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DEVELOPMENT OF A TWO DIMENSIONAL FLOW TEST SECTION FOR A WIND TUNNEL AND ITS USE WITH A HYBRID FLAPPED MULTIPLANE

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DEVELOPMENT OF A TWO DIMENSIONAL FLOW TEST SECTION FOR A WIND TUNNEL AND ITS USE WITH A HYBRID FLAPPED MULTIPLANE

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SUMMARY

The report describes the development of a two dimensional flow wind tunnel test section, suitable for measuring lift. Its principal use was in developing aerofoils for windship propulsion and results for one of these provide an illustrative example. These results indicate that a C_L of around 4.2 can be achieved without flow separation and a C_{LMAX} of around 4.7 with separation.

ACKNOWLEDGEMENTS

1. The grant of an Industrial Research Fellowship by the Wolfson Foundation to the author is gratefully acknowledged as it made the present work possible.

2. The assistance of colleagues in the Department of Ship Science, Southampton University is also gratefully acknowledged and in particular, led to a relatively trouble-free balance installation.

INTRODUCTION

The work described formed part of a Wolfson Industrial Research Fellowship to design marine aerofoils for ship propulsion. To develop marine aerofoils ideally requires exclusive use of a wind tunnel throughout one or more cycles of rig testing, modification and re-testing. Unfortunately, most Southampton University wind tunnels are heavily utilised. Aims of the project were to produce a design in which aerodynamic virtues were a high C_{LMAX} and low C_{DO}. Project requirements and wind tunnel availability conflicted, with the result that it became attractive to modify an under-utilised wind tunnel, with little instrumentation, into an apparatus for testing marine aerofoil designs. It must be appreciated that the aerofoil development process can take place with measurements of limited accuracy and that there is a difference between a development wind tunnel and a wind tunnel for precise absolute measurements. Development can continue with a series of relative measurements, providing errors are consistent throughout those measurements.

The aim of this report is to describe the techniques used and the results obtanied. This is intended both to enable future researchers to use similar techniques and provide the necessary background to assess current results.

The tunnel was used to assess a number of initial marine aerofoil concepts, usually involving simple models, airspeed and balance readings. Results shown here are for one of those concepts known as a hybrid flapped multiplane (HFM). This particular device is an array of flapped and unflapped aerofoils, capable of producing positive or negative lift, orientatable in yaw and intended to produce maximum lift from minimal blighted deck area.

TUNNEL DETAILS

Tests were carried out in a low speed, 3 ft x 2 ft working section wind tunnel, shown in Figure 1. The working section dimensions were reduced to 3 ft x 1.64 ft (914 x 500 mm) by means of inserts fitted to the floor and ceiling. Details are shown in Figure 2. An aerofoil section spanned the distance between the inserts, contained between circular discs at either end. These discs were flush with the inserts, but separated from them by 25mm of low-modulus foam. A balance was fitted beneath the tunnel and the aerofoil section connected to it by means of a mounting pillar.

The aerofoil section formed part of a cantilever structure, with its base at the balance. This arrangement is shown in Figure 3.

BALANCE CALIBRATION AND LIMITATIONS

Details of the balance are given in ref. 1. For the present application, the cantilevered aerofoil causes some deformation of the foam when an airload is produced. Forces measured at the balance therefore consist of the airload, as well as some input from the deflected foam. The original balance calibration in ref. 1 must therefore be modified to account for the force input from the foam. At this point, it should be noted that at very high foam deflections a progressive slippage takes place between the foam and aerofoil end disc, which makes it impossible to produce a consistent calibration curve. The practical consequence is that the accuracy of the force measurements progressively declines beyond values of about 100N.

Drag measurements at the balance consist of the foam force, drag of the disc and drag of the aerofoil section. It is not possible to accurately separate balance drag measurements into individual components, implying that aerofoil drag cannot be measured on the balance. Aerofoil drag could have been measured by a wake traverse, but was not sought as part of the tests described.

Yawing moments (corresponding to conventional aerofoil section pitching moments) measured at the balance were heavily influenced by inconsistent foam/insert frictional forces. This implied that aerofoil section pitching moments could not be directly measured.

Pitching moments would best be obtained from a pressure-tapped model.

Lift can be measured on the balance, providing appropriate allowance is made for foam forces. This was done by applying known calibration forces to the centre-span of the aerofoil section and noting the readings on the balance. This technique is a direct way of obtaining a lift v. balance-reading graph for use in estimating lift coefficients. It ignores interactions between sideforce and other loads on the balance. These interactions have been shown to be small in ref. 1. (Typically up to 1% for the present model). A calibration graph for lift measurement is shown in Figure 4. Such graphs are slightly incidence-sensitive as eccentricity in the disc and mounting results in foam deformation when incidence is changed. At loads above 100N the disc slippage problem referred to earlier became pronounced and the lift calibration graph (Figure 4) could not be relied on. Readings were taken after the bulk of disc slippage had taken place, but if is by no means clear that the disc slippage process associated with an aerodynmaically-loaded aerofoil is the same as that under static load. For this reason all lift measurements above 100N must be regarded as suspect. Lift readings taken with the fluctuating airload did not show the same tendency to change with time, implying less slippage takes place with airload rather than static load. Reasons for this have yet to be found. This observation implies that there may be some underrecording of lift above 100N.

TUNNEL AIRFLOW

Some initial investigations were conducted to establish the variability of airflow over the tunnel cross section. The tunnel cross section (within the working sectin) was subdivided into nine equal rectangles and a probe inserted to measure axial flow speed at the centroid of each rectangle, at a number of tunnel speeds. Results are shown in Table I.

Table I

% Axial Speed Variation
Over the Tunnel Cross
Section (Looking in Flow
Direction)

(a)			(b)			(c)		
40 ft/sec			80 ft/sec			120 ft/sec		
-.83	-2.35	-1.38	-.77	-2.62	-1.6	-1.21	-2.86	-1.75
+2.78	-.83	+.69	+2.89	-1.18	+1.7	+3.1	-1.5	+2.0
+1.3	-.83	-.83	+1.42	-1.30	+.77	+1.95	-1.4	+.3

For the lifting performance of the aerofoil section, a relationship is needed between indicated tunnel speed and the mean speed encountered by the section. This is shown on Figure 5. The mean speed over the section is taken as the mean of the individual speeds measured at the centroids of the centre rectangles, corresponding to the central columns of Tables I(a), (b) and (c).

