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AERODYNAMIC PITCH STABILITY OF CATAMARAN TYPE HIGH SPEED POWER BOATS.

BY.

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ABSTRACT

A general discussion on the aerodynamic forces which cause longitudinal pitch instability in catamaran type or other aerodynamic type high speed powerboats is given. Formulae simplified into an emperical form are provided to give close approximations of the nature and magnitude of such forces.

Suggestions are offered to facilitate design of craft with improved aerodynamic stability and performance.

NOMENCLATURE

A_T	=	Area of tailplane (sq.metres)
A_1	=	Effective wing area (sq.metres)
A_2	=	Area of cut away forefoot (sq.metres)
c	=	Chord of centre hull (wing) section (metres)
C_D	=	Aerodynamic drag co-efficient
C_H	=	Hull co-efficient
C_L	=	Aerodynamic lift co-efficient
C_M	=	Aerodynamic pitching moment co-efficient ($\frac{1}{4}$ chord)
Cpl	=	Underwing pressure co-efficient
F	=	Speed Factor
h_o	=	Height of trailing edge of wing above waterline (metres)
h	=	Height of keel at transom above waterline (positive only) (metres)

H	=	Height factor
L_A	=	Aerofoil effect lift (Kgms)
L_G	=	Ground effect lift (Kgms)
L_T	=	Tailplane lift (Kgms)
M	=	Pitching moment (Kgm metres)
S	=	Wing Span (metres)
V	=	Speed (Km/hr)
x_1	=	Distance from trailing edge to centre of area cut away forefoot (metres)
X	=	Distance from trailing edge to centre of ground effect lift (metres)
Y	=	Length factor
Z	=	Ground co-efficient
α	=	Angle of Attack (degrees)
ζ	=	Tailplane interferance co-efficient

Where:

$$C_H = \frac{A_2 F}{(c-\ell)\left\{h_o + \frac{\sin\alpha}{2}(\ell+c)\right\}} \qquad \ldots 1$$

$$Y = \frac{(c-\ell)}{2} - \frac{1}{2}\left\{1 - \frac{(x_1-\lambda)}{(c-\ell)}\right\}\left\{\frac{C_H(c-\ell)}{1-C_H}\right\} \qquad \ldots 2$$

$$H = \frac{h^3 c \sin\alpha}{h_o^2 (h_o+h)^2} \qquad \ldots 3$$

Values of F and Z can be gained from Graphs Figs 1 and 2 respectively. (Ref.1)

INTRODUCTION

The catamaran or tunnel hull form of racing powerboat which basically consists of two narrow outer hulls or sponsons joined by a central wing or deck, achieves higher speeds than comparable monohull craft, due not only to the hydrodynamic design facility of reducing waterline beam and wetted area whilst retaining static and dynamic roll stability, but also to the considerable aerodynamic lift induced on the section of the craft which joins the two outer hulls.

The form of craft however is inherently unstable and the backward 'flip' is commonplace and accepted even though such accidents have caused serious injury and death.

It has been generally accepted that the tendancy to pitch backwards is due to a forward shift of the underhull aerodynamic centre of pressure with an increased angle of attack of the hull.

From previous theoretical analysis and experimental data on ram wing surface effect vehicles (Ref.1,5), there are two separate and independent aerodynamic lifting forces acting on the craft, and the variations in moments created by these forces constitute the major factor in backward pitching.

Over the normal operational range of angle of attack of the centre wing section, one force acts at a point between 22% and 28% of the total length of the chord of the centre or wing section of the hull behind the leading edge and is, given a constant angle of attack and speed, approximately constant (Ref.2) (Fig.3). The second force acts at a point between 52% and 65% of the chord behind the leading edge depending upon hull configuration and waterline position (Fig.4), and is directly proportional to the height of the underside of the wing above the water given constant conditions of angle of attack and speed. It diminishes rapidly when the craft lifts off the water (Ref.1).

AERODYNAMIC FORCES ACTING ON CRAFT

A description of the forces is as follows:

1. Aerofoil Lift and Pitching Moment

An aerofoil or wing section generates lift because of its shape and the nature of its movement through the air. For any wing section this lift is primarily proportional to the angle of attack, the surface area, and the square of the velocity, associated with this lift is a drag in a direction opposite to the direction of propogation. Both lift and drag are results of pressure distribution around the aerofoil and are the single resultant forces of the combined pressure distribution.

The position on the chord where the single lift force acts is termed the centre of pressure. Changes in angle of attack alter the pressure distribution and consequently there is a movement of the centre of pressure. Over the normal operational range of angles of attack as the angle is increased so is the resultant lift, and in addition the centre of pressure moves forward (Fig.5)(Ref.2)

The characteristics of an aerofoil are established by considering that the lift and drag act through a single point which is located $\frac{1}{4}$ of the chord behind the leading edge and termed the Aerodynamic Centre and replacing the effect of change of centre of pressure by the addition of a moment about the aerodynamic centre.

Some commonly used forms of centre or wing section are shown in Fig.6 and are used in later considerations. In the case of the Types III and IV sections with an incomplete trailing edge the aerodynamic centre is determined by considering that the complete section existed (Ref.3).

Position of the aerodynamic centre for wing plan forms other than parallel can be determined as shown in Fig. 7 (Ref.3).

These characteristics are then expressed in terms of non dimensional co-efficients termed Lift Co-efficient (C_L), Drag Co-efficient (C_D), Moment Co-efficient (C_M), Lift Drag Ratio $\left\{\frac{L}{D}\right\}$ and are plotted against angle of attack.

For a typical wing section these are shown in Fig.7A (Ref.2,4).

For hull forms in which the centre section is a true aerofoil (i.e. twin engine or large catamarans) accurate aerodynamic characteristics are available from existing aerofoil data. In craft in which additional superstructure in the form of cockpits, engine cowlings, etc. is built above what would be the normal upper surface of the wing, each design must be tested using a wind tunnel to determine the characteristics. The figures and graphs provided should be considered as a guide only.

The magnitude of the aerodynamic lift on the centre section of the craft may be approximated using the formulae (Ref.2, 4):

$$L_A = 4.74 \times 10^{-2} C_L V^2 A_1 \quad \ldots 4$$

The lift co-efficient used depends upon the general type of aerofoil and the shape of the upper surface of the wing. Approximate figures can be gained from the Graph Fig.8. These graphs are for wing sections having an aspect ratio of approximately $\frac{1}{4}$ at Reynolds number of 1.5×10^6, which represents average characteristics for craft presently operating. The effective wing area A_1 is determined as shown in Fig.9 (Ref.1,2,4).

Changes in aspect ratio $\left\{\frac{s}{c}\right\}$ change the value of C_L An indication of the nature of the change for a typical aerofoil section is shown in Fig.17 (Ref.4).

Similarly the magnitude of the pitching moment may be determined using the formulae:

$$M = 4.74 \times 10^{-2} \; C_M \; V^2 \; A_1 c \qquad \ldots \; 5$$

An approximate value of the moment co-efficient can be determined using Graph Fig.10 (Ref.1,2,4).

2. Lift due to Ram or Ground Effect

Consider the wedge shape formed by the underside of the wing, the inside edges of sponsons, and the water surface (Fig.11). The forward movement of this wedge entrains air which leaks sideways from the gap between the keel line and the water surface in the region ahead of the point of contact of the keel with the water, the degree of leakage being a function (interalia) of the shape of this gap, with the remaining air passing through the trailing edge gap. The restriction caused by the reduction in cross sectional area of the wedge to the trailing edge position, reduces the incoming air velocity with a consequent increase in pressure on the underside of the wing. This increase in pressure or 'ground effect' produces lifting forces of a much greater magnitude than are achievable from a normal aerofoil in free flight. (Ref.1,5)

Fig.12 shows comparative pressure distributions on two craft with different hull profile. Hulls with a deep forefoot have reduced side leakage and therefore are subject to a greater lift due to ground effect. It should also be noted that craft with a comparatively greater waterline length also have increased ground effect and the centre of lift due to ground effect is further forward than that of craft with a reduced waterline length. (Ref.1).

Generally within limitations imposed by the hull design and wave height in keeping the underside of the trailing edge of the wing above the dynamic waterline to reduce wetted area, the smaller the trailing edge gap the greater will be the ground effect.

Determination of the magnitude and position of the lift due to ground effect requires a detailed analysis of each individual design and involves a hydrodynamic study in conjunction with aerodynamic considerations to establish the dynamic waterline position and angle of attack.

An approximate solution can be obtained as follows:

Consider a craft having an underwing hull profile as shown in Fig.13 then the lift due to ground effect can be approximated using the formulae (Ref.1):

$$L_G = 4.84 \times 10^{-2} V^2 Z \, Cpl \, S \cos\alpha \left\{ (c-\ell)(1-C_H) + \ell \right\} \qquad \ldots \quad 6$$

The value of Cpl can be obtained from Graph Fig.14.

The approximate position of the point of application of the lift due to ground effect can be determined using the formulae (Ref.1):

$$X = \frac{\frac{\ell^2}{2} + (c-\ell)(Y+\ell)(1-C_H)}{(c-\ell)(1-C_H) +} \qquad \ldots \quad 7$$

COMBINED EFFECT ON STABILITY

The nature of operation of the craft being considered is such that two different changes to the equilibrium state can occur, either independently or at the same time. These are:

A. A water disturbance at the bow which causes a rapid increase in angle of attack.

B. A water disturbance or sufficiently high speed which lifts the craft clear of the water.

An indication of the forces acting on the craft in steady state running trim can be gained from Fig.15.

In A. the forces acting on the craft with increase in angle of attack for a typical hull form is shown in the diagram Fig.16.

Except where the craft has left the water entirely (in which case pitching occurs about the centre of gravity) there is a restraint to downward vertical movement offered by the point of contact of the craft with the water. In the unstepped form of craft the point about which the craft will pitchis determined generally by the point of hydrodynamic lift and buouyancy characteristics.

An indication of the nature and magnitude of the pitching moments can be gained by considering moments about the transom.

As the angle of attack increases the moment due to aerodynamic lift, drag and pressure effect increase rapidly whilst the moments due to ground effect and weight of the craft remain by comparison relatively constant.

In B. when the craft is thrown, or lifts clear of the water because of the aerodynamic lift exceeding the total weight, Fig.18, the hydrodynamic lift and drag moments become zero, the motor thrust moment is reduced or becomes zero if the propellor leaves the water completely, and the ground effect moment is reduced considerably. Thus with this reduction in these countering moments, the overall effect is to increase the total moment which tends to pitch the craft backwards.

The reduction in lift due to ground effect increases the effective weight of the craft and it tends to return to its equilibrium position, this effectively increases the angle of attack and the condition described in A. above becomes into effect.

Changes of L_A and L_G and the pitching moment due to L_A and L_G for a typical craft are shown in the Graphs Fig.19 and 20 plotted against the non dimensional height factor H. Whilst not considered here, in free flight the general hull form also exhibits poor roll stability.

From dynamics considerations it is desirable to avoid coupling between different degrees of freedom and consequently the centre of gravity should be located at the point at which the lifting force which varies with ground clearance acts, and both of these should be located as nearly as possible to the point of hydrodynamic lift Fig. 21.

DESIGN FACTORS AND HULL FORMS

In conventional catamaran type craft the position of the point of hydrodynamic lift varies considerably with speed and angle of attack, consequently the requirement of positions of CG, L_G and hydrodynamic lift is difficult to achieve, however in a stepped craft the position of the effective hydrodynamic lift remains relatively constant Fig.22.

Generally repositioning of L_A and L_G can be achieved by changing the chord of the wing section, moving the wing section further aft with respect to the hull, or a combination of both.

The effect of waves or water disturbances on the bow of a craft in inducing pitching can be reduced by selection of a suitable hull form. Stepped hull configuration is generally associated with a reduced performance in comparison to unstepped hulls due to hydrodynamic considerations over the lower speed range (up to 140 kM/hr.), and does not provide the facility for varying angle of attack to suit water conditions that is a desirable characteristic exhibited by unstepped craft, but where the craft will be continuously operating in relatively rough water, the hydrodynamic pitch stability offered by this form has considerable advantage.

