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FURTHER STUDIES IN HELICOPTER BODY AERODYNAMICS

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ABSTRACT

Using a model from the series of untapered bases in reference 2, wind tunnel tests have been made of a number of devices aimed at eliminating or postponing the drag jump which occurs when the flow behind an upswept rear fuselage changes from eddy type to strong (i.e. high drag) vortex type. The devices include spoilers, strakes, deflectors and edge rounding. Various degrees of success are recorded but, in particular, an array of small deflectors provides a perfect solution, eliminating the drag jump completely at no cost in drag in the eddy flow mode. On a separate model which has no drag jump, measurements of yawing moment have been coupled with wake traverses in an examination of the effectiveness of a vertical fin operating in the fuselage wake. It is found that low fin effectiveness can be related to the existence in the fin position of a centre of low total pressure in the wake of the upper fuselage and superstructure. The presence of a high drag rotorhead aggravates this situation.

1. INTRODUCTION

Following on the work of references 1 and 2, some further studies have been made with the general aim of improving the understanding of helicopter body aerodynamics, in which flow separations have important and varied roles, and in one case with additionally the specific aim of devising practical ways of improving a particular situation.

The same basic model (Fig.1) has been employed as was used for the earlier studies. In the present work two rear end variants, Model U and Model T, have been used: details of these are given in Fig.2. As before, the experiments were made in the 7ft x 5ft low speed wind tunnel of the Aero Engineering Department of the University of Bristol.

The work was done partly by the present author and partly by students. Fuller accounts of the students' experiments are contained in references 3 and 4.

2. DRAG OF REAR FUSELAGE UPSWEEP

2.1. Occurrence of High Drag Vortex Flow

In reference 2, the aerodynamics of rear fuselage upsweep were examined and it was shown that within a medium range of upsweep angles - roughly 35° to 70° - the flow behind the upsweep takes one of two radically different forms, depending on aircraft incidence. At positive (nose-up) incidences, flow separation is of the standing eddy type characteristic of most bluff bodies, but as incidence is decreased a change takes place to a form of separation characterised by streamwise vortices analogous to those which occur over the upper surface of a slender wing at positive incidence (or equivalently below the lower surface at negative incidence) as discussed for example by Kuchemann (ref.5 p.339 et seq). Depending on particulars of the rear fuselage shape - whether or not there is lateral taper, edge rounding etc - the change can take place gradually over a range of incidences or it may occur suddenly when a critical incidence is reached. Generally the vortex flow when established has associated with it an increased drag, resulting from suction on the upswept rear face produced by the vortices, and if the changeover to vortex flow occurs suddenly the upward jump in drag can be very large. In reference 2, changeover boundaries were determined for two basically different configurations (untapered sharp-edged and tapered round-edged) and were represented on $\alpha\phi$ diagrams*. These are shown on a common diagram in the present Fig.3, which indicates also the regions of eddy flow, vortex flow and streamlined or unseparated flow, as defined in reference 2.

Experiments have now been made on a number of devices aimed at preventing the onset of vortex flow or reducing the severity of the associated drag rise. This work was done for the most part on Model U (Fig.2), a reconstructed version of one of the previous "untapered base" series of models of varying upsweep angle. An upsweep angle of 40° was chosen for Model U: this ensured, as is seen from Fig.3, that a transition from eddy flow to vortex flow or vice versa would occur at some negative angle of incidence. The side edges and bottom edge of the upsweep were made sharp, except for specific tests (section 2.5) to measure the effect of edge rounding. Owing to the use of a different method of construction, there were some discrepancies in geometric detail between this model and the corresponding one of the earlier series (in particular the length from the corner of the base to the top of the upsweep was greater for the later model) and as it turned out there was a sizeable shift in critical angle of incidence between the two. Precise reasons for the discrepancy have not been pursued since the present series of comparative results is self-contained.

