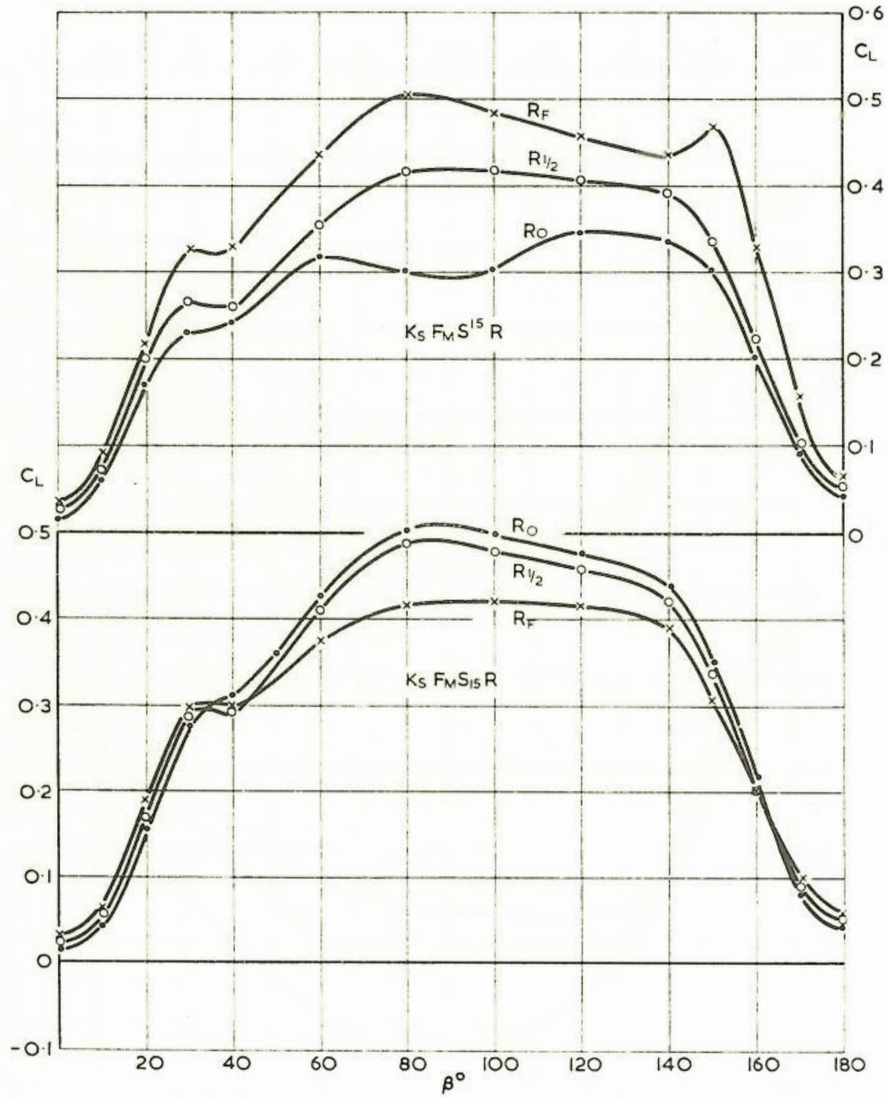

FIG.12. EFFECT OF EDGE RADII ON LIFT.