In addition, in stepped hulls the requirement for accurate positioning of the effective points of application of forces acting on the craft is less critical, and the effect of aerodynamic lift on instability over a wide range of angles of attack reduced. Thus changes in angle of attack induced by waves within the design range will not induce additional pitch instability. The Graph Fig.22A shows typical characteristics of pitching for a stepped catamaran with varying ratios of aerodynamic lift to total weight (R). It should be noted that the greater the value of R the smaller the range of angle of attack in which the craft remains stable and the greater the initial rate of increase of instability once the unstable point has been reached. Effective countering of the pitching moment due to L_A becomes increasingly important as the value of R increases, and where R is low the wide stability range available reduces the necessity for countering provisions.

The factor R should always be less than one to ensure adequate control of the craft and to maintain efficiency of drive.

The exact value is a matter for individual design and preference, however, as a general guide for this, the following values are offered.

Water Conditions	R
Rough water large swell - open sea	.20 - .30
Choppy water - bays	.25 - .45
Calm water - Lakes, etc.	.35 - .65
Perfect Conditions - Record breaking craft	.65 - .85

MEANS OF INTRODUCING GREATER PITCH STABILITY

For unstepped craft and stepped craft with high R values which characteristically exhibit considerable pitch instability, a simple solution to countering the pitching moment due to L_A, is the installation of a rear horizontal stabilizer Fig.23 (Ref.1,5).

By considering moments about a neutral point (Overall Aerodynamic Centre) located between 5% and 10% of the main wing chord behind the C.G. position, at the design angle of attack of the main wing, the moment due to the lift and pitching moment of the main wing is counteracted by the moment due to the tailplane lift. In practice, because of limitations of size and main wing form, the tailplane C_L will be greater than the main wing C_L contrary to three dimensional free flight requirements of aircraft. For the type of craft being considered the effect of C_L variation in moment which occurs on a backward pitching displacement from the design angle of attack initially produces a righting moment which increases as the angle of attack increases Fig.23A. The C.G. ahead of the neutral point produces free flight pitch stability and also brings the neutral point towards the transom of the craft about which hydrodynamic pitching occurs.

As the stabilizer lift is required in the vertical up direction only the aerofoil section can be assymetrical and determined using the following formulae (Ref.2):

$$L_T = 4.74 \times 10^{-2} C_{L_T} V^2 A_T \qquad \ldots \quad 8$$

The lift co-efficient for a suitable section can be determined using Graph Fig.24. (Ref.4).

The co-efficient ζ provides for the reduction of the effective angle of attack of the tailplane by downwash due to airflow over the main hull section and also the interference to the tailplane airflow by the vertical mounting fin or brackets. The value of ζ is determined not only by the main hull form, but also the relative position of the tailplane to both the main hull and the water surface. The general effect of the proximity of both the main hull and tailplane to the water is to reduce the downwash compared to aircraft free flight characteristics. With the tailplane located approximately one half main wing chord behind and above the main wing, ζ varies between 0.75 and 0.85 (Ref.6). Determination of exact value is difficult and an increase of angle of attack of the tailplane by approximately 2° to 3° above the theoretical value can be used as a starting point for final adjustments.in practice.

Provision for in operation variation of tailplane angle of attack is not considered necessary unless to provide for variation overall boat angle of attack to suit varying water conditions.

RESTRICTIONS ON RACING CRAFT

It should be noted that the use of a stabilizer such as proposed contravenes existing rules governing this form of racing craft both nationally and internationally, however, a strict interpretation of these rules would also preclude the present catamaran type craft, and as safety considerations must be paramount in the formulation and application of racing rules; the use of such stabilizers or other aerodynamic means of control are imperative.

APPLICATION OF CONCEPT

As there also exists considerable facility for trimming the craft by hydrodynamic means utilizing 'trim tabs', modifications to underwater hull form, and where available variation of thrust angle of drive shaft, precise balance to suit the conditions under which the craft is operating can be achieved without recourse to major changes in the aerodynamic characteristics.

The application of an aerodynamic pitch control principle enables considerations of greater total aerodynamic lift in this form of craft (by increase of wing area and/or greater angle of attack) such that greater speeds will safely be attained.

A possible form for a single engine outboard boat is shown in Fig.25. The boat has a greater wing area than present craft and has the engine mounted well behind the transom of the sponsons to move the centre of gravity further aft, and to position the ground effect lift, hydrodynamic lift and centre of gravity at the same point. This positioning of the motor also increases the turning moment available to induce cornering. The inner walls of the tunnel are carried back to the motor transom to increase ground effect lift, and a pitch countering moment can be created hydrodynamically at the motor position. A rear mounted aerodynamic stabilizer to counteract the aerodynamic pitching of the main hull is situated aft of the main hull.

Where a craft is designed for high wave conditions and thus having a significant trailing edge height, an adjustable flap to reduce the gap in calm water conditions would appear to have considerable advantage.

Models of proposed craft incorporating these features have been tested both in wind tunnels and in free flight conditions, and have exhibited the desired stability characteristics.

A U.I.M. Class OPII offshore race boat of this concept is presently being constructed. The craft is a tricycle form stepped craft having an overall length of 10.5 metres and a design speed of 145 Km/hr. In addition to the rear stabilizer, the design incorporates facility for reducing the trailing edge gap at the rear of the main hull wing section, and also of increasing the angle of attack of the main wing section by increasing the step height of the forward sponson.

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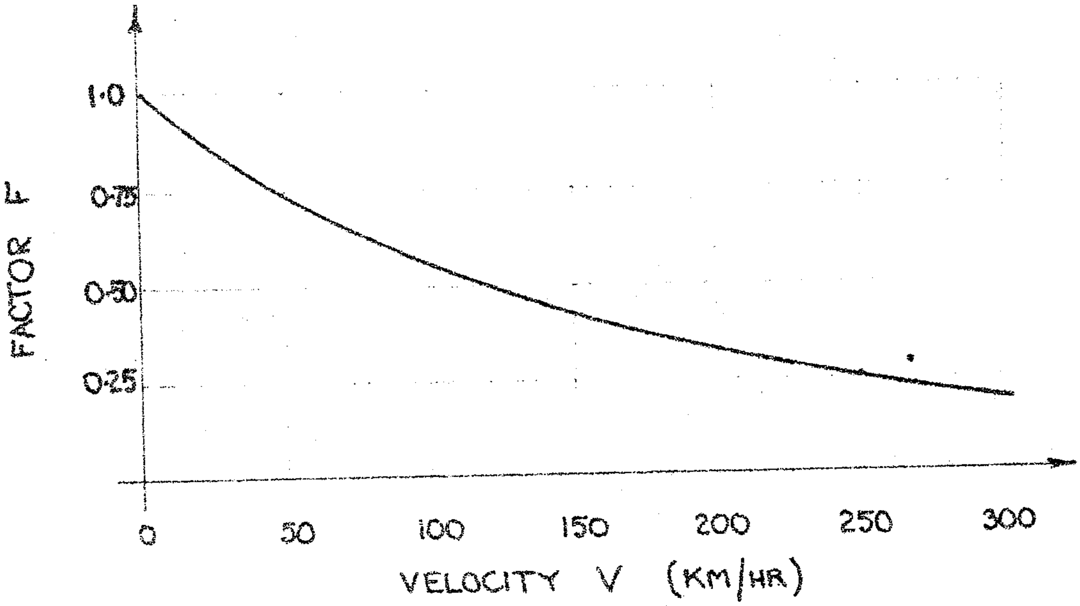
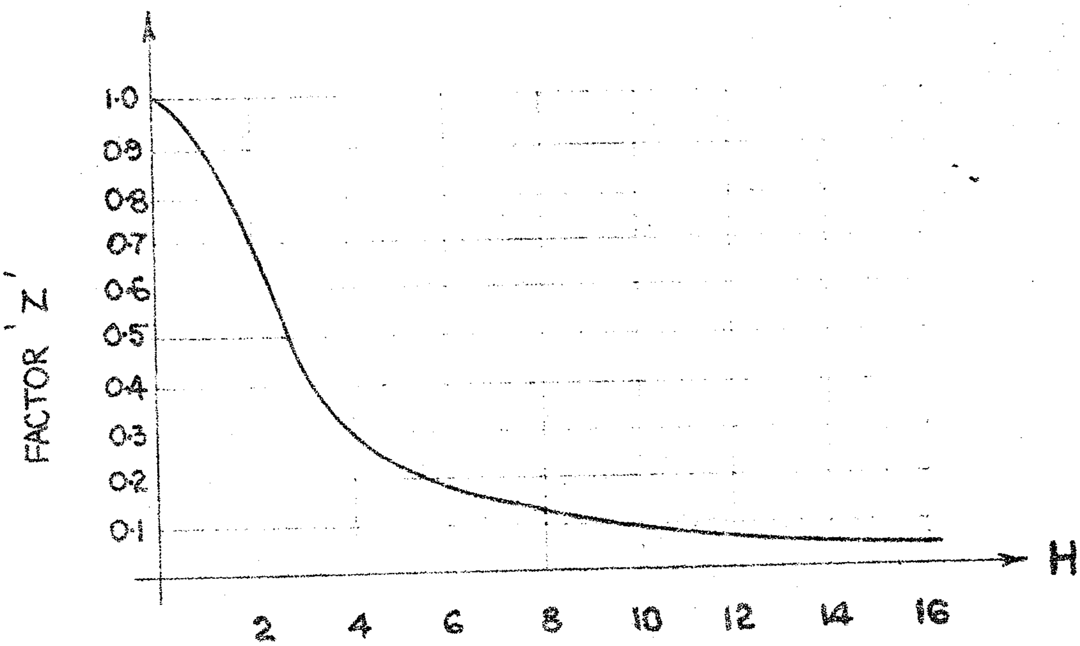


1·0
0·75
0·50
0·25
FACTOR 'F'
0
50
100
150
200
250
300
VELOCITY V (KM/HR)

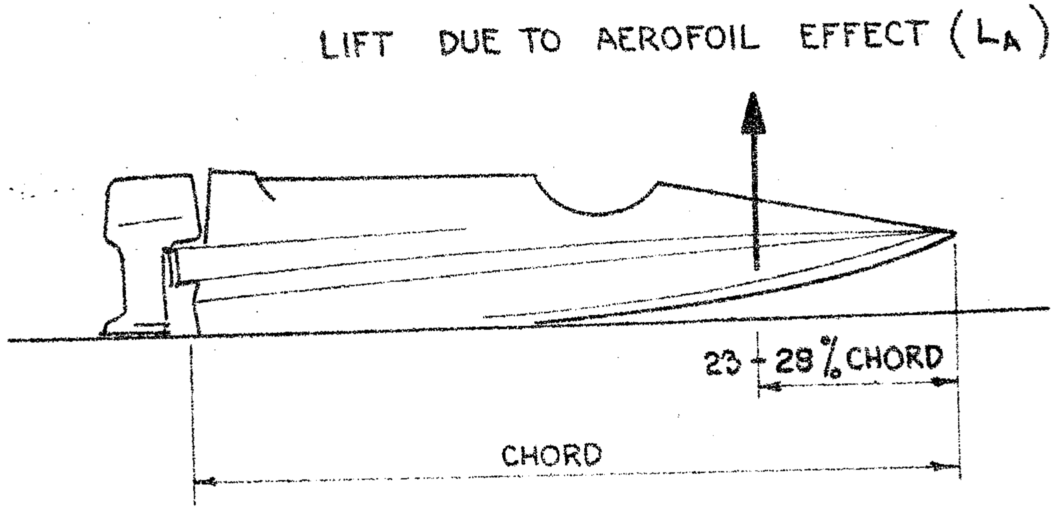
FIG. 1.