2.2. Use of a spoiler

In the eddy mode, airflow along the bottom surface of the fuselage separates at the start of the upsweep: in the vortex mode it is drawn round on to the face of the upsweep. A spoiler fitted across the base just ahead of the upsweep would therefore be expected, by ensuring flow separation, to prevent or at least delay the formation of vortex flow. The results of a test with and without such a spoiler are shown in Fig.4.

Without spoiler, the drag curve shows the expected characteristics of two flow regimes separated by a drag jump, the jump occurring in this case at -4°C incidence. The curve of downward lift shown in the lower half of the diagram reflects the drag situation exactly, indicating that the two force characteristics are reacting to a common flow situation, the principal feature of which is the high suction produced on the upswept surface in the presence of vortex flow.

With spoiler, the drag at positive and small negative incidences shows the relatively flat characteristic typical of eddy flow. This extends deeply into the negative incidence range, so that at incidences below -4° the spoiler actually produces a reduction in drag, although where the flow is of the same type as without spoiler, namely at incidences above -4°, the spoiler, by increasing the scale of the eddy flow, gives a significant drag increase. It is of interest to note that at large negative incidence the vortex flow eventually takes over despite the presence of the spoiler. The changeover, occurring around -10°, has not been precisely detailed in the experiment;

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* α is angle of incidence, ϕ is angle of upsweep of rear fuselage.

but there is no doubt about its occurrence, the effect being seen clearly in the lift characteristic as well as in the drag.

Two other tests with spoiler have been made, the one using the same spoiler on Model U with rounded edges and the other using a similar spoiler on Model T (the model used principally for a study of fin effectiveness). The results (Fig.5) exhibit similar characteristics to those already described. The spoiler always gives a significant increase in drag at positive incidence: the increment decreases progressively as incidence is lowered, though it may not always actually become negative. If strong vortex flow exists without spoiler, then in the presence of a spoiler the vortex flow will, it appears, take over again at sufficiently negative incidence, though the postponement to high negative incidence produced by the spoiler may be adequate for practical purposes.

2.3. Use of strakes

It was surmised in reference 2 that a significant factor in initiating vortex flow was the directional relationship between flow along the base of the fuselage and that along the fuselage side: broadly speaking, these two flows would be divergent at positive incidences and convergent at negative incidences and the latter situation might be conducive to the initial formation of vortices at the start of the upsweep. Following this line of thought, it might be expected that a longitudinal strake on the fuselage side near the base, controlling the direction of flow on the side as it approaches the upsweep, would delay the onset of vortex flow to more negative incidence.

Accordingly a series of strake tests has been made. The strakes were 4" long and 1" wide: these dimensions compare with an overall body length of 63". From one to three strakes at a time (per side) were used, one always being placed at the bottom of the fuselage side, any others being spaced up the length of the upsweep. The setting angle was varied between 0° and 10°. This general arrangement is illustrated in Fig.6, which actually shows the optimum combination as investigated.

Generally the results were disappointing. Although all arrangements produced some shift in the critical incidence for vortex flow, movements were usually of only one or two degrees and the strake in bottom position did not emerge as being more significant than the others. The best result achieved was with three strakes inclined at 10° nose down: this arrangement produced a delay in transition to vortex flow of about 4° aircraft incidence (Fig.6).

2.4. Use of deflectors

The unimpressive results of strake tests led to the view being taken that in order to prevent the formation of streamwise vortices it was necessary to suppress the mechanism of continuous feeding along the length of the upswept edge. With hindsight it may be said that this was to be expected from the analogy of slender wing flow. It was thought that it might be achieved by means of an array of small but closely spaced deflectors on the side of the fuselage at the edge position - see Fig.7. Examination of surface flow pictures showed that in vortex mode there was a downturn of flow on the fuselage side as the edge was approached. Deflectors would counter this, particularly if set at a suitable nose-down angle. An angle of 10° was chosen to provide a compromise between this requirement and that of not producing a large drag increment in the eddy flow mode.

Fig.7 shows the deflectors to have been entirely successful: the drag jump is completely eliminated, there is no sign of change to vortex flow over the range of incidence investigated and no measurable drag penalty at the positive incidence end, where the model without deflectors is itself in the eddy flow mode.