Figure 5 excludes the effect of the boundary layer on the tunnel wall and ceiling. Probes were inserted into the flow in this region, to measure the loss of total head. The aim of this exercise was to obtain a span correction for the aerofoil section, to reflect the lift loss due to reduced dynamic pressure in the tunnel floor boundary layer. Figures 6(a), (b) and (c) show the total head profiles, measured above the tunnel floor and the required span correction to account for loss of dyanmic pressure. Span is corrected to correspond to the lift that would be produced if the mean dynamic pressure were present over the whole span, based on the assumption that lift is proportional to dynamic pressure. The graphs shown in Figure 6 do involve subjective assessments of flow conditions close to the floor, but in spite of this they consistently indicate that span should be reduced by around 6mm at both the floor and ceiling. A span reduction of 12mm is therefore used to account for floor and ceiling boundary layer effects.

TEST TECHNIQUE

The presence of a mechanical connection (foam) between the aerofoil model and wind tunnel introduces the possibility of variable frictional forces interferring with the balance reading. If load is applied and then relaxed, some hysteresis effect is present on any graph of load against balance reading. This is illustrated in Figure 7.

Some reduction in the hysteresis effect was achieved by using lower modulus foam. A test technique was adopted to try to always operate on a known part of the hysteresis curve, shown by the line A B on Figure 7.

Firstly, to start off at point 'A' requires zero friction between the disc and foam. Over a period of time this is achieved by disc/foam slippage and can be shown to correspond to a consistent balance reading, independent of the starting point. To accelerate this process for testing purposes, the aerofoil was manually 'jiggled' with progressively decreasing force, to come within 3µv of point 'A'. During testing, there is a potential problem of straying down the line B-C on Figure 7. This was avoided by avoiding any reduction in tunnel speed (and hence load) between starting a test and taking balance readings. This procedure was repeated for every incidence change.

HFM MODEL DETAILS

A drawing of the hybrid flapped multiplane in the tests is shown in Figure 8. A system of panel pins, external plates, plastercine and strategically-drilled holes in the end plates enabled flap settings to be varied. Wool tufts were attached to the model with masking tape, for flow visualisation. Flap settings were varied to try to maximise lift whilst retaining attached flow. This process produced the final flap settings shown in Figure 9. Essential dimensions of the model are:

Uncorrected span	.5m
Corrected span	.48m
Compactness cylinder diameter	.292m
Corrected area	.140m^2

TEST RESULTS

Observations from wool tufts indicate attached flow is present everywhere, at incidences below 0°. The stall mechanism begins with a separation bubble on the leading edge of the centre aerofoil This is followed by an intermittent stall at 1° and full stall at 2°, also on the centre aerofoil. At 4° incidence, separation was present on the upper aerofoil and at 6° incidence a stall interchange noted between the centre and upper aerofoil. No observations could be made of the airflow over the lower aerofoil. Theory suggests its contribution to overall lift is small. This stall mechanism indicates it would be desirable to fit a slat or drooped leading edge to the centre aerofoil.

Test results are given in Table II. The limitations of the balance in measuring forces above 100N must be appreciated in interpreting these figures. The absence of a drag measurement makes an accurate wake blockage correction impossible. A blockage correction was obtained using an empirical formula based on the ratio of model cross sectional area to tunnel cross sectional area. (Ref. 2) This type of formula tends to produce a slightly pessimistic value of C_L below the stall and an optimistic value above it. Typical total blockage corrections for isolated aerofoils are around .005. For a triplane this can be expected to rise to .015. Close to the stall, wake blockage will increase as drag increases. An empirical formula has been derived to describe the speed increase to blockage (Δu) as:

$$\frac{\Delta u}{u} = \varepsilon_T = \frac{1}{4}\,\frac{\text{Model Frontal Area}}{\text{Test Section Area}}$$

For the HFM model used, this formula indicates ε_T should be .023, which is consistent with the earlier assessment of magnitude. Indicated tunnel speeds are therefore corrected (i) to coincide with the mean speed over the aerofoil model and (ii) to allow for a total blockage (ε_T) of .023 throughout the tests.

Table II

Lift Measurements on a Hybrid Flapped Multiplane

Incidence o	Corrected Speed m/s	Lift N	C_L
-7	17.31	76.52	2.98
-7	21.51	118.70	2.99
-7	26.19	166.77	2.84
-5	20.73	120.66	3.27
-5	26.22	183.45	3.11
-3	17.94	102.02	3.69
-3	23.85	170.69	3.50
-3	27.13	219.74	3.48
-1	17.30	100.06	3.90
-1	22.61	159.90	3.65
-1	26.66	223.67	3.67
+1	18.24	120.66	4.23
+1	23.39	183.45	3.91
+1	27.44	255.06	3.95
+3	18.24	129.49	4.54
+3	24.32	215.82	4.26
+4	18.24	129.49	4.54
+4	20.89	169.71	4.53
+5	17.93	129.49	4.70
+5	22.14	188.35	4.48
+5	25.57	252.11	4.50
+6	19.45	152.06	4.69
+6	22.61	198.16	4.52
+6	22.76	203.07	4.57
+7	18.24	135.38	4.75
+7	22.61	194.24	4.43
+9	18.08	127.53	4.54
+9	21.51	171.68	4.33

DISCUSSION OF RESULTS

Inspection of Table II shows that most results involve force readings beyond the 100N accurate limit of the balance/model/foam arrangement. Tests were carried out at nominal tunnel speeds of 18, 22 and 26 m/s. To avoid hysteresis problems, no downward adjustment of tunnel speed was possible and so speed variations around the nominal figures are very noticeable. Readings at the nominal speed of 18 m/s are thought to be the most accurate, since associated force measurements were closest to the accurate balance limit, A $C_L \simeq \alpha$ curve for these measurements is shown in Figure 10. Despite foam slippage and hysteresis problems, values of C_L at different speeds are generally within 4% of each other and points in Figure 10 produce a reasonable curve. Results at 22 and 26 m/s show lower C_L's than for 18 m/s. At this stage, it is thought the most probable explanation lies in balance inaccuracies for the associated high force readings, as the possibility of a genuine C_L reduction of around 4% at marginally higher Reynolds numbers seems unlikely. It cannot however be ruled out as a possible explanation of the results.

A reasonable curve drawn through data points on Figure 10 suggests a C_{LMAX} of around 4.7 at an incidence of 6^o. Most data points are within a C_L increment of .07 of the line shown.