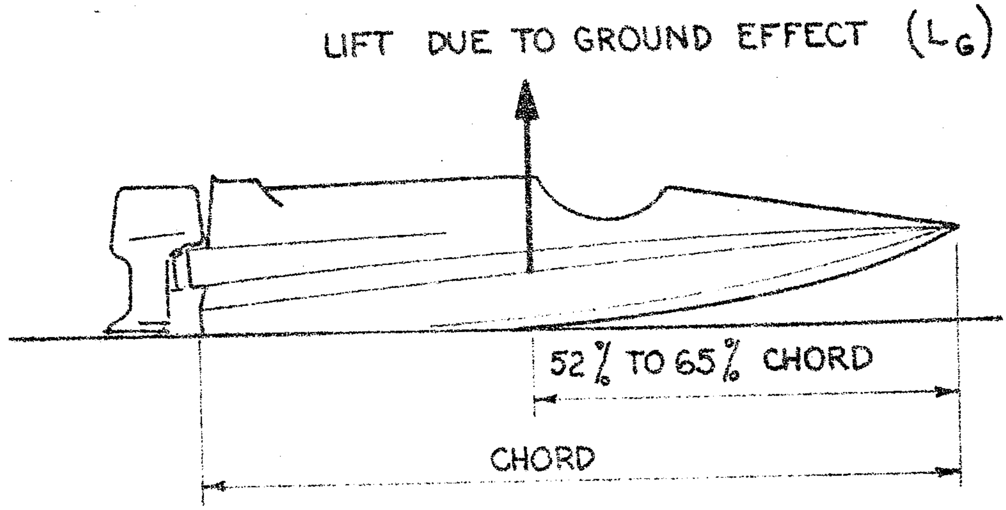


1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
FACTOR 'Z'
H
2
4
6
8
10
12
14
16

FIG. 2

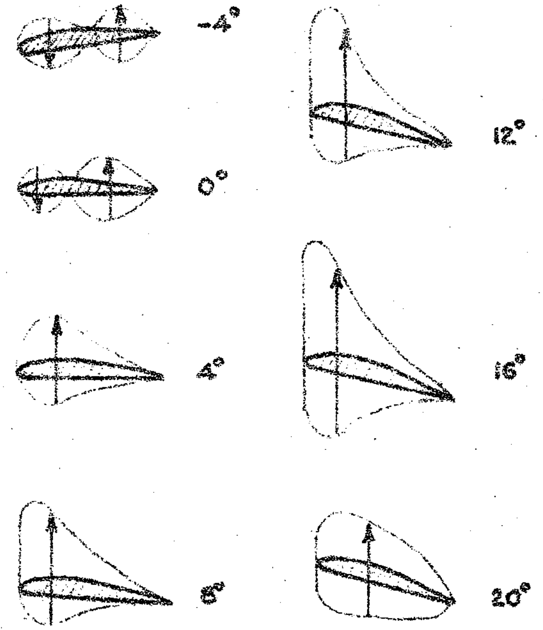
FIG. 3





SINGLE RESULTANT LIFT FORCES ACTING ON A TYPICAL CRAFT

FIG. 4



CHANGES IN LIFT DISTRIBUTION

TYPICAL CENTRE OF PRESSURE CURVE

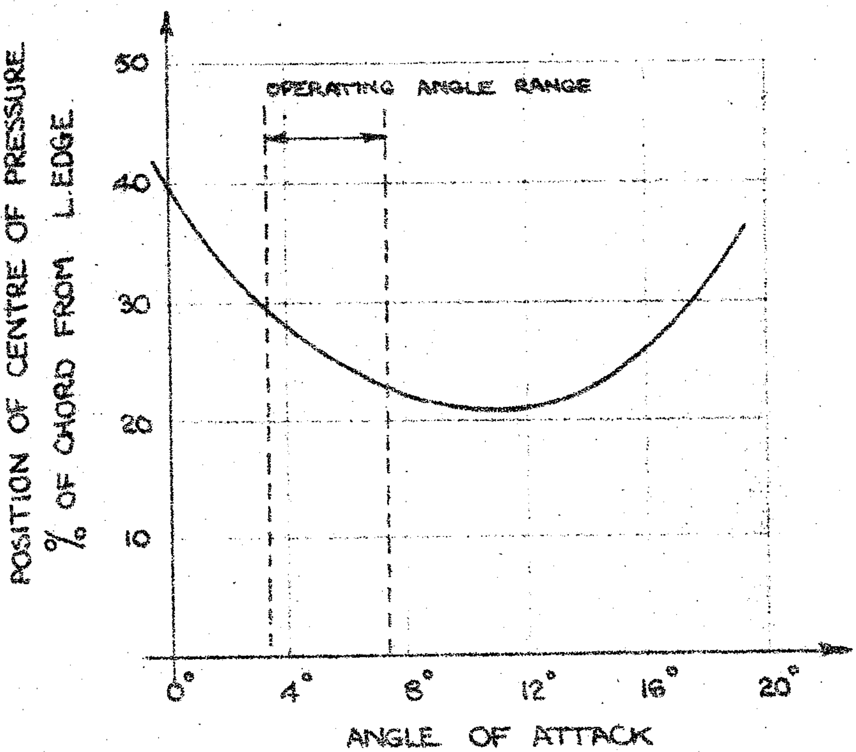


FIG.5

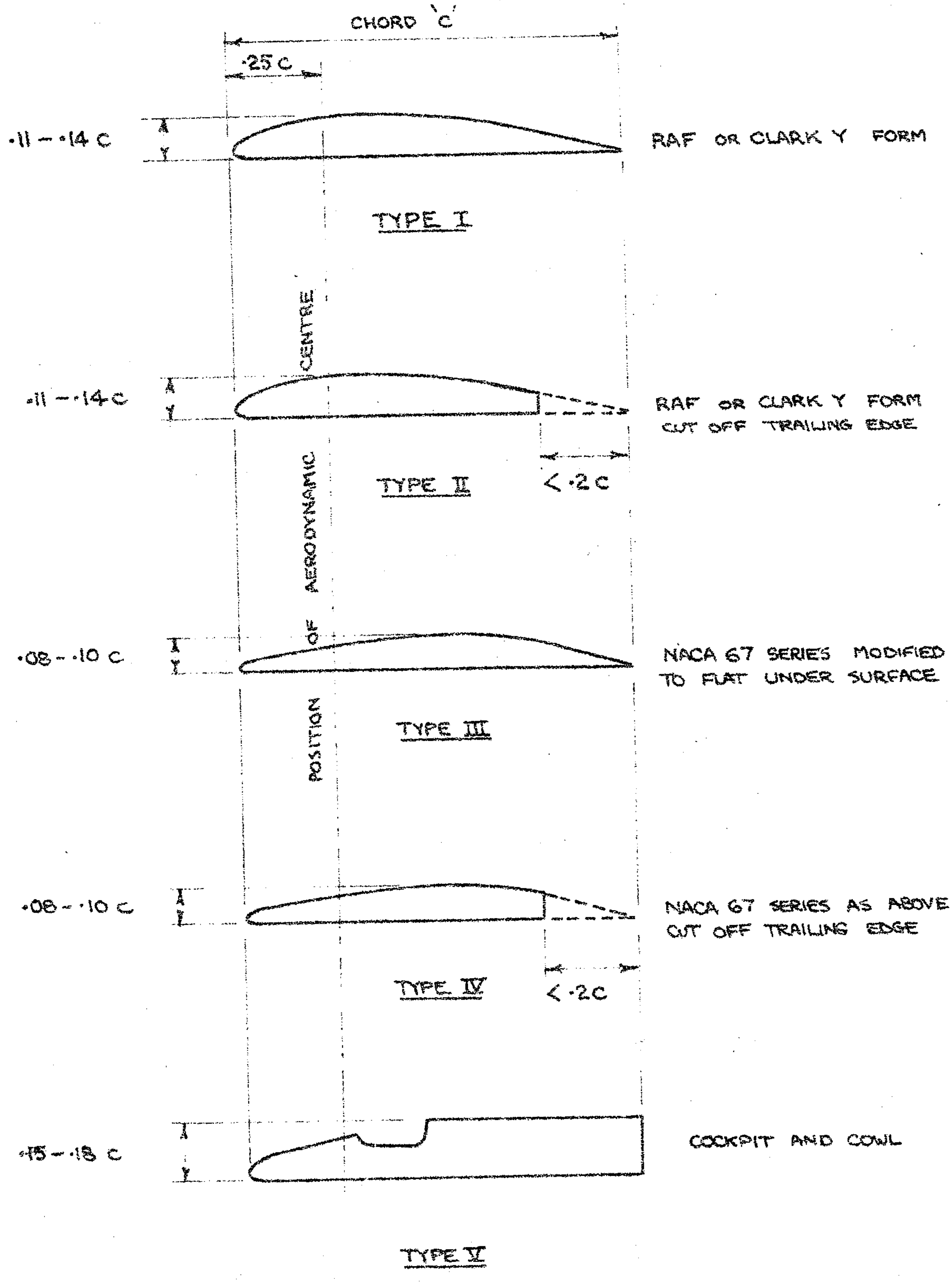
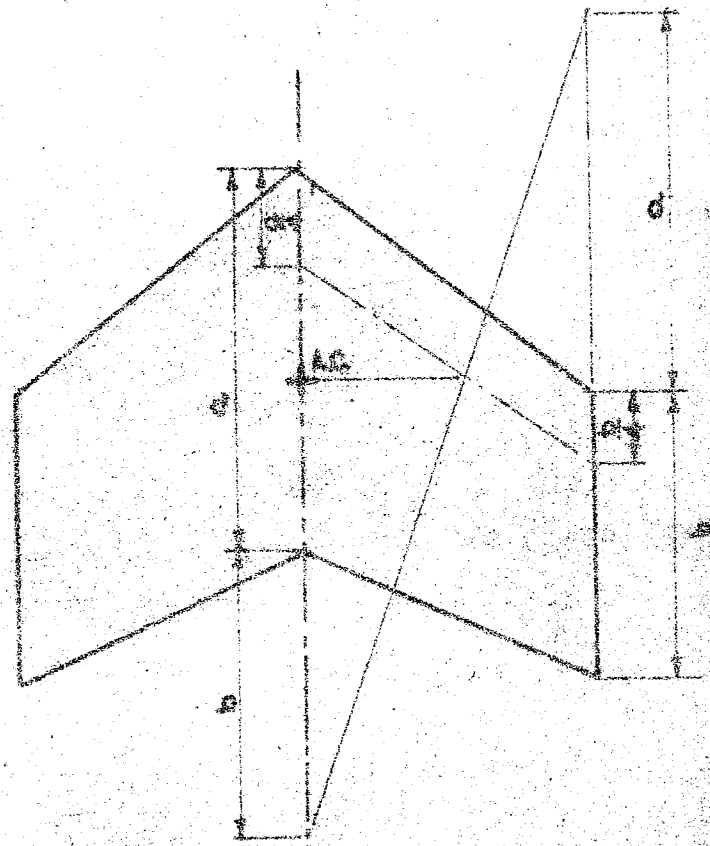
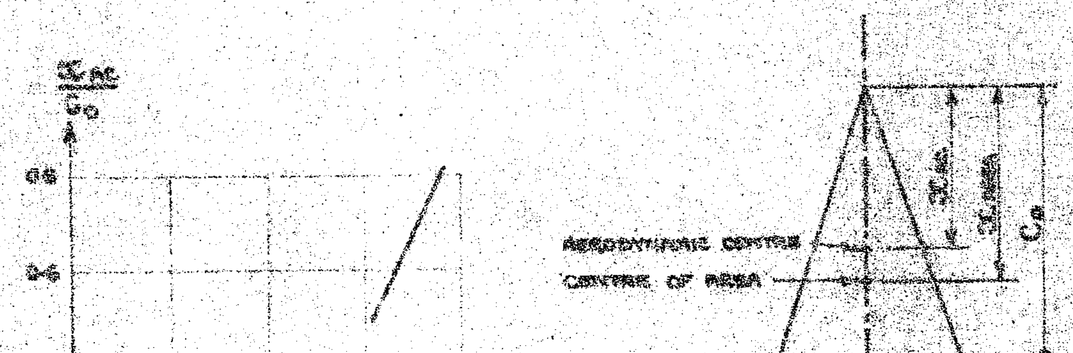