Pressure plotting on the upswept surface, of which a sample is given in Fig.8, confirms that the presence of deflectors prevents development of the high suction associated with vortex flow and the drag jump. The sample shown is for a line of pressure points near the bottom of the upsweep, where the suction is at its highest: analogous comparisons are obtained from points further up the face, the level of suction however decreasing progressively. Further confirmation of the mechanisms involved was obtained from surface flow visualisation on the upswept face. Overall patterns on the surface were complex but in the region of each side edge the development of an edge vortex could be seen in absence of the deflectors and this was eliminated when the deflectors were present.

Omitting the top deflectors progressively produces a gradual increase in drag (Fig.9) until, when three deflectors are omitted, the drag jump reappears at the negative extreme of the incidence range. Clearly, for best results a full row of deflectors should be used.

As a reminder of the scale of drag changes involved, we note that the drag jump without deflectors is approximately 0.3 in D/q at model scale, or 7.5 sq.ft. in equivalent flat plate area at full scale (model scale assumed to be 1/5 for a 10,000lb. AUW helicopter). As was estimated in reference 2, this is about twice the total body drag of the basic "stream-lined" shape shown in Fig.1. The deflectors of Fig.7 therefore can be said to produce a drag saving of at least this amount at incidences below the critical, with no drag penalty at incidences above the critical and for very little increase in weight.

2.5. Effect of edge rounding

Drag measurements were made with three successive degrees of rounding of the side and bottom edges of the upswept face. This was done by adding a 1" thick extension plate, with the appropriate rounding, to the back of the model. The following are the principal features of the results (fig.10) :-

(i) The smallest rounding (radius approximately ½" or one twelfth of the face semi-span) gives a large change, reducing the drag jump by about one half. The critical incidence is unchanged.

(ii) A second degree of rounding gives a further small improvement, again without change of the critical incidence.

(iii) With large rounding (radius one sixth of semi span) the drag trend below the critical is reversed and in this case the critical change itself disappears in the sense that the higher drag characteristic of vortex flow is maintained at the less negative incidences (-4° to zero).

It should be noted that the lift changes (not presented here, in the interests of brevity) reflect these drag changes exactly, including the last-mentioned feature of an adverse effect at the less negative incidences with the highest degree of rounding. Also an additional test of this case but with the bottom edge alone resharpened showed no change in drag at the higher incidences but a general unsteadiness of flow at -4° and just above, denoting uncertainty between vortex flow as favoured by the rounded side edges and eddy flow as favoured by the sharp bottom edge.

It seems therefore that the extremely high drag jump present with sharp edges can be greatly reduced by a relatively small degree of edge rounding but that with large rounding the improvement is not maintained and also a large rounding tends to extend the range of application of high drag vortex flow to more positive incidences. A tentative explanation of these trends might go as follows: for small rounding the high suction area on the upswept face is concentrated in a narrow band near the edge (see Fig.8) with the level varying approximately as 1/r (r being the edge radius of curvature), this by analogy with some other flows (slender wings, intake ducts at zero forward speed etc); with larger rounding the flow remains essentially vortex type, with lower suction but spread over a larger area of the face, giving higher drag and, as incidence is increased, no eddy flow range before proceeding eventually to streamlined flow (beyond the present range of measurement). This having been said, it remains to be stressed that the present tests are not regarded as being fully definitive on the edge rounding effect. Certain approximations had to be made in the shapes because of shortage of time, so that whilst the indications obtained are thought to be genuine in a qualitative way, it is regarded as desirable for more extensive and perhaps more accurate information to be provided.