Although the apparatus was never intended to acquire accurate absolute data, any substantial inaccuracies in force or tunnel speed measurements should result in inconsistencies in lift coefficients obtained at different tunnel speeds. Despite the acquisition of 'inaccurate' force measurements above 100N, lift coefficients obtained at varying speeds are usually within 4% of each other. This provides an unexpectedly high level of agreement and suggests the figure of 4% describes the accuracy of the apparatus within the load range 150-400N. At lower force levels, accuracy is suggested by the scatter of data points on Figure 10, which lies below 2%. These indications do not provide absolute proof of accuracy, but rather an assessment of accuracy based on known problems and results analysed to date. This assessment of accuracy must be restricted to the balance measurement/tunnel speed data acquisition system and leave open any questions of further aerodynamic corrections.

REFERENCES

1. Molland, A.F. 'The Design, Construction and Calibration of a Five-Component Strain Guage Wind Tunnel Dynamometer'. Southampton University, Ship Science Report No. 1/77, 1976.

2. Pope, A. and Harper, J.J. 'Low Speed Wind Tunnel Testing'. John Wiley and Sons, 1966.

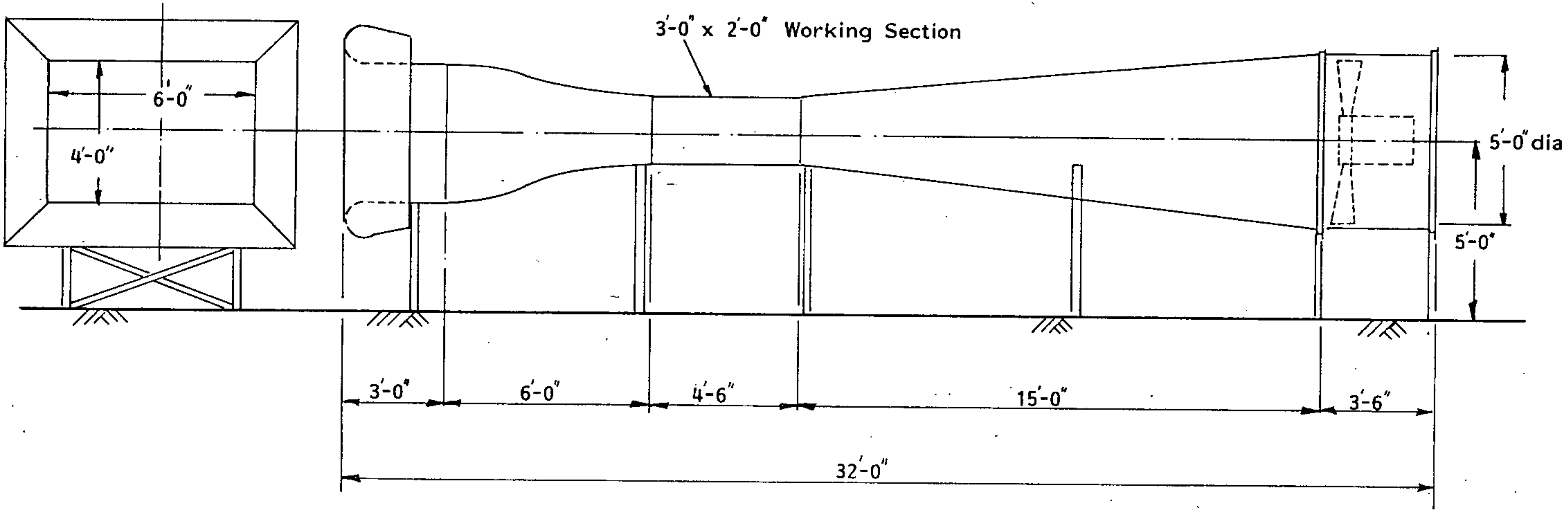
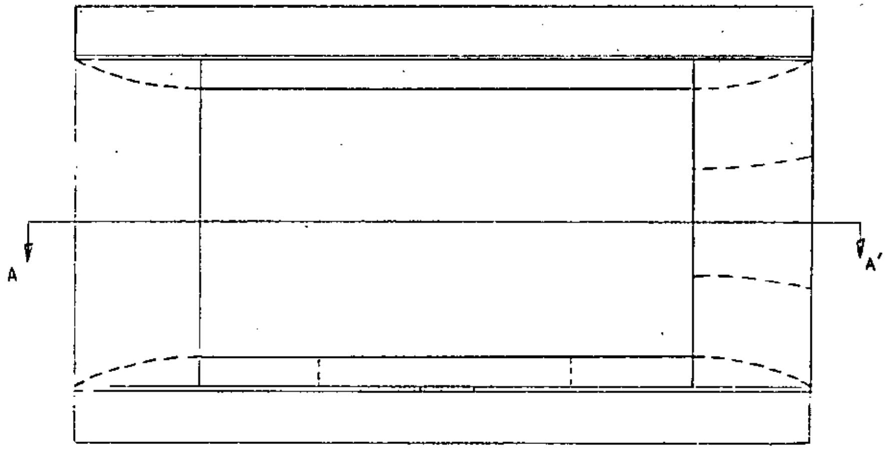