CHORD 'C'
·25 C
·11 – ·14 C
RAF OR CLARK Y FORM
TYPE I
CENTRE OF AERODYNAMIC POSITION
·11 – ·14 C
RAF OR CLARK Y FORM
CUT OFF TRAILING EDGE
TYPE II
< ·2 C
·08 – ·10 C
NACA 67 SERIES MODIFIED
TO FLAT UNDER SURFACE
TYPE III
·08 – ·10 C
NACA 67 SERIES AS ABOVE
CUT OFF TRAILING EDGE
TYPE IV
< ·2 C
·15 – ·18 C
COCKPIT AND COWL
TYPE V

FIG. 6

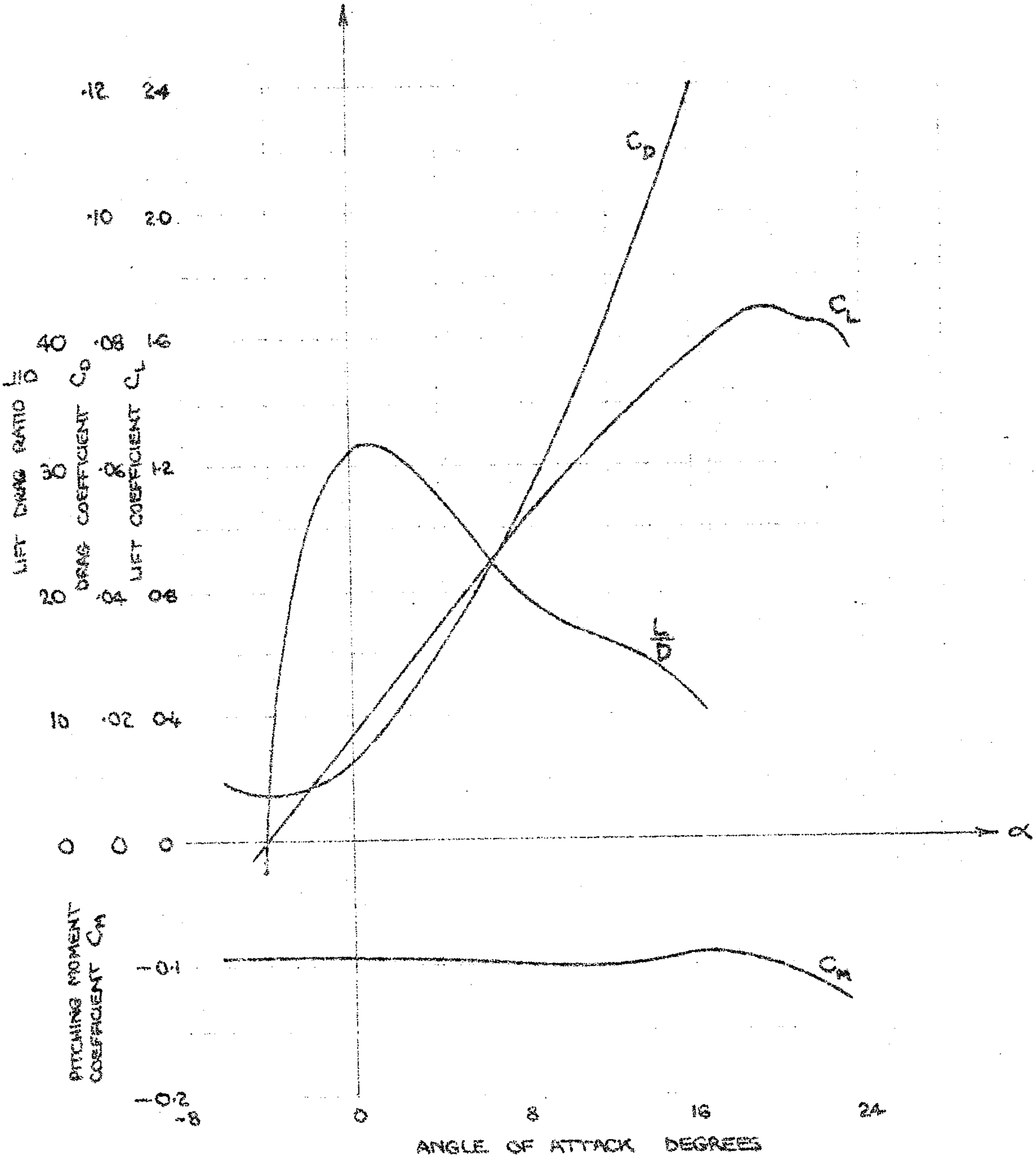


AERODYNAMIC CENTRE OF SWEPTBACK WINGS



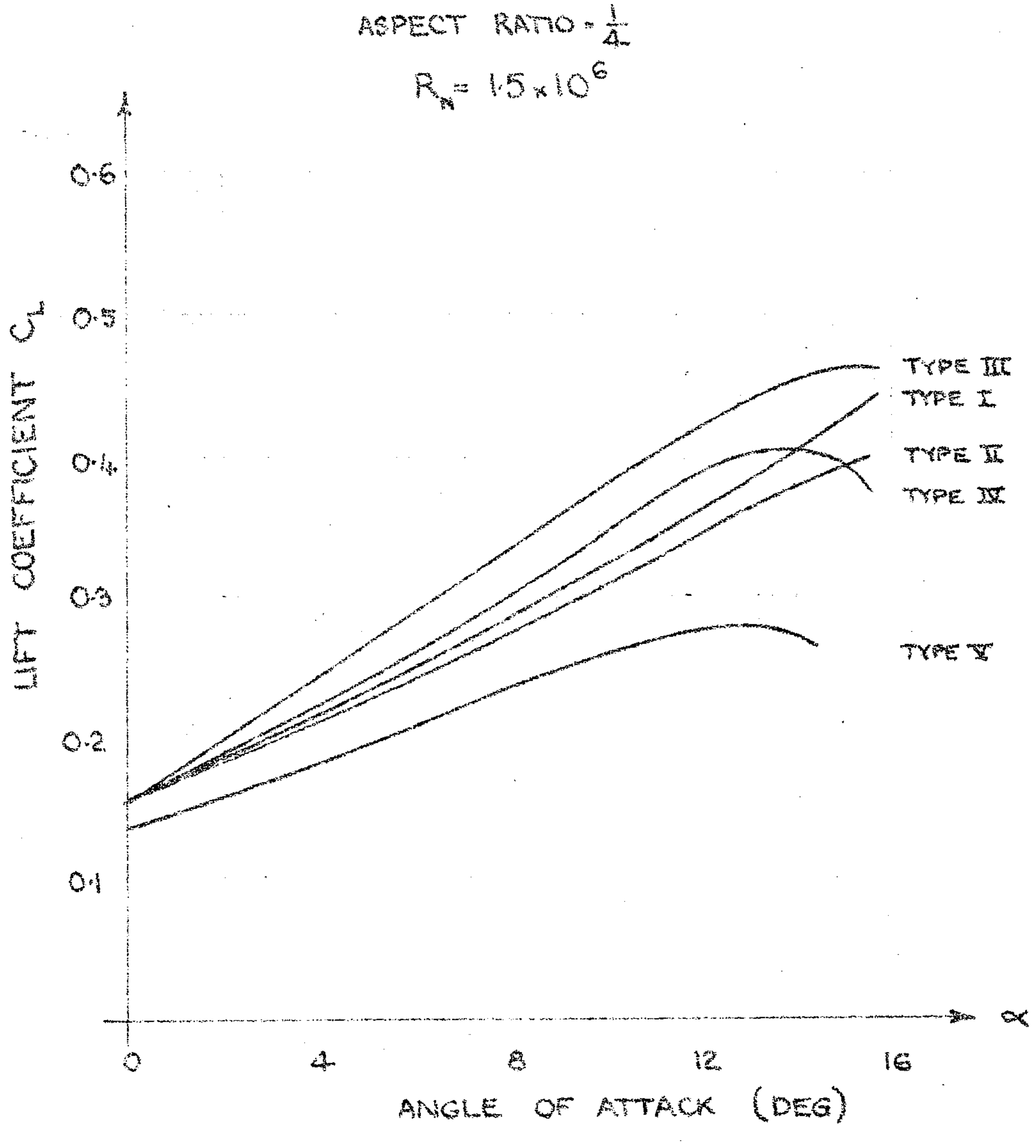
AERODYNAMIC CENTRE OF SLENDER WINGS

FIG. 7.