3. FIN EFFECTIVENESS

3.1. General

Low fin effectiveness at small angles of sideslip is a problem common to many helicopters. In reference 2 were quoted some results by Hinchcliffe and Westland[6] showing that with untapered sharp-edged upsweeps such as the present Model U, a change from eddy flow to vortex flow produced a sudden drop in effectiveness of the fin, even though this was mounted on top of the tail boom (as in Fig.1) where it might have been thought sufficiently far removed from the influence of the vortices. The problem of low effectiveness, however, is too widespread to be related exclusively to the occurrence of high-drag vortex flow from the rear fuselage upsweep. An experiment has therefore been made to look at the problem for a case which it was considered would not be dominated by the presence of a high-drag upsweep. For this purpose Model T (Fig.2) was chosen, a tapered base having rounded edges and 31° upsweep. It is seen from Fig.3 that a rear fuselage shape with these characteristics gives vortex flow at negative incidence merging to streamlined flow at positive incidence and nowhere encounters the boundary between vortex and eddy flow which denotes a sudden flow change and the accompanying (on the vortex flow side) high drag.

The experiment was in two parts, consisting of (i) measurements of yawing moment due to sideslip of the model with and without fin and (ii) wake surveys of total pressure and flow direction in the plane of the fin but with fin removed.

3.2. Yawing moment due to sideslip

Yawing moments for Model T without fin are presented in Fig.11(a) and for comparison results for the basic model (Fig.1) are given in Fig.11(b). The feature of these is the abnormal characteristic of Model T at negative incidences and angles of sideslip up to about 7°, where reduced slope is shown, even going negative for -8° incidence and sideslip angles up to $3\frac{1}{2}^{\circ}$. This is a self-stabilizing influence of the body flow; and since it is not present for the basic model, it is surmised to be caused by asymmetrical development of suction on the rear fuselage upsweep, a higher suction on the windward side producing the restoring moment.

Yawing moments with fin on are given in Fig.12. Using the curve for 0^o incidence as a basis of comparison, the increased stability for negative incidences and sideslip angles up to 7^o is a carry over from the characteristics without fin. For positive incidences, however, a markedly different characteristic is seen, in which the stabilizing effect of the fin is very small at zero sideslip (by comparison with the dashed curves for fin off) and becomes "normal" only at about 10^o sideslip.

The results are summarised in Fig.13 in which fin effectiveness, defined as the change in slope of the yawing moment curves between fin off and fin on, is plotted as a function of incidence for three different angles of sideslip, 0^o, 5^o and 10^o. We see that for negative incidences the effectiveness remains more or less at a constant level but for positive incidences, whereas the same level of effectiveness is maintained at 10^o sideslip, at 0^o and 5^o sideslip there is a marked fall in effectiveness with increase of incidence, reaching practically zero at 6^o or 7^o incidence.

As a point of interest, the curves of Fig.12 of reference 2 have been added to the present Fig.13: these show fin effectiveness at zero yaw for the series of untapered bases with various angles of upsweep. In the present context they serve to emphasize the multiple complications introduced at negative incidences by the changing flow patterns emanating from the rear fuselage upsweep. Positive incidences were not investigated in these cases.

3.3. Wake surveys

Selected wake surveys are presented in Figs.14-17: a further presentation is given in reference 5. The form of presentation is to show isobars of total pressure together with flow direction indicators in the plane of the fin. The view is looking forward from the tail and the positions of the fin (not actually in position for the measurements), tail boom and fuselage at maximum section are shown. The direction indicators are to be read relative to the free stream direction, indicated at the top of each picture.

The pressure contours in all cases show an upper and a lower region of low total pressure. It seems clear that the lower region is associated with the lower part of the fuselage, including the upsweep, while the upper region is associated with the fuselage superstructure and tail boom. With increase of incidence the loss of total pressure in each region increases in magnitude and extent: the regions also move upwards relative to the fin position. In sideslip the movements are complex: at zero incidence both regions move round with the fin to begin with but break away at high sideslip; at 6^o incidence the lower region breaks away from the fin immediately but the upper region goes round with the fin to beyond 5^o sideslip, breaking away, however, before 10^o sideslip. At no time does the lower region overlap with the position of the working part of the fin and it seems clear that in this case the details of flow shed by the fuselage upsweep can have little or no effect on the performance of the fin.