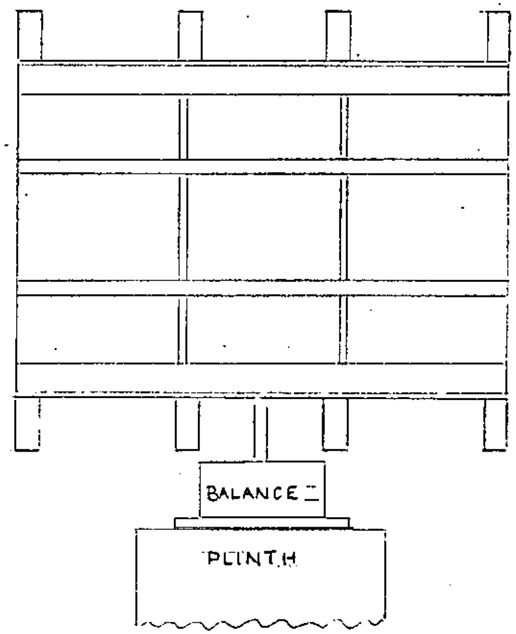
Fig. 1 3ft x 2ft Low Speed Wind Tunnel

3'x2' WIND TUNNEL WORKING SECTION

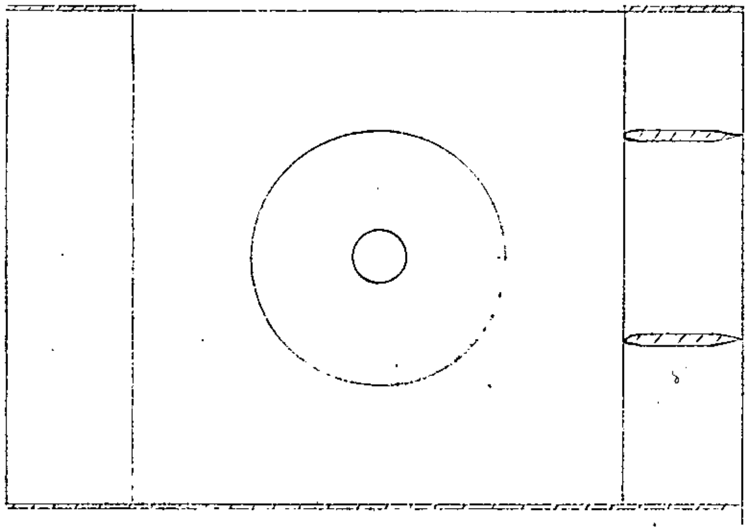
GENERAL ARRANGEMENT AFTER MODIFICATION



SIDE ELEVATION



FRONT ELEVATION



PLAN SECTION LOOKING IN DIRECTION A-A'

Fig 2

MODEL MOUNTING DETAIL

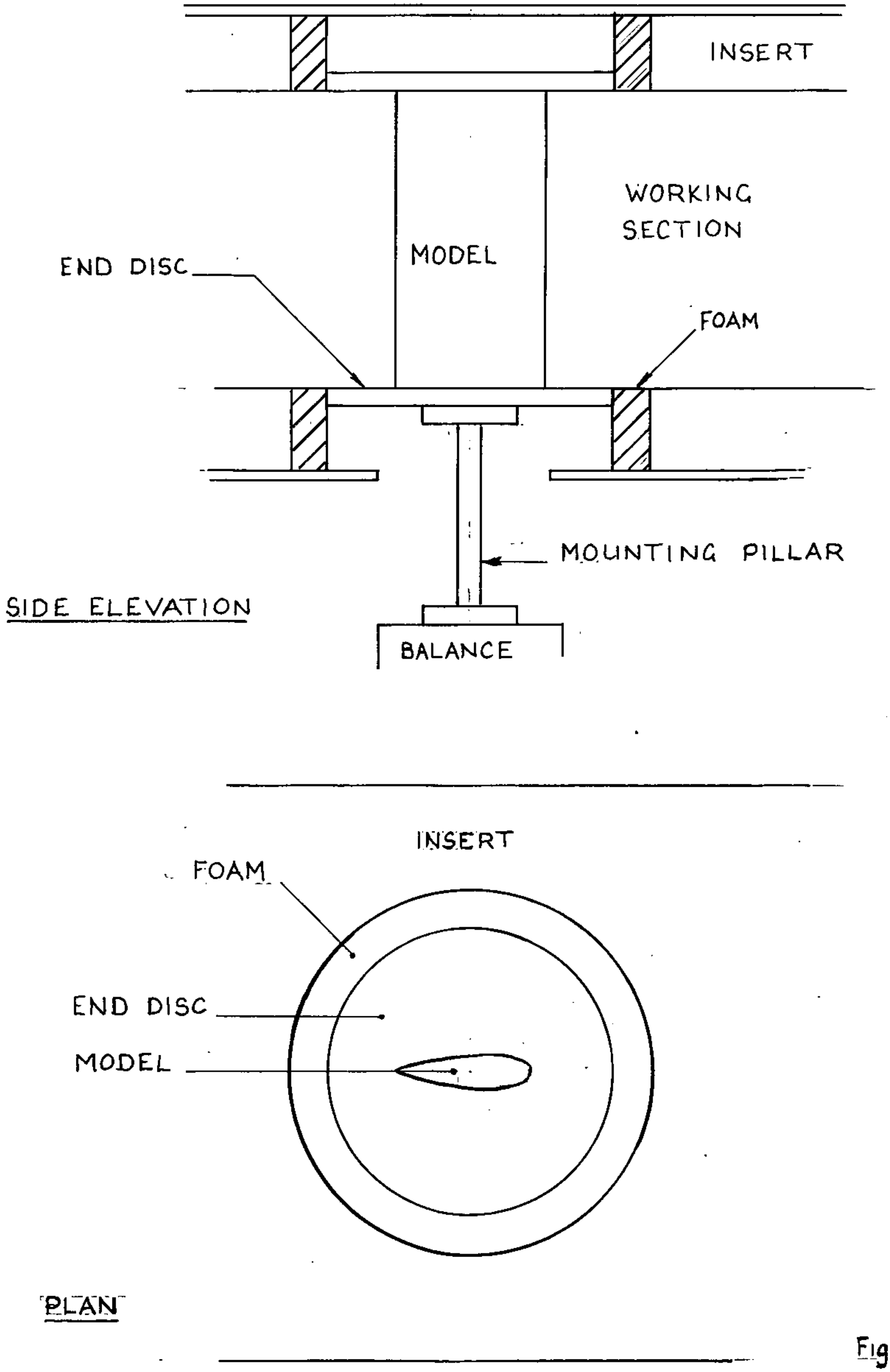


Fig 3

LIFT CALIBRATION GRAPH ($\alpha = 3^0$)