TYPICAL WING CHARACTERISTICS

FIG. 7A



LIFT COEFFICIENT v ANGLE OF ATTACK FOR TYPICAL WING FORMS

FIG. 8

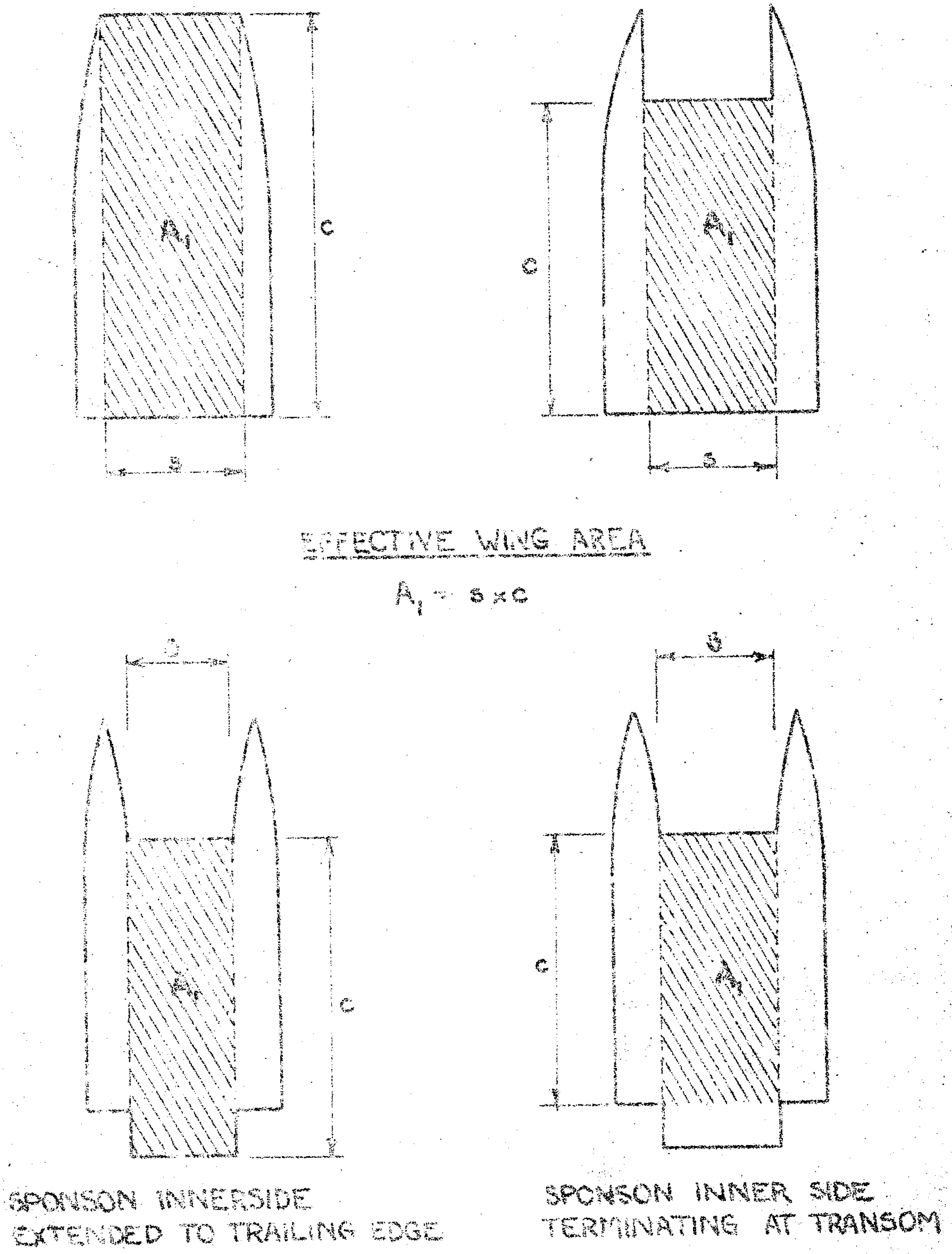
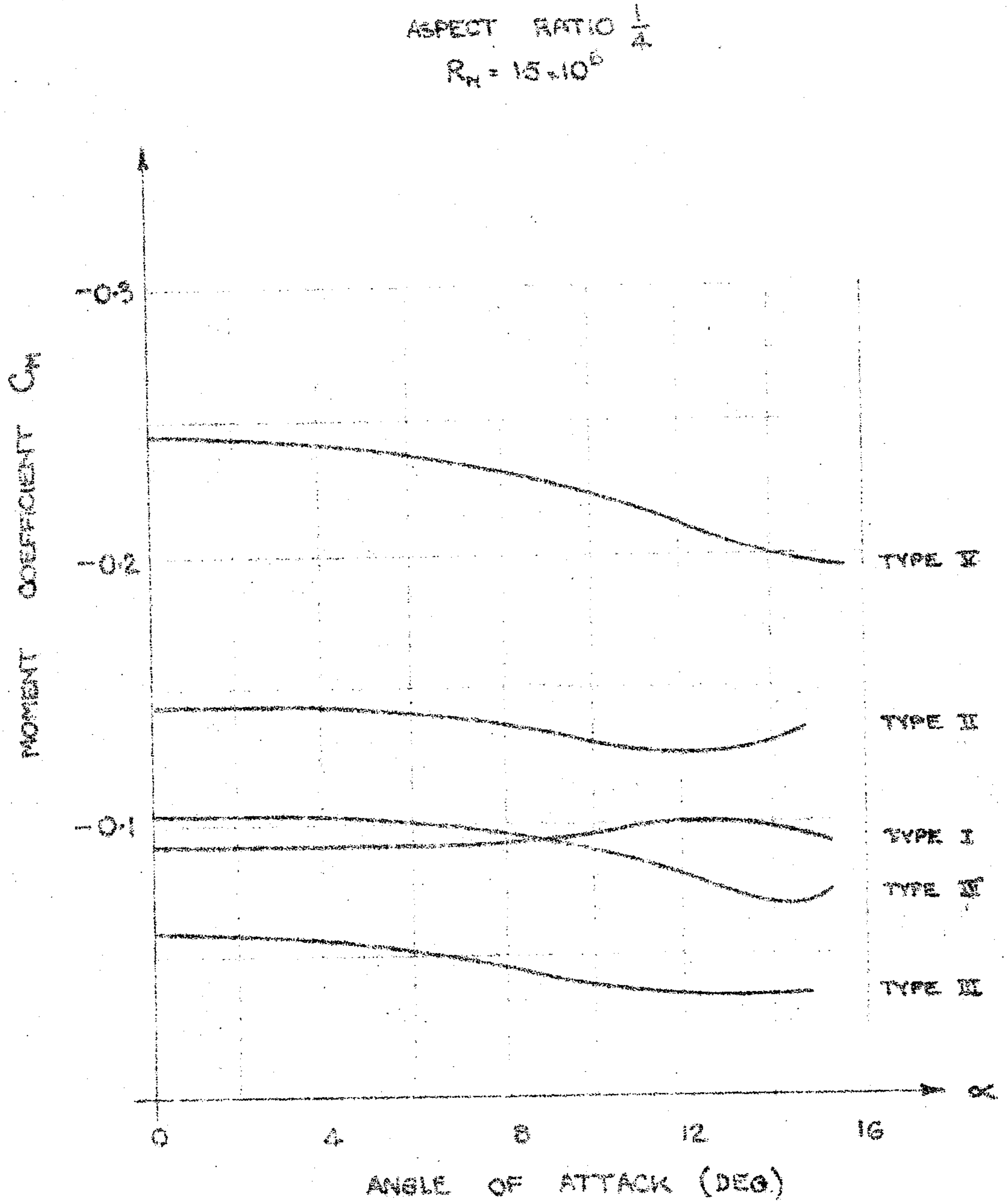
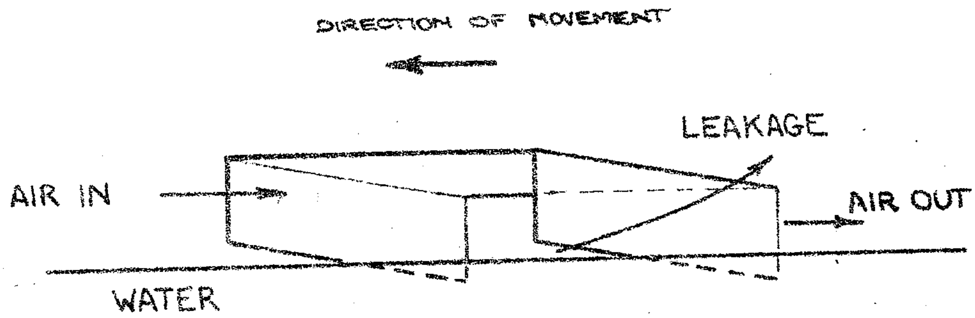

A1
c
s
EFFECTIVE WING AREA
A1 = s x c
SPONSON INNERSIDE
EXTENDED TO TRAILING EDGE
SPONSON INNER SIDE
TERMINATING AT TRANSOM

FIG. 9



MOMENT COEFFICIENT v ANGLE OF ATTACK FOR TYPICAL WING FORMS

FIG. 10



UNDERWING TUNNEL

FIG. 11

EFFECT OF SPONSON PROFILE ON UNDERWING PRESSURE DISTRIBUTION

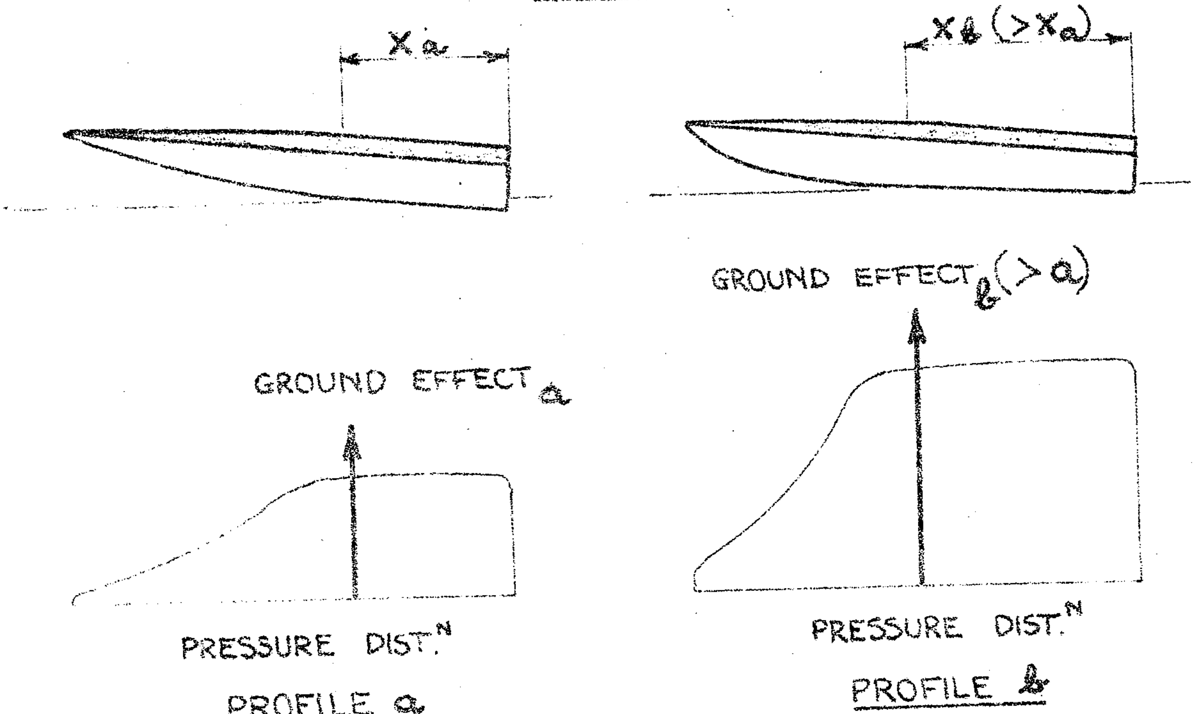
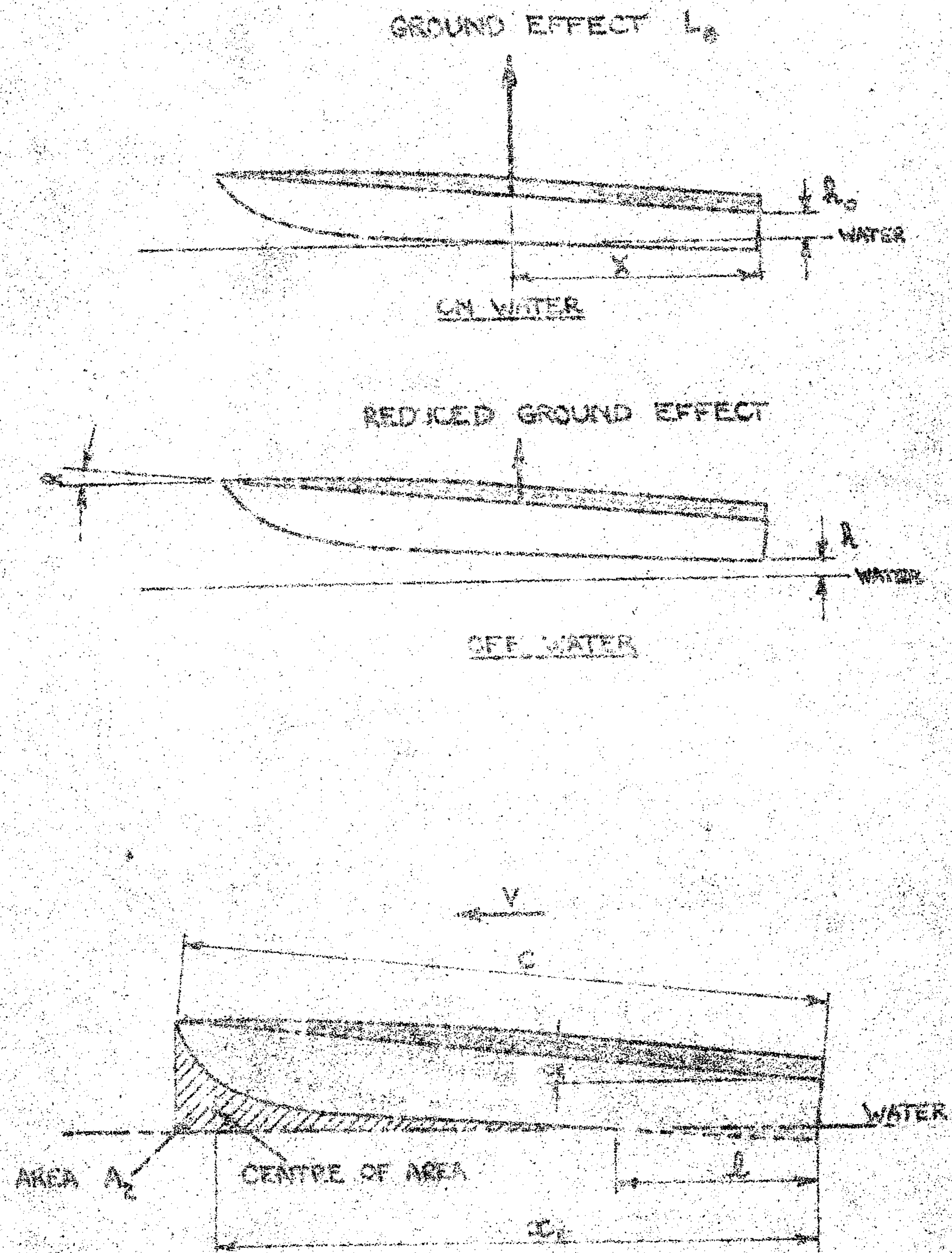
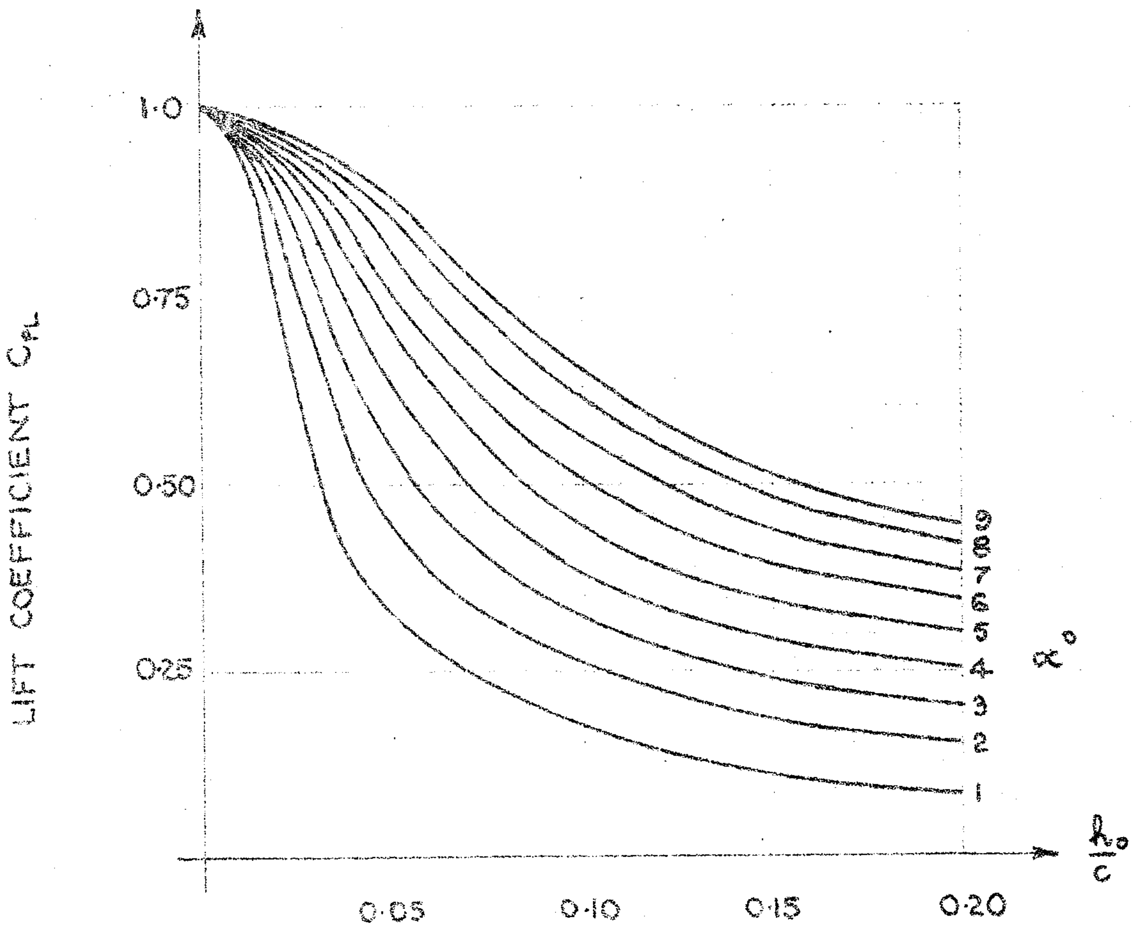