The flow direction indicators are not easily interpreted in terms of effects produced by the body because, although the fin itself is not present, the presence of the tail boom means that local flow directions are superimposed on the main body flow. There is however evidence, to be seen best in Fig.15(b), of a pair of vortices such as would be shed by the sideways lift effect of the main body in sideslip. The lower vortex of this pair lies below the tail boom but the upper one is in close proximity to the fin position. Overall the evidence is that flow directions different from the free stream direction do occur locally and these can be expected to affect the level of restoring moment produced by the fin.

In reference 4 it is shown that calculations of yawing moment produced by the fin, incorporating local details of both total pressure and flow direction as given by the wake surveys, agree reasonably well with the direct moment measurements already discussed. A large contribution to low fin effectiveness comes from the low total pressure levels and this particular correspondence can readily be seen by examining the movement of the upper region of low total pressure in Figs.14-16. Taking the 0.7 contour as representative, it can be seen that for 0° and 5° sideslip at 6° incidence, this contour embraces the lower half of the working span of the fin: for all other combinations of incidence and sideslip the 0.7 contour, where it exists, lies to one side of the fin. Thus the drop in fin effectiveness at positive incidence and small sideslip, shown in Fig.13, is qualitatively explained.

A few wake surveys have been made with a simulated high drag rotorhead, as used in reference 1, added to the model. Fig.17 shows typical results: the principal feature is that the loss of total pressure in the upper region is significantly increased both in magnitude and in extent. This links the upper region of the wake firmly with the flow created by the general superstructure of the helicopter. It also suggests that a high drag rotorhead may itself have a significant adverse effect on fin effectiveness.

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4.	G.A. Johnson and C.M. Wu	Helicopter fin effectiveness; University of Bristol, Aero Engineering Report No.271, 1982.
5.	D. Kuchemann	The aerodynamic design of aircraft. Pergamon Press 1978.
6.	R.A. Hinchcliffe and P.G. Westland	The effect of sideslip on the vortices shed from the upswept rear fuselage of a helicopter; University of Bristol, Aero Engineering Report No.267, 1981.