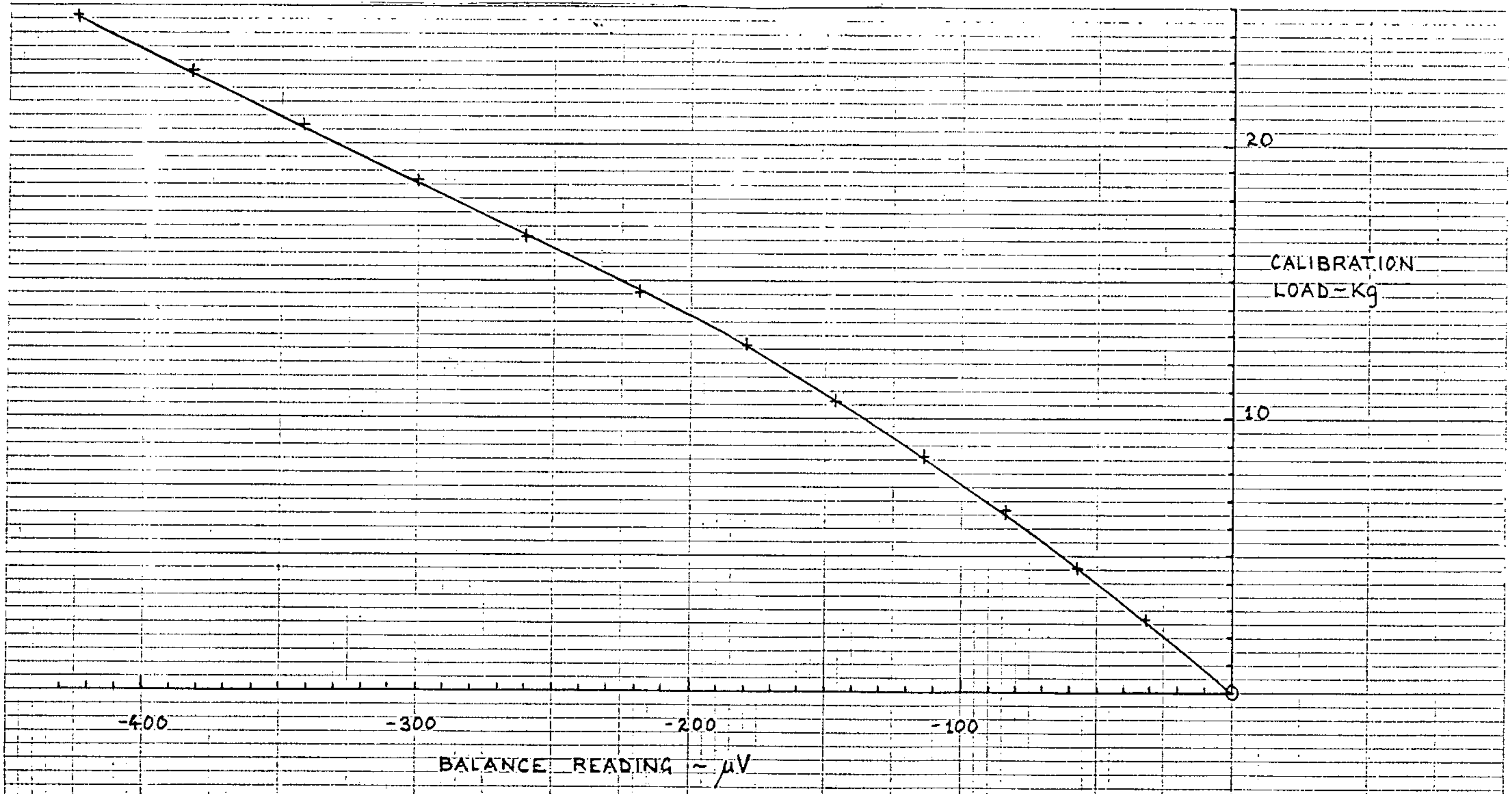


Fig 4

CALIBRATION CURVE OF MEAN AIRSPEED OVER AEROFOIL AGAINST INDICATED TUNNEL AIRSPEED

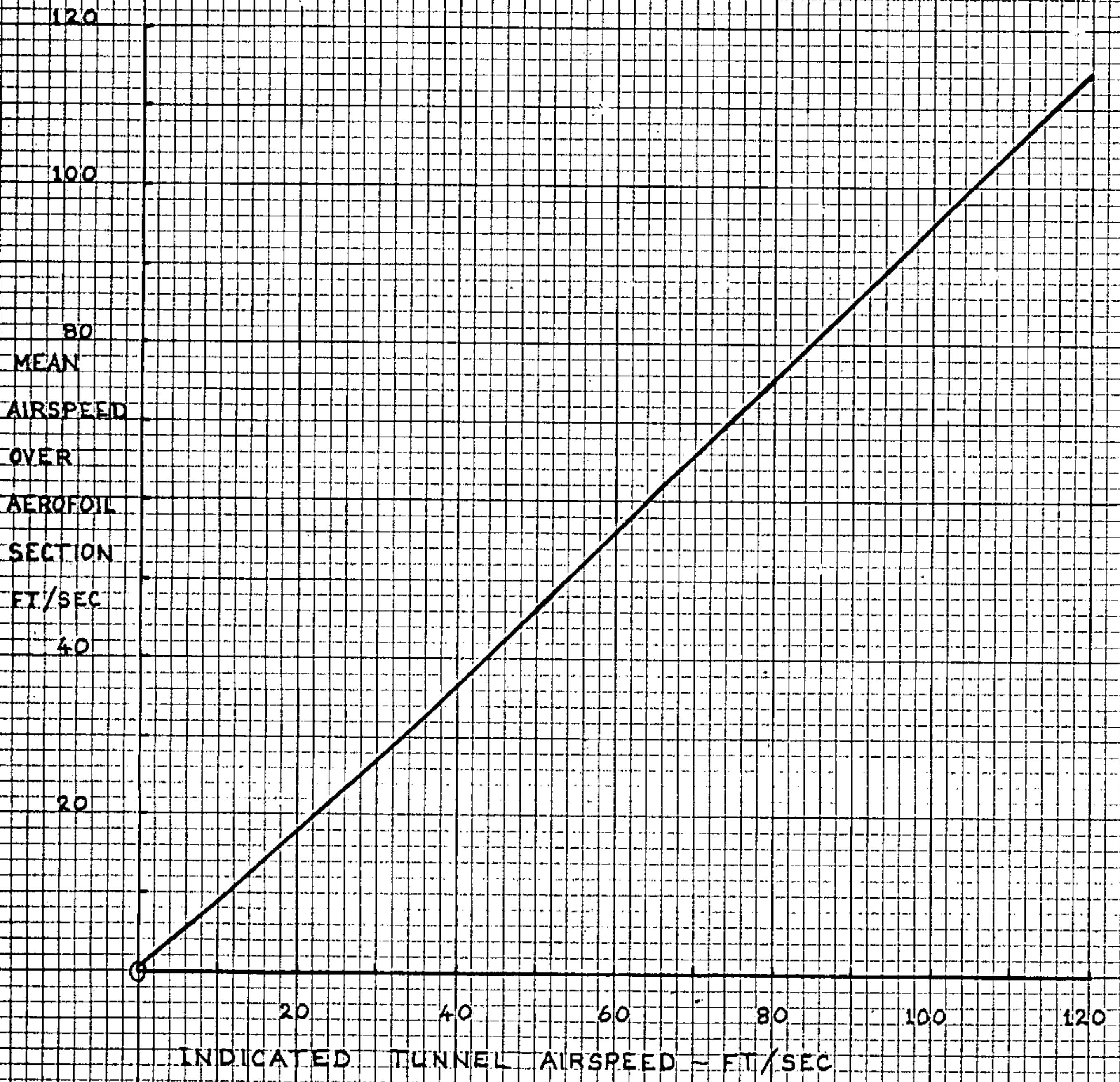