FIG. 12



NOTATION DIAGRAMS

FIG. 13

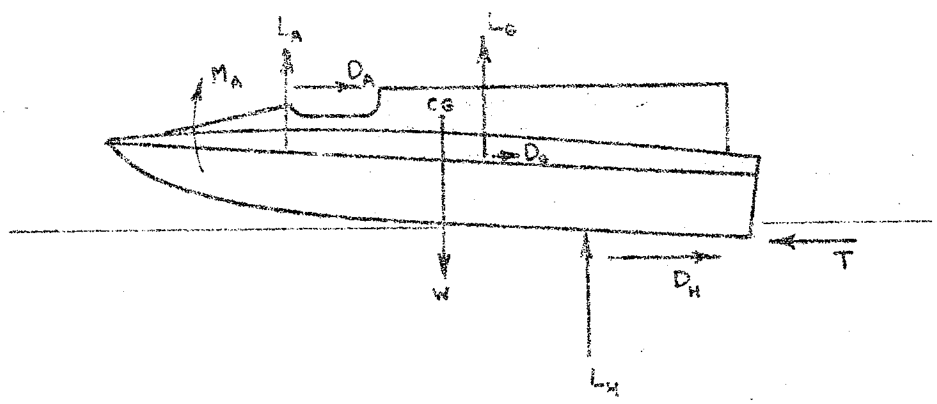


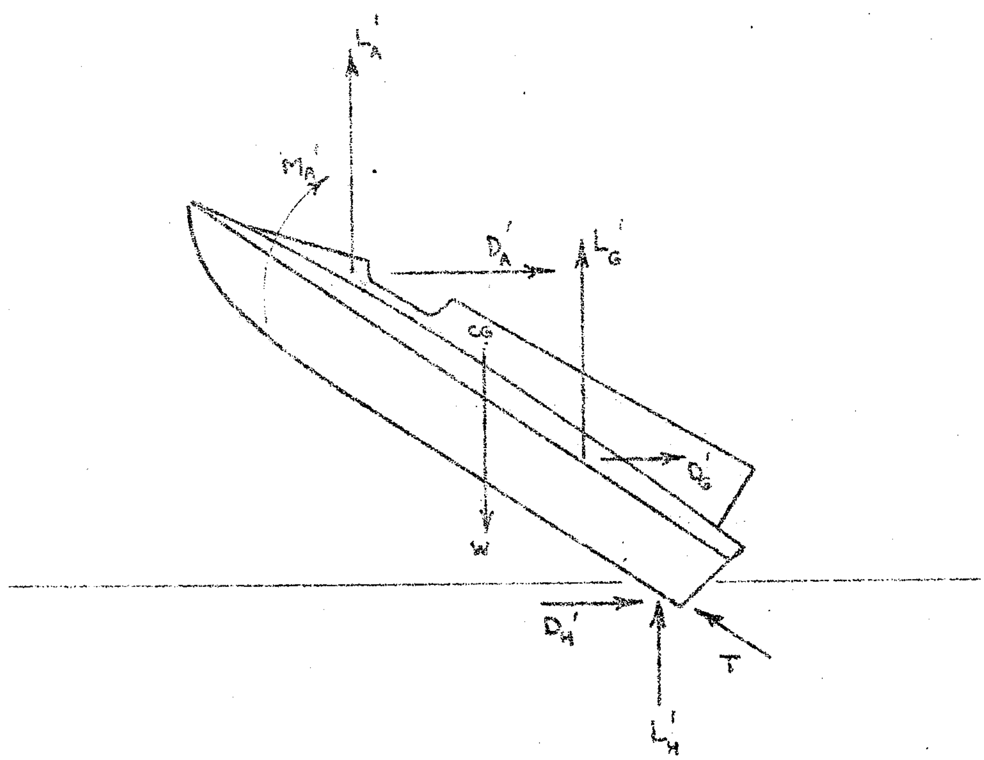
LIFT COEFFICIENT v HEIGHT CHORD FACTOR

FIG. 14

FIG.15

FORCES ON CRAFT – CORRECT RUNNING ANGLE OF ATTACK





FORCES ON CRAFT – EXCESSIVE ANGLE OF ATTACK

FIG.16

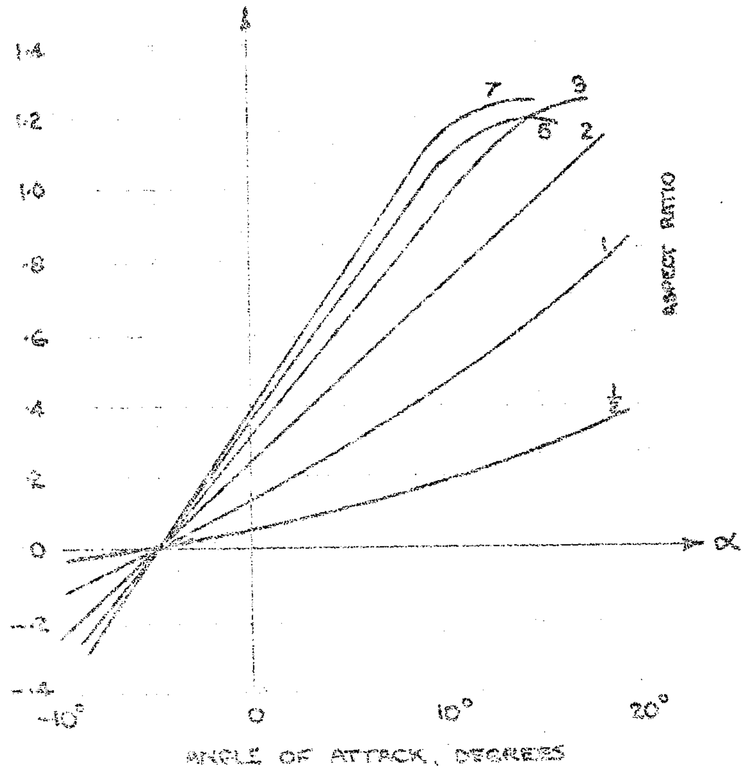
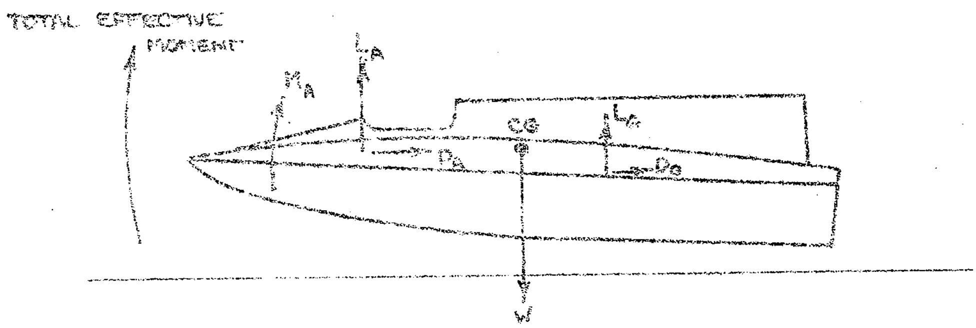