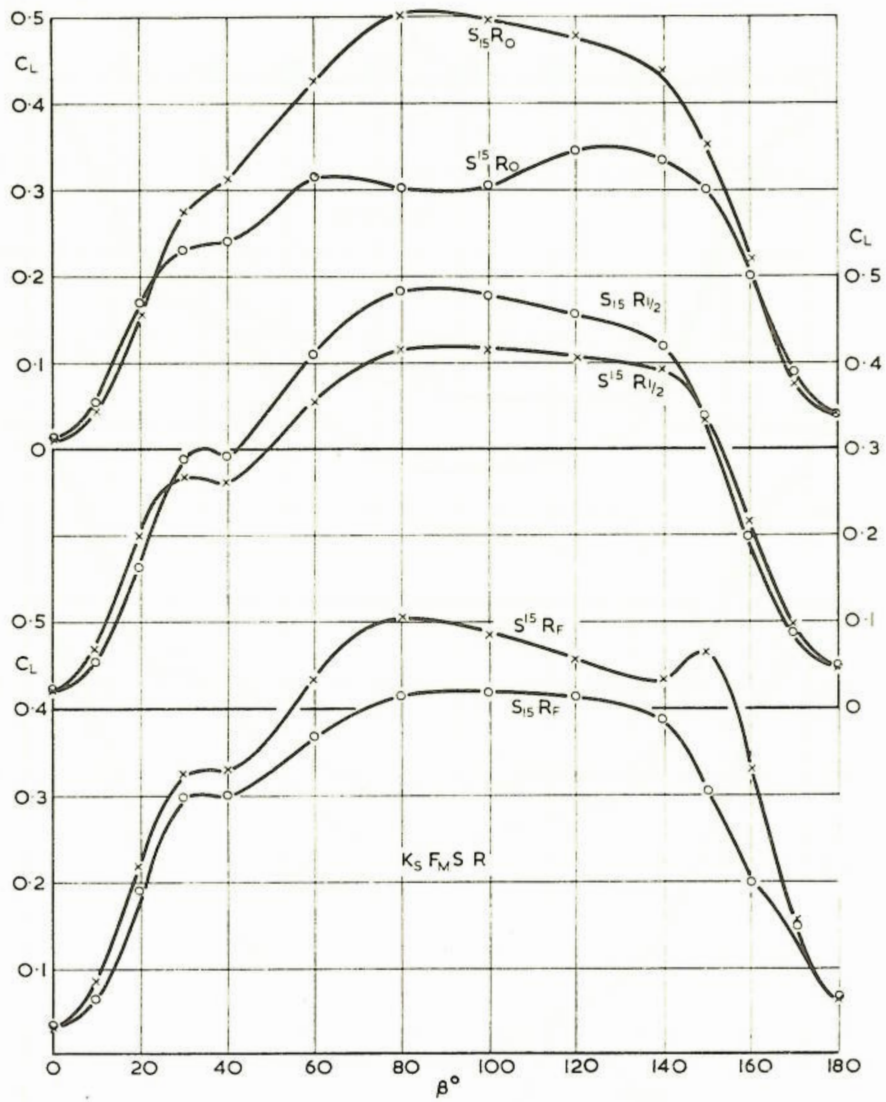

FIG.13. EFFECT OF SUPER-STRUCTURE HEIGHT AND EDGE RADII ON LIFT.