Fig 5

LOSS OF TOTAL HEAD DUE TO BOUNDARY LAYER OVER TUNNEL FLOOR

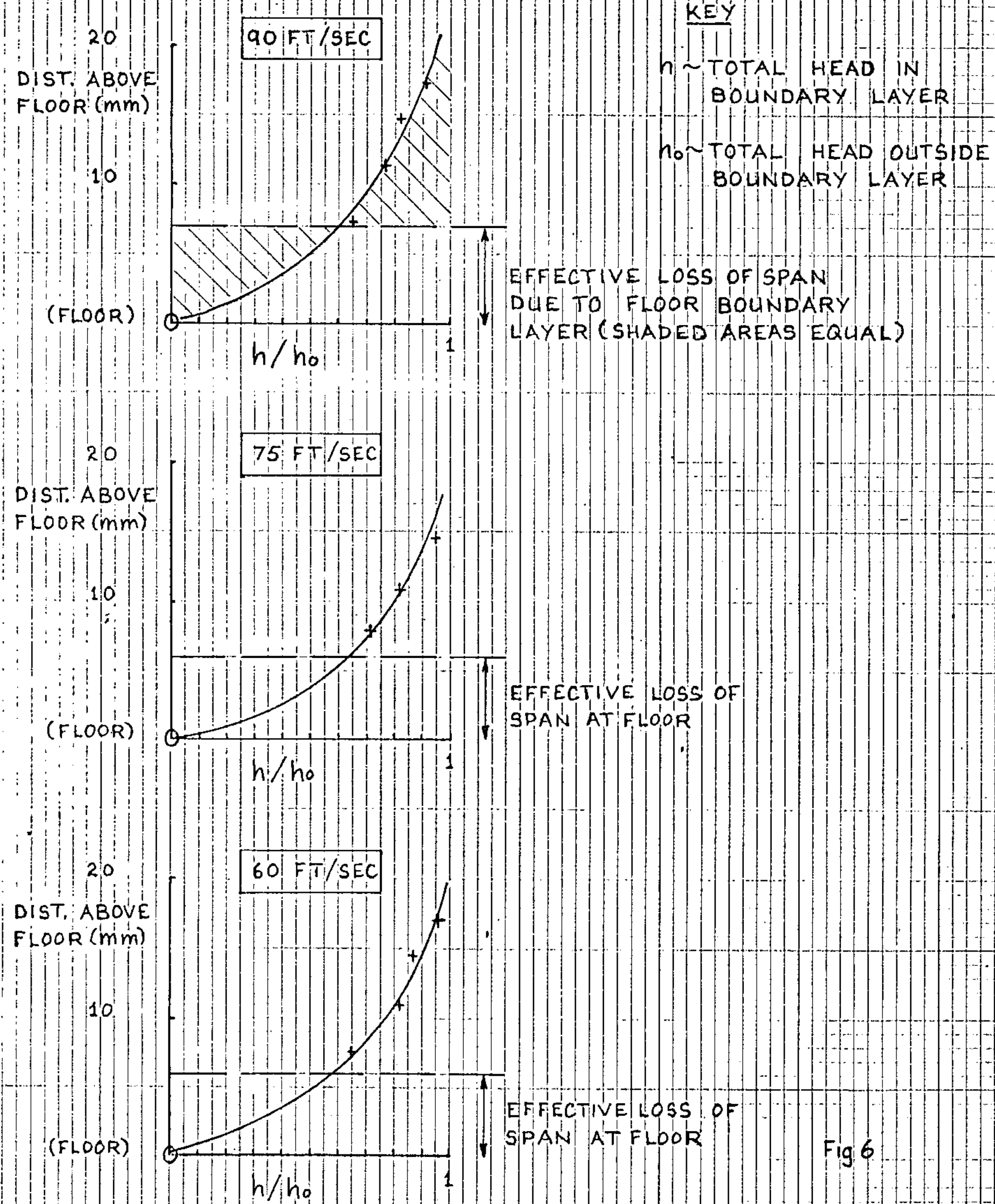


Fig 6

ILLUSTRATIVE LOAD v. BALANCE READING GRAPH

TO SHOW HYSTERESIS EFFECT