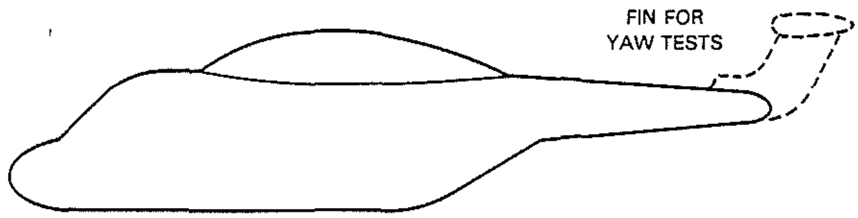


FIG. 1 BASIC MODEL

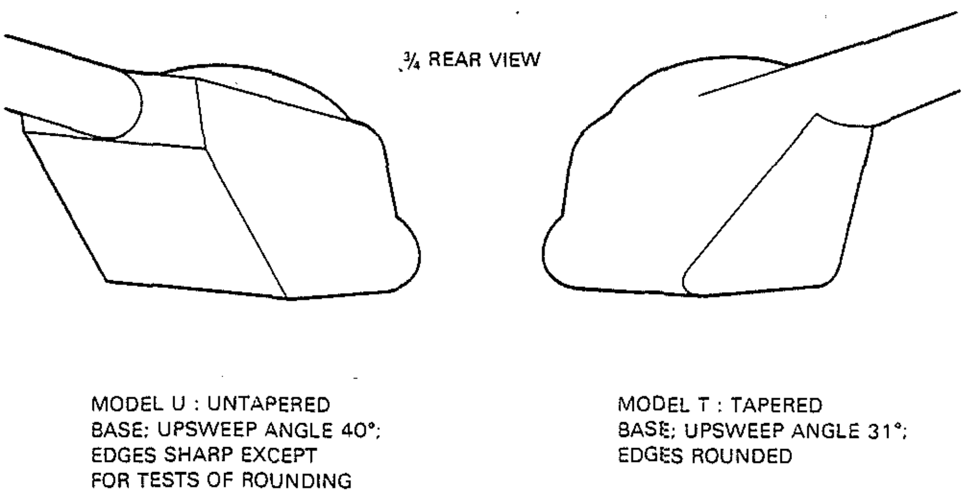


FIG. 2 REAR SHAPES

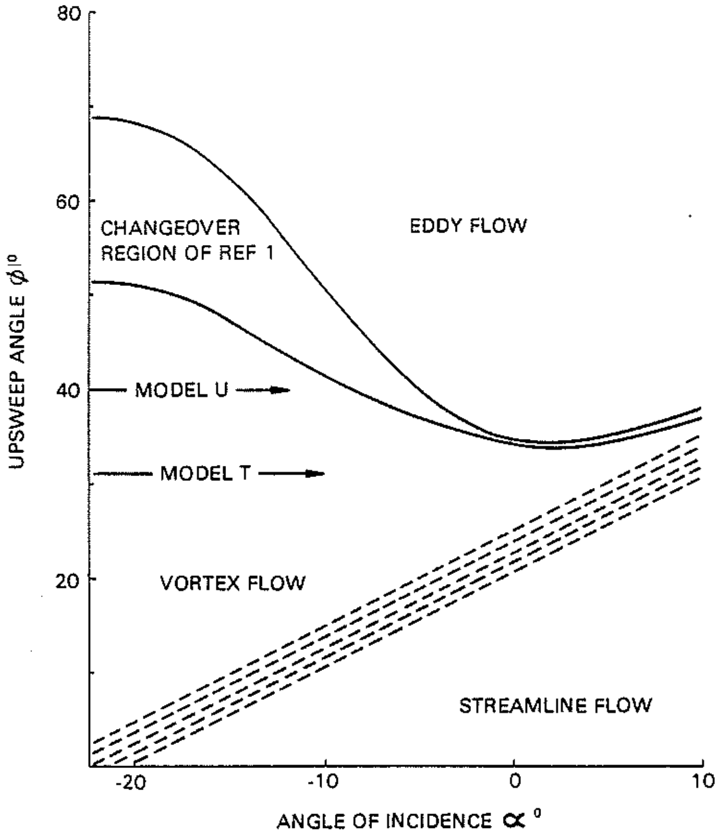


FIG. 3 MODELS U AND T IN RELATION TO ∝ ∅ DIAGRAMS OF REF 1