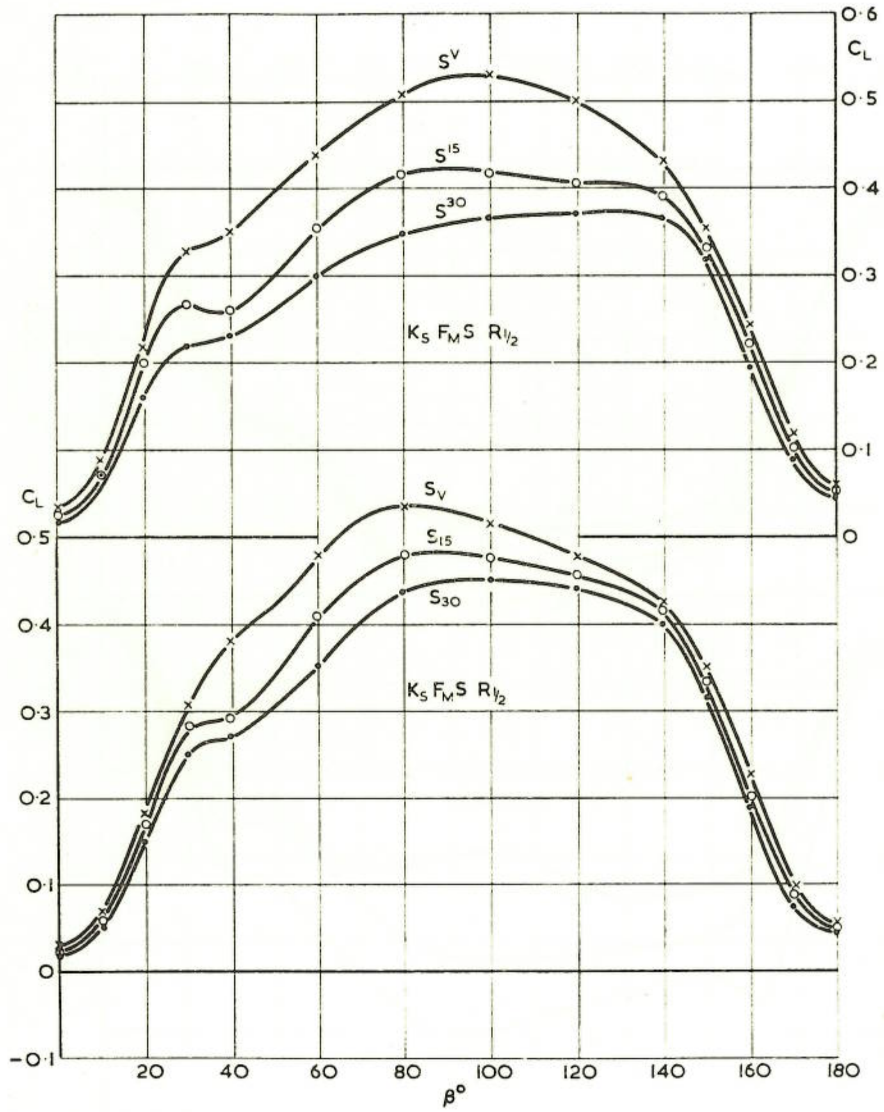

FIG. 14. EFFECT OF SIDE INCLINATION ON LIFT.

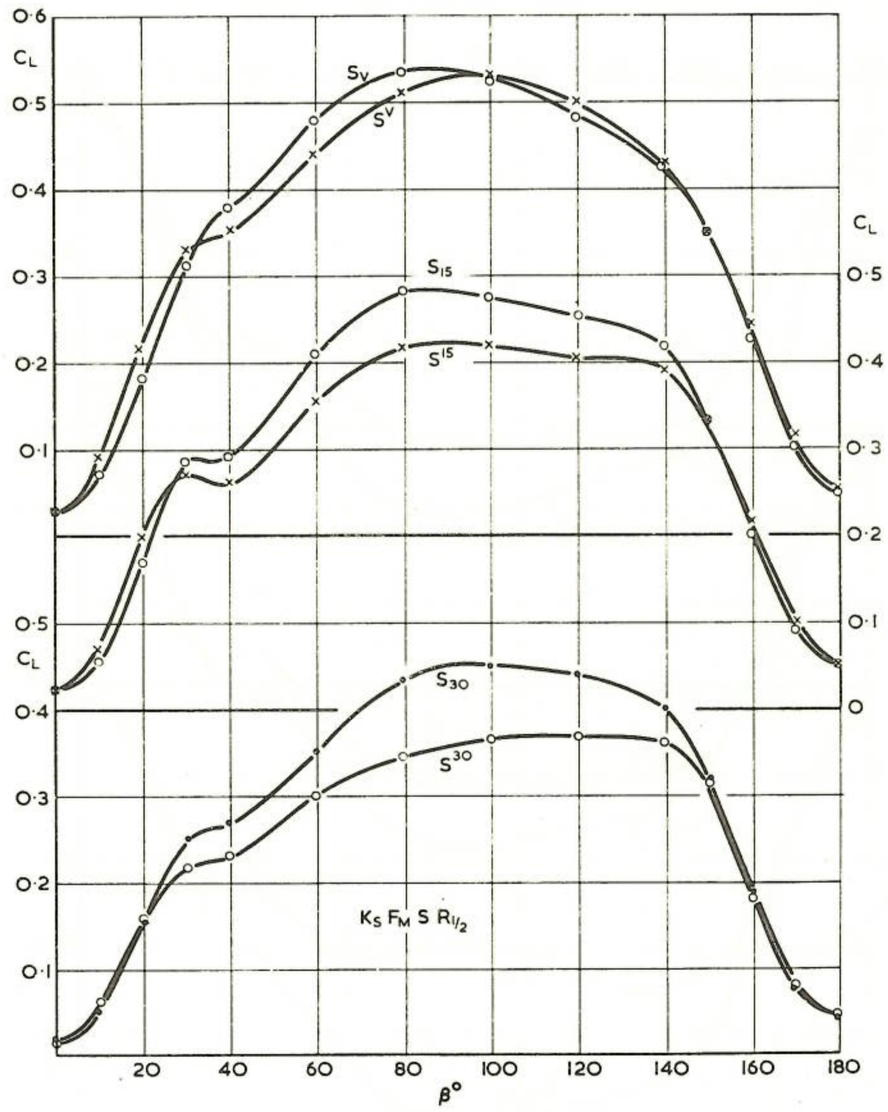

FIG. 15. EFFECT OF SUPER-STRUCTURE HEIGHT AND SIDE INCLINATION ON LIFT.

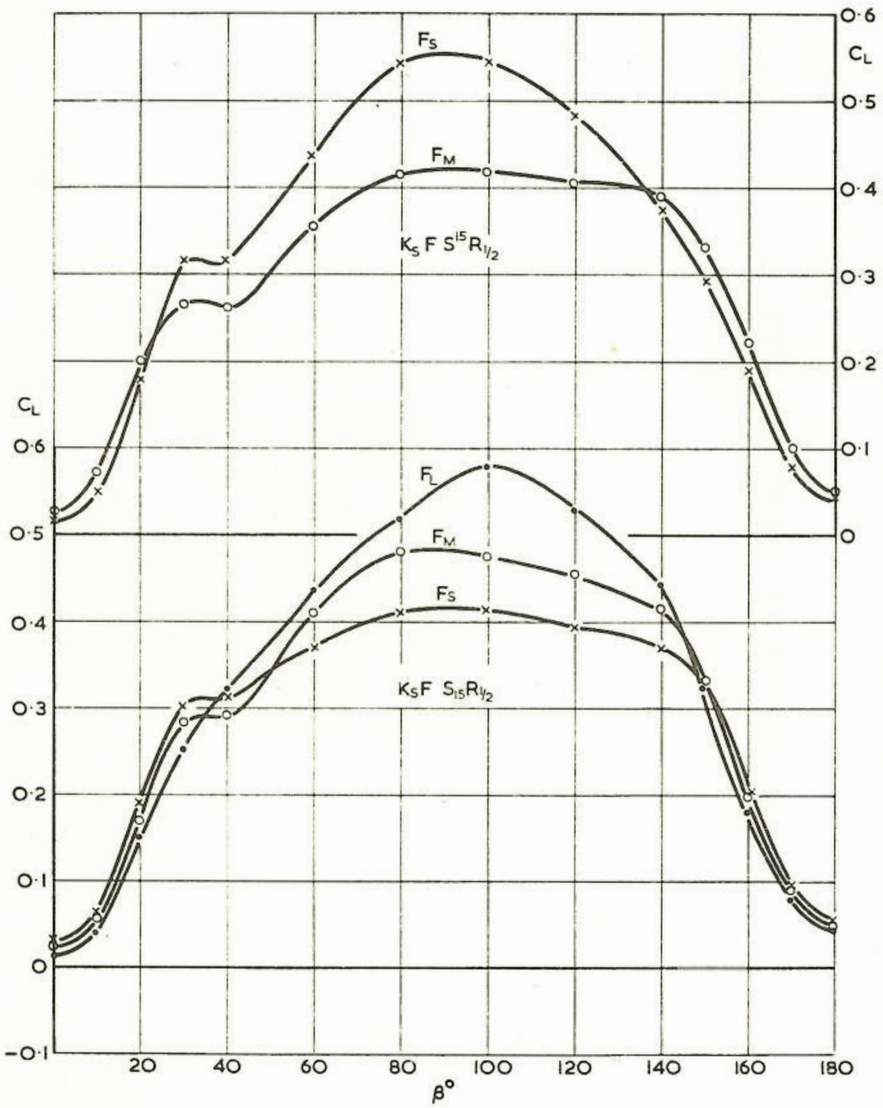

FIG. 16. EFFECT OF FOREDECK LENGTH ON LIFT.

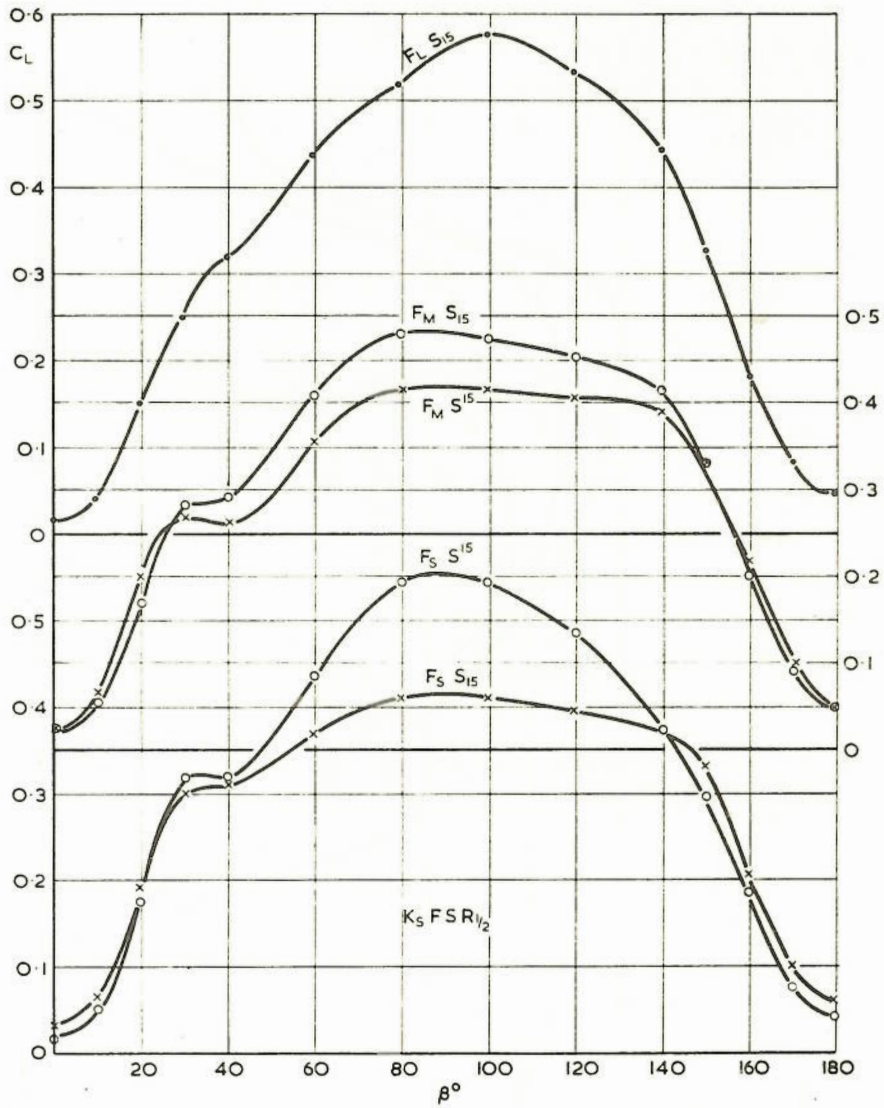

FIG. 17. EFFECT OF SUPER-STRUCTURE HEIGHT AND FOREDECK LENGTH ON LIFT.

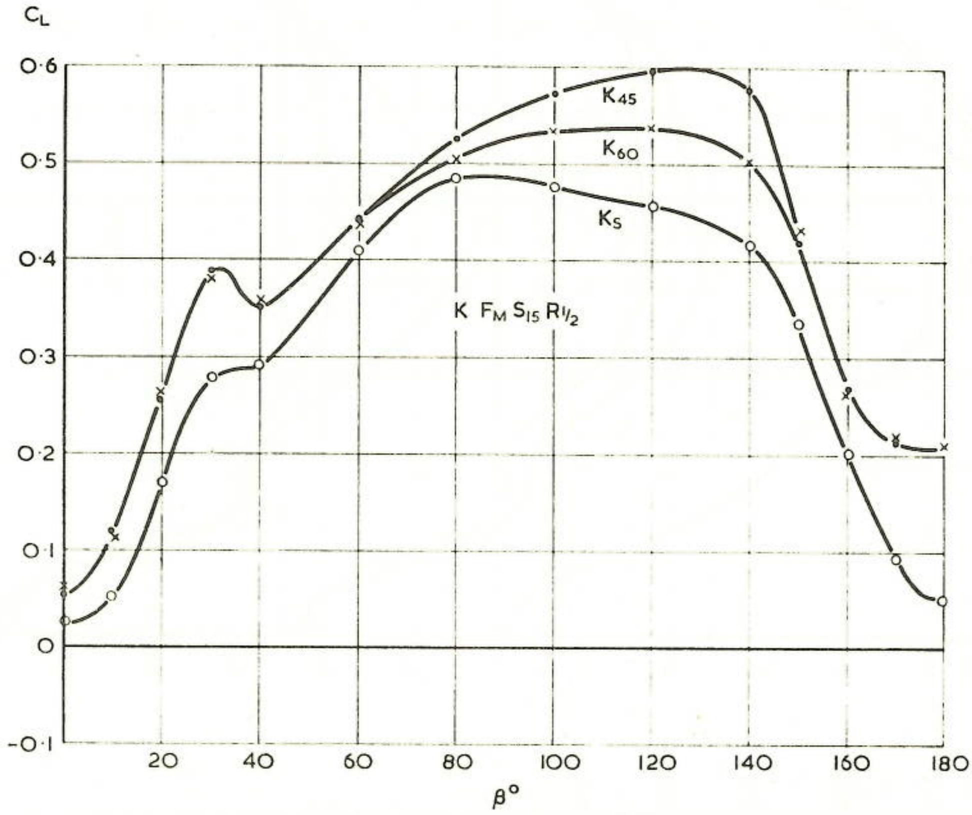

FIG. 18. EFFECT OF SKIRT ON LIFT.