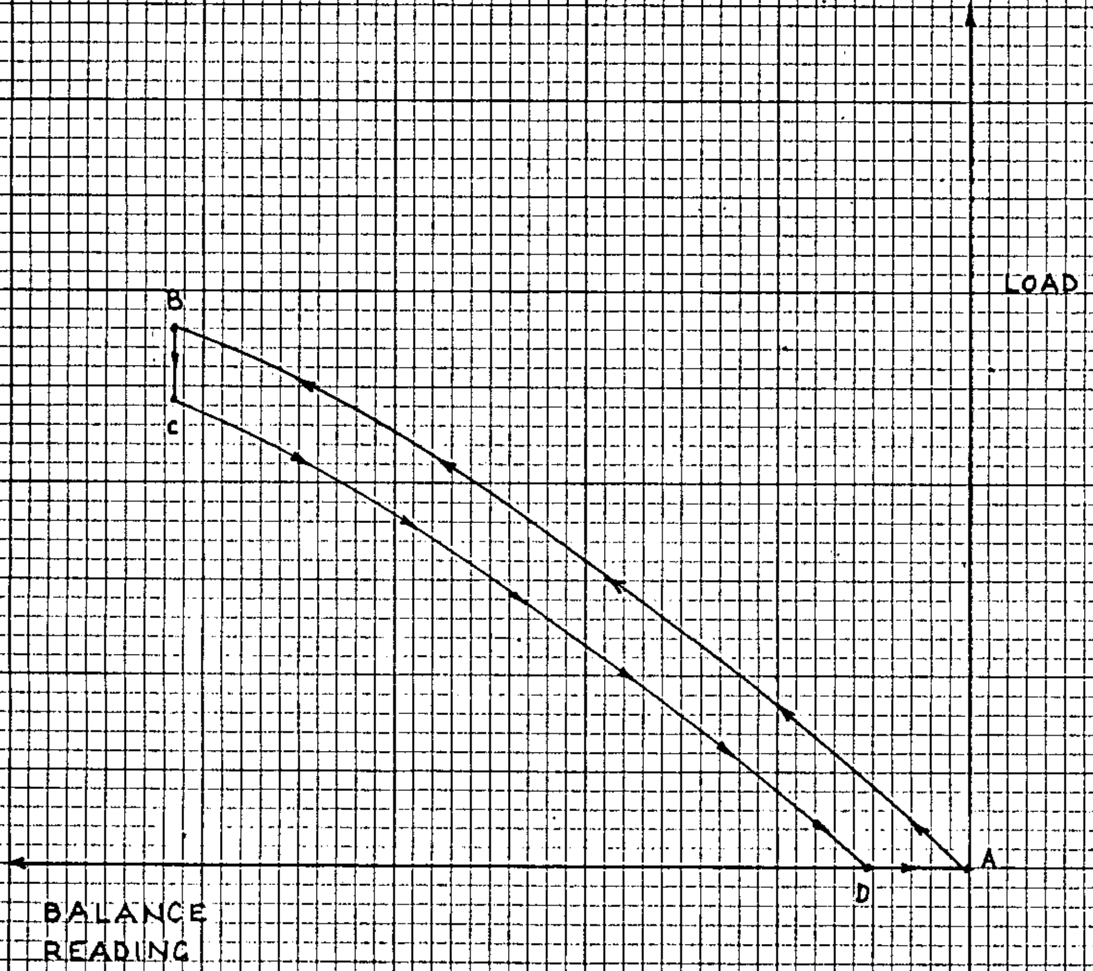


Fig 7

HYBRID FLAPPED MULTI PLANE

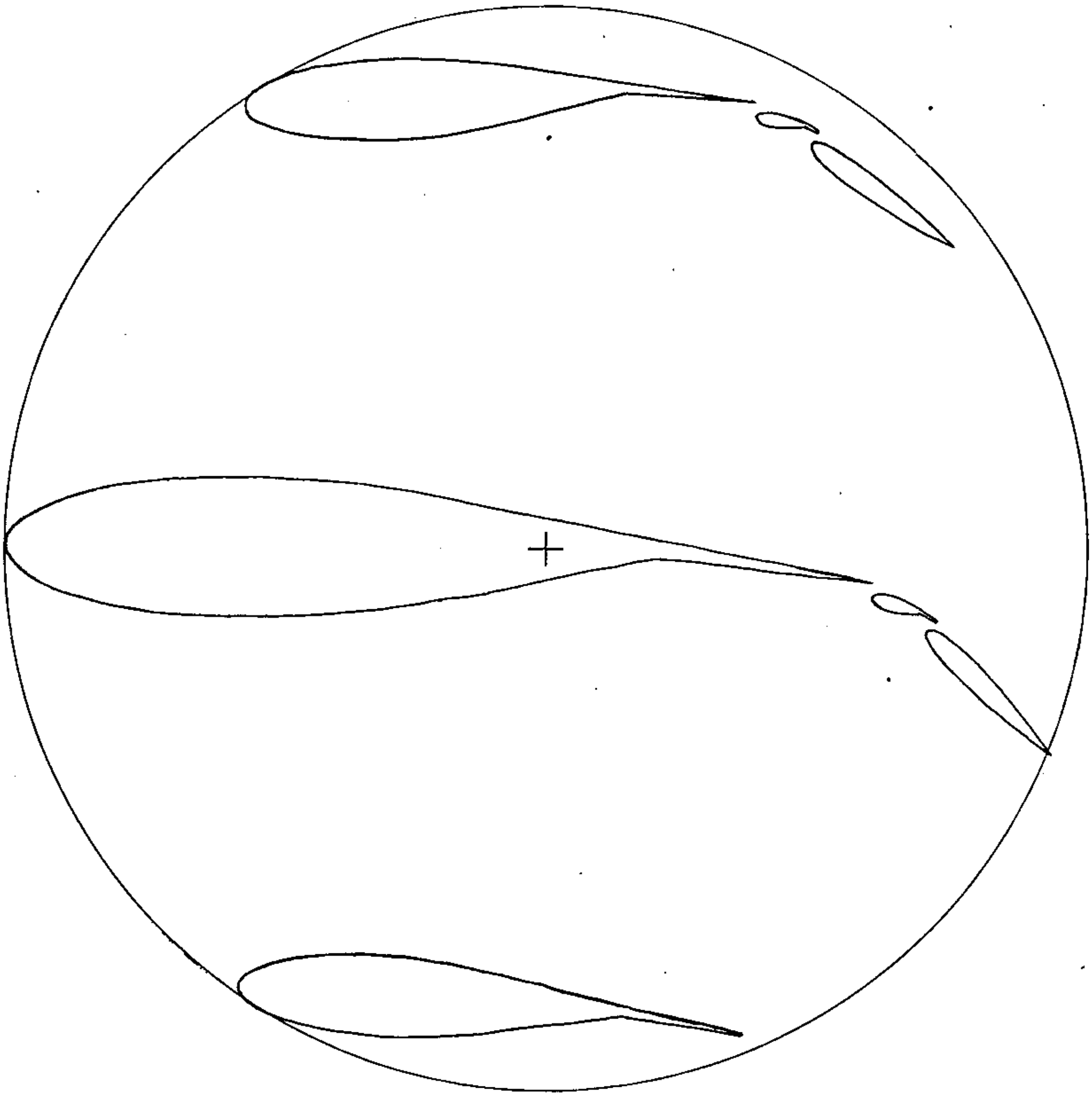


Fig 8

FINAL FLAP SETTINGS USED IN H.F.M.