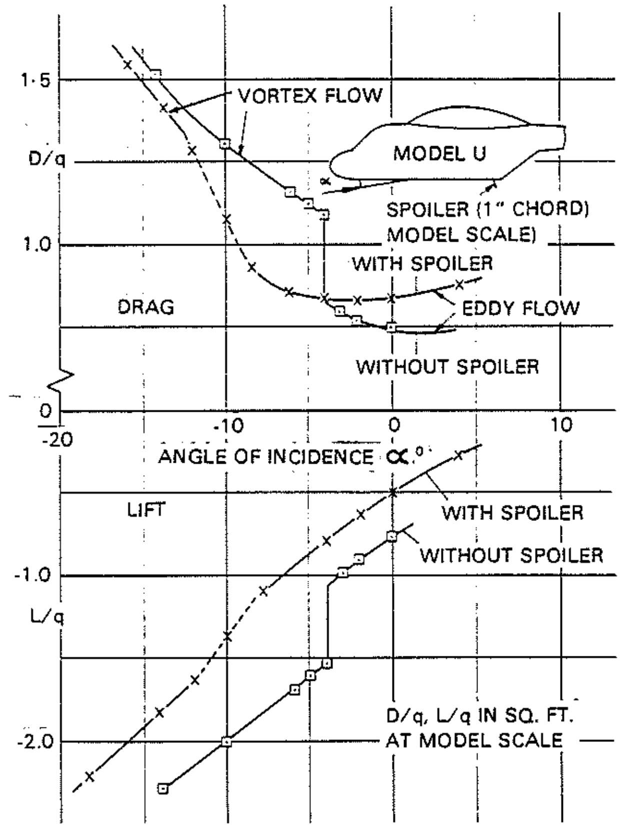


FIG. 4 EFFECT OF A SPOILER

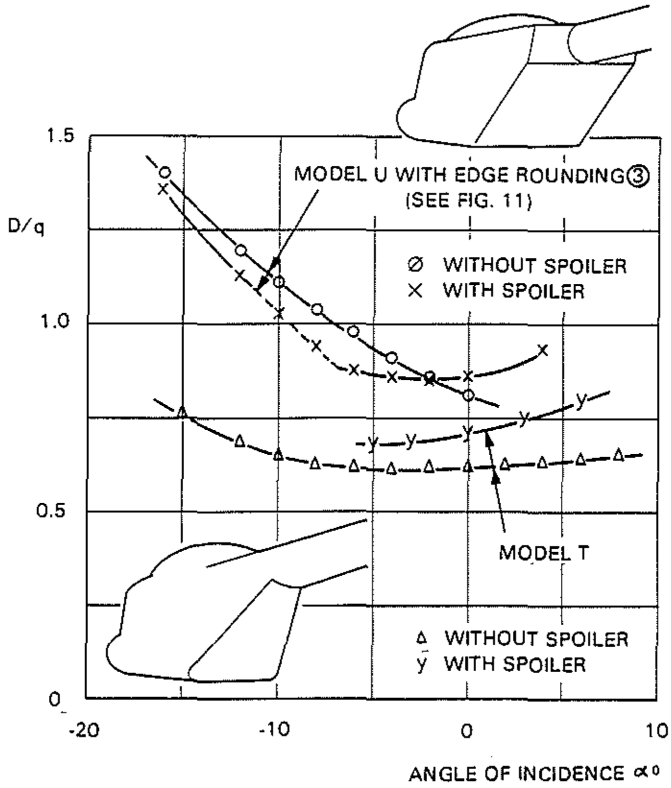


FIG. 5 SPOILERS WITH OTHER REAR SHAPES

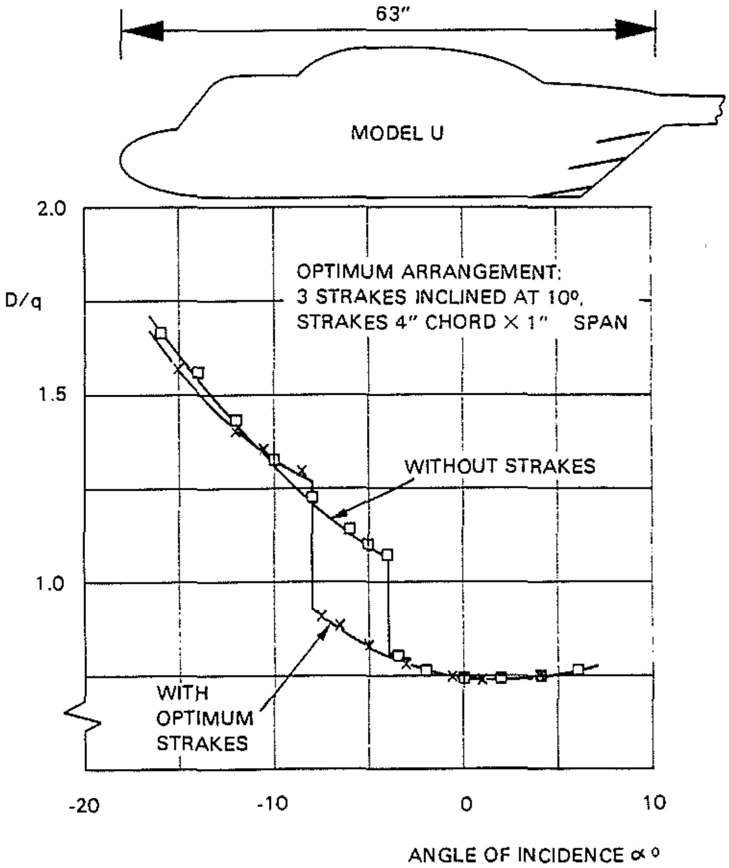


FIG. 6 EFFECT OF STRAKES