FIG. 17



FORCES ON CRAFT OUT OF WATER

FIG. 18

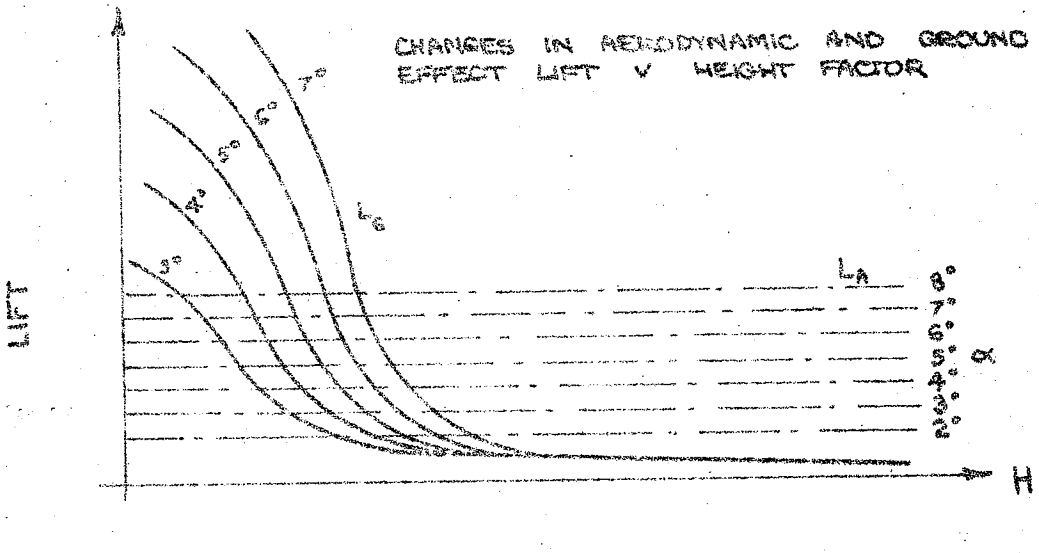

CHANGES IN AERODYNAMIC AND GROUND EFFECT LIFT V HEIGHT FACTOR
LIFT
H
α
L_A
L_G

FIG 19

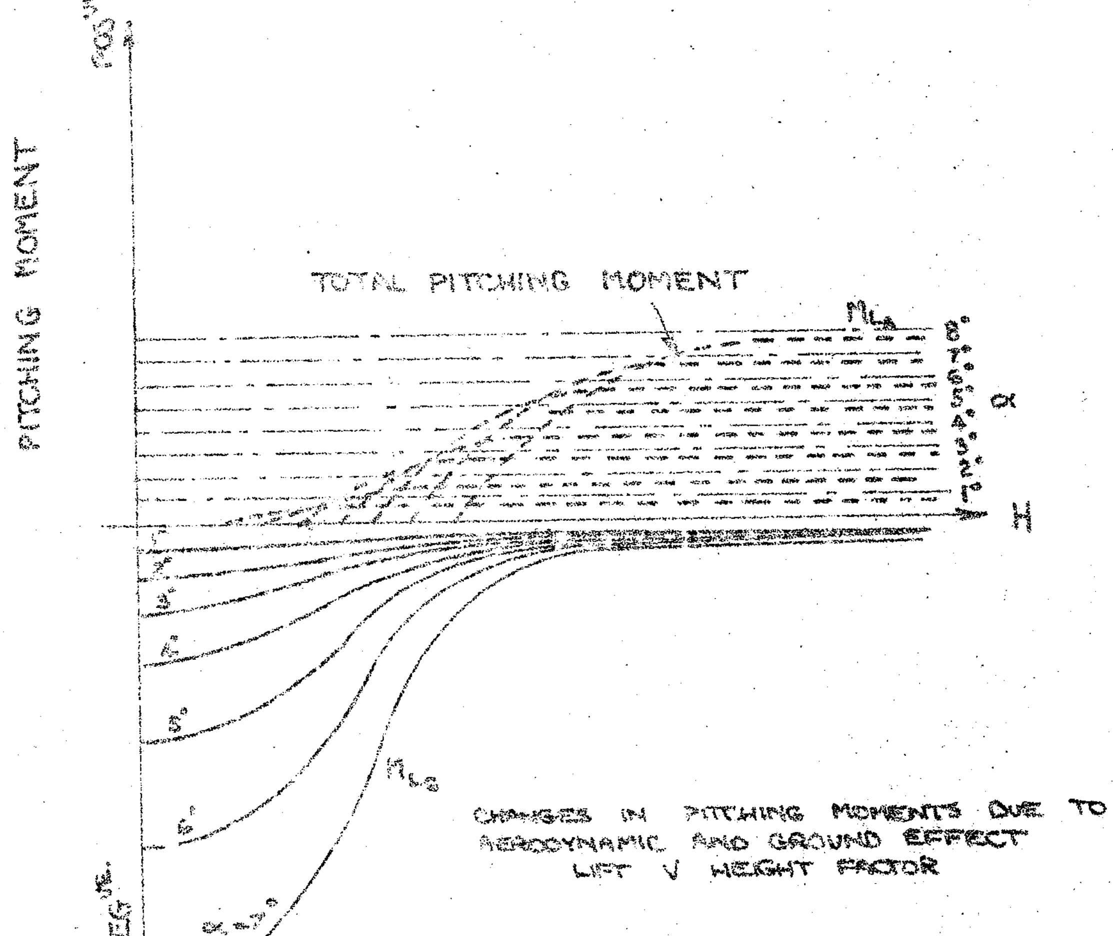
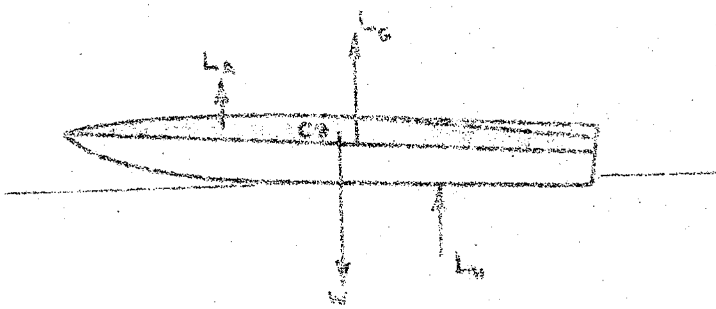
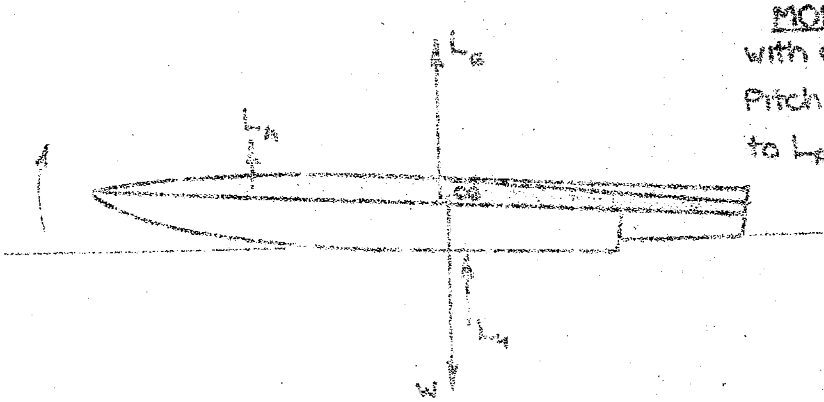

PITCHING MOMENT
POS^VE
NEG^VE
TOTAL PITCHING MOMENT
M_LA
M_LG
H
α
α = 7°
CHANGES IN PITCHING MOMENTS DUE TO AERODYNAMIC AND GROUND EFFECT LIFT V HEIGHT FACTOR

FIG 20

FIG.21 UNSTEPPED CATAMARAN

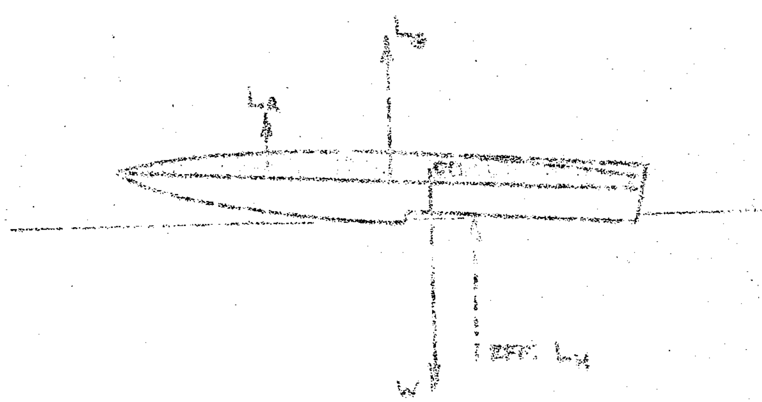


CONVENTIONAL FORM
In dynamic equil^{m}. at one value of α. only - otherwise unstable.

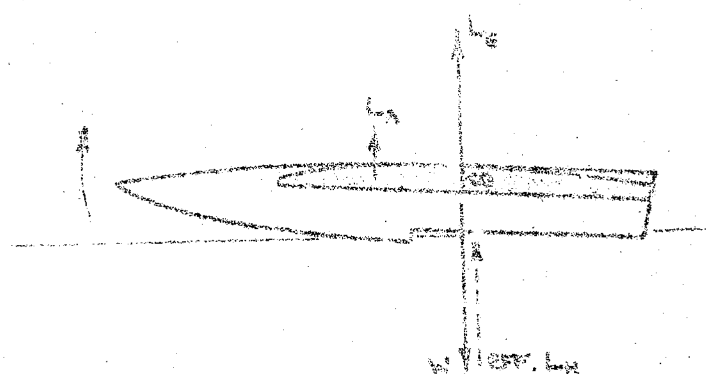


MODIFIED FORM
with extended chord. Pitching moment due to L_A only - otherwise stable.

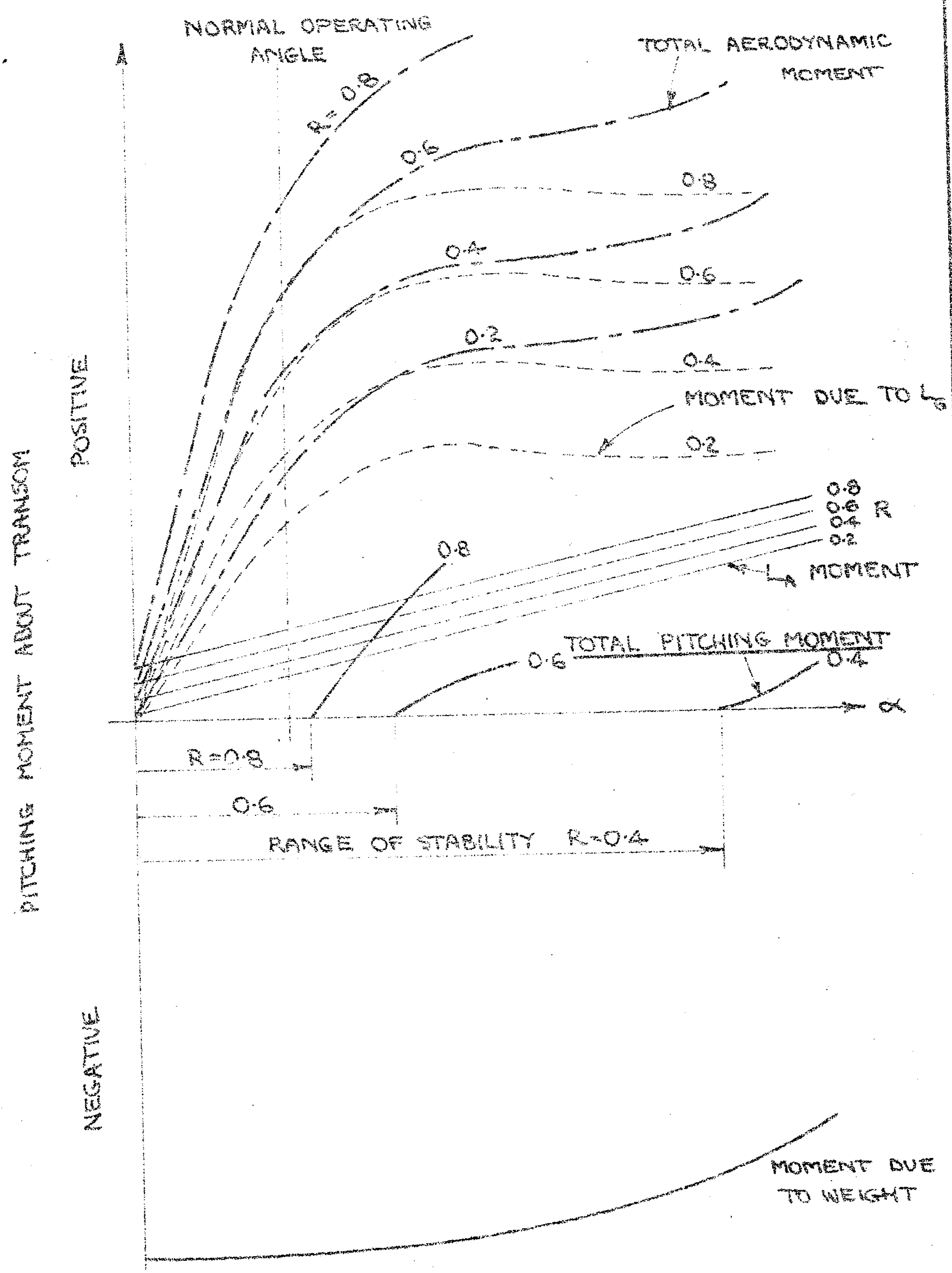
FIG.22 STEPPED CATAMARAN



CONVENTIONAL FORM
In dynamic equil^{m}. over wide range α. Unstable at high R or α values.

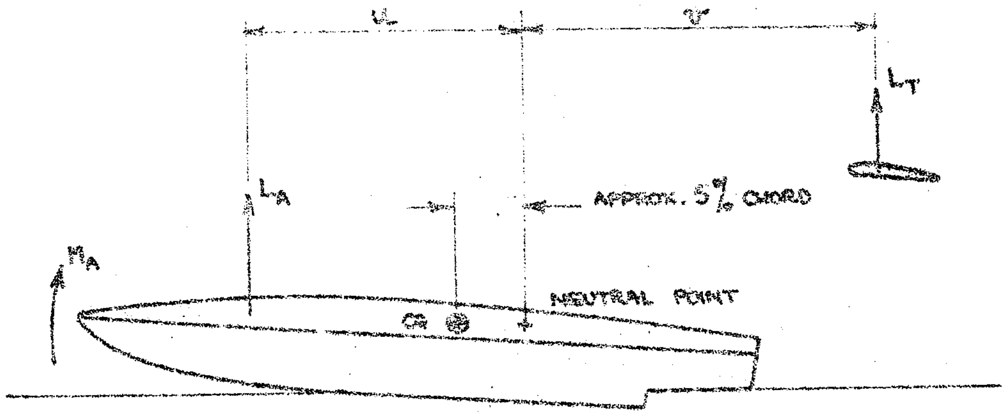


MODIFIED FORM
with reduced chord. Pitching moment due to L_A only - otherwise stable. Countering moment to L_A required only for high R or α.



STATIC PITCH CHARACTERISTICS FOR TYPICAL STEPPED CATAMARAN

FIG. 22A



MOMENTS ABOUT NEUTRAL POINT

$$M_A + (L_A \times u) = (L_T \times v)$$

FIG. 23

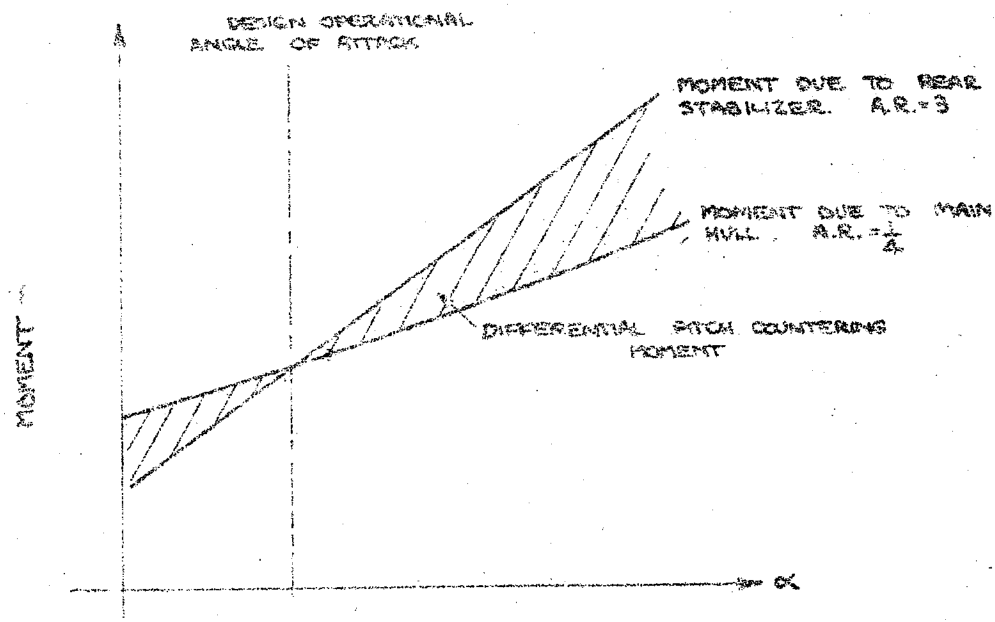
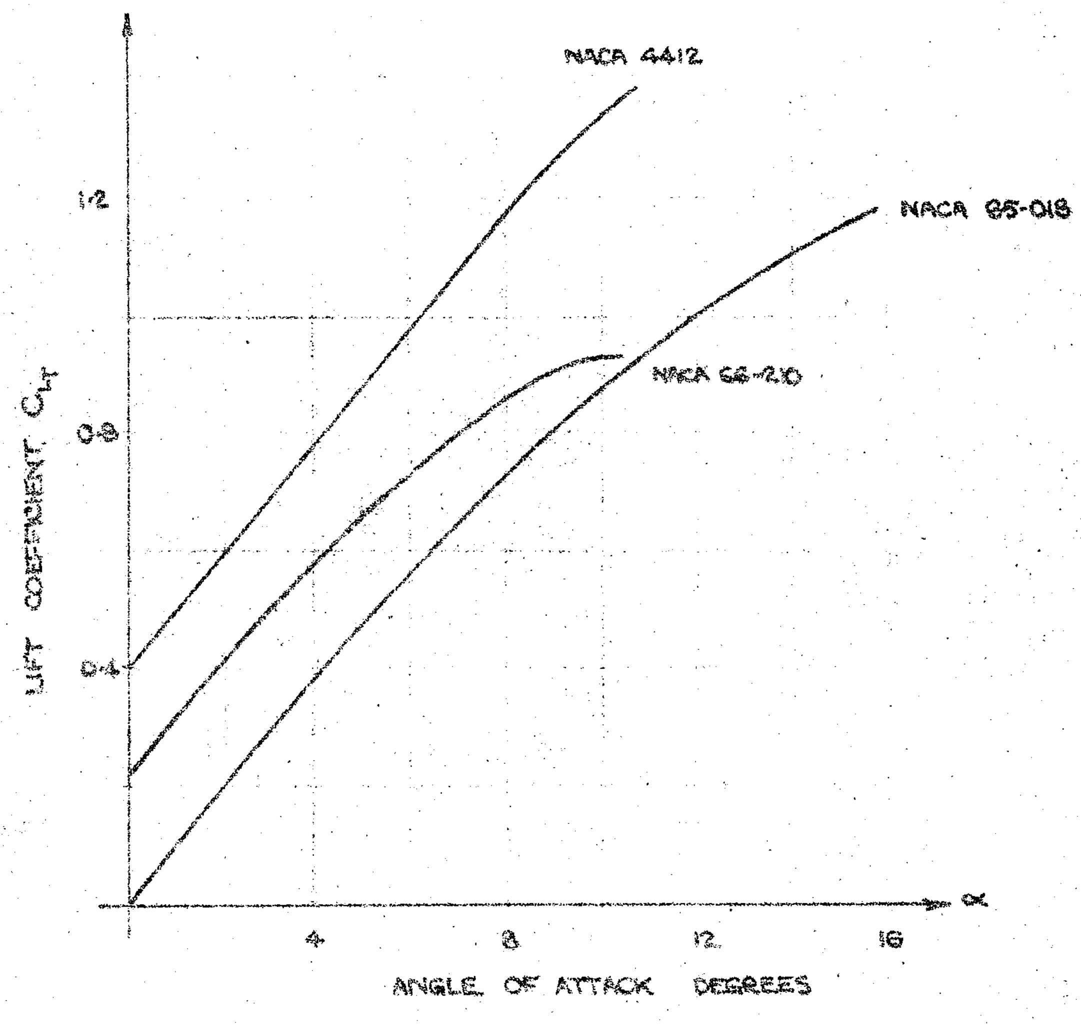


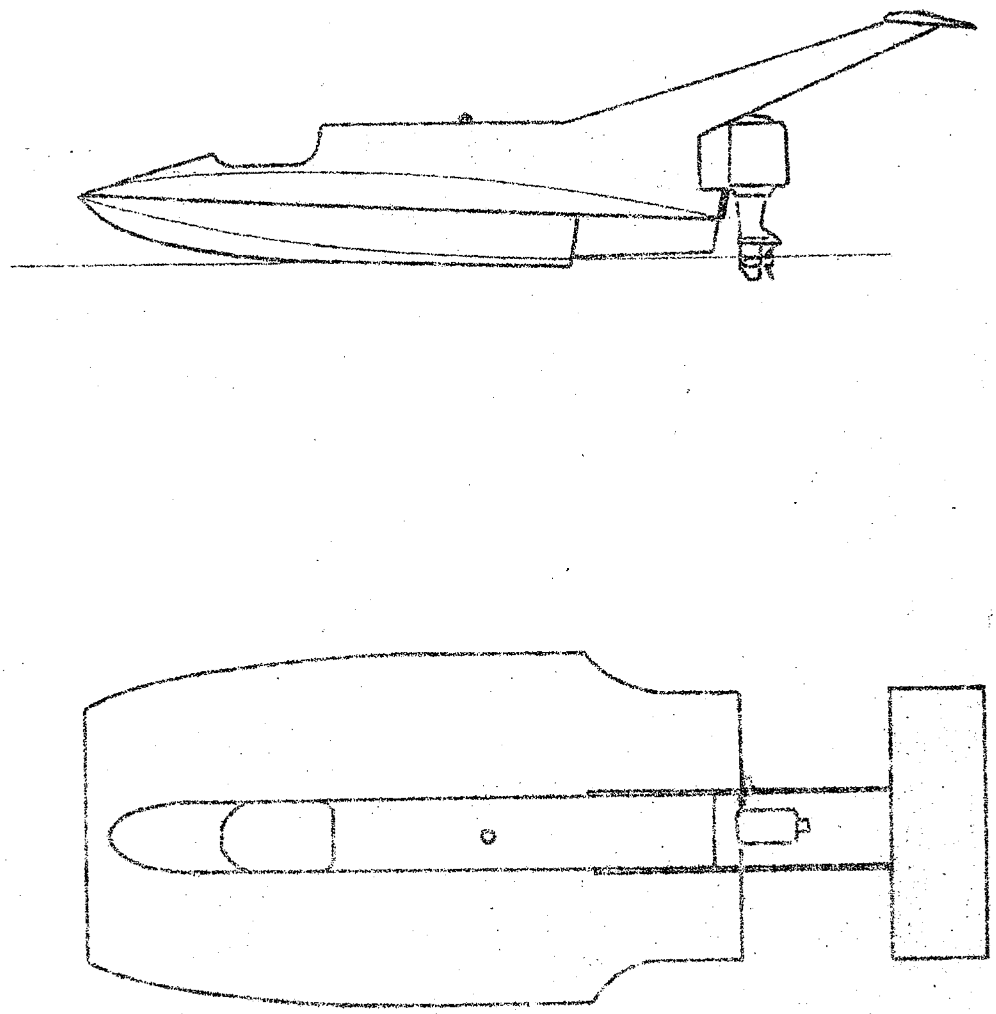
FIG. 23A



LIFT COEFFICIENT v ANGLE OF ATTACK

ASPECT RATIO 3 ; $R_N = 1{\cdot}5 \times 10^6$

FIG. 24



SUGGESTED FORM OF SINGLE ENGINE OUTBOARD CIRCUIT RACING BOAT WITH REAR STABILIZER.

FIG. 25