TWO-DIMENSIONAL FLOW WIND TUNNEL TESTS

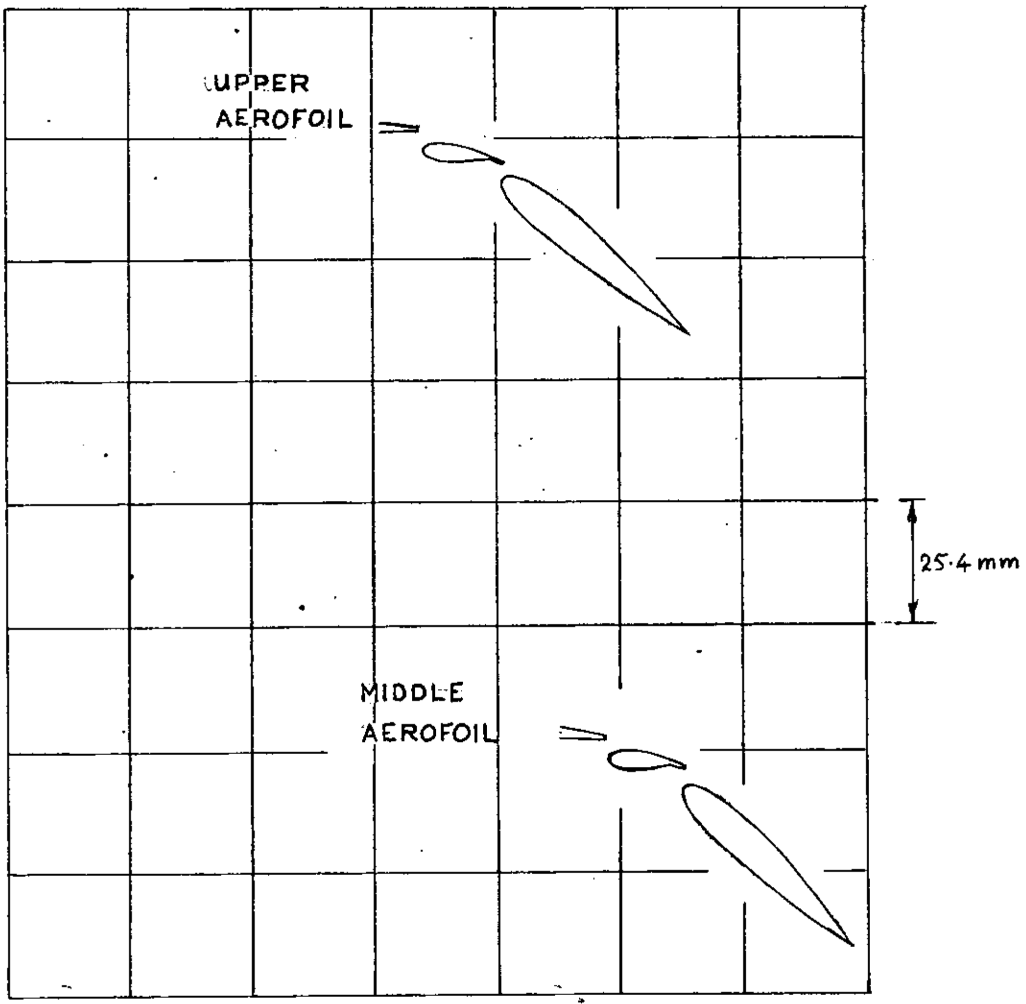


Fig 9

$C_L \sim \alpha$ FOR A HYBRID FLAPPED MULTIPLANE

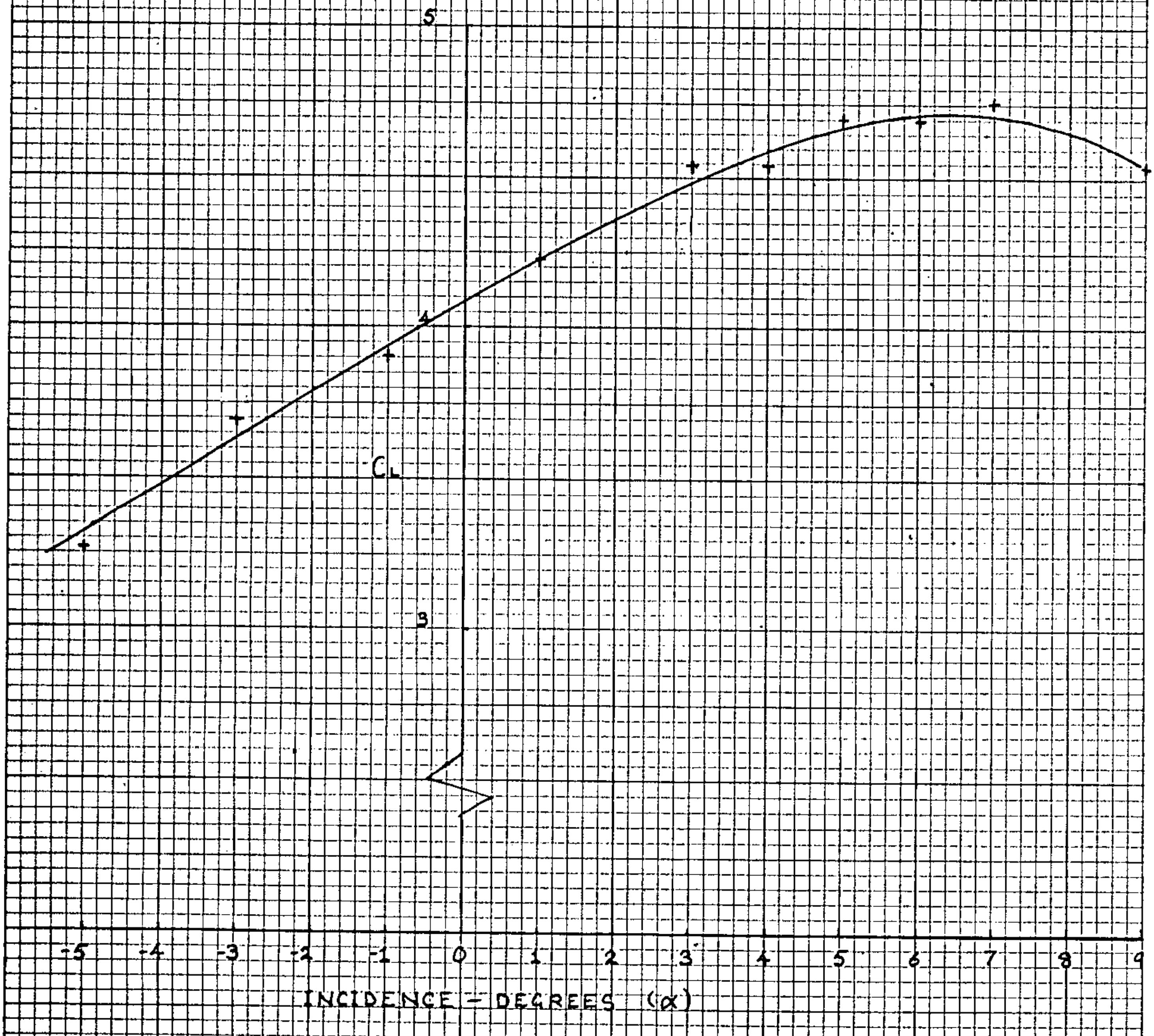


Fig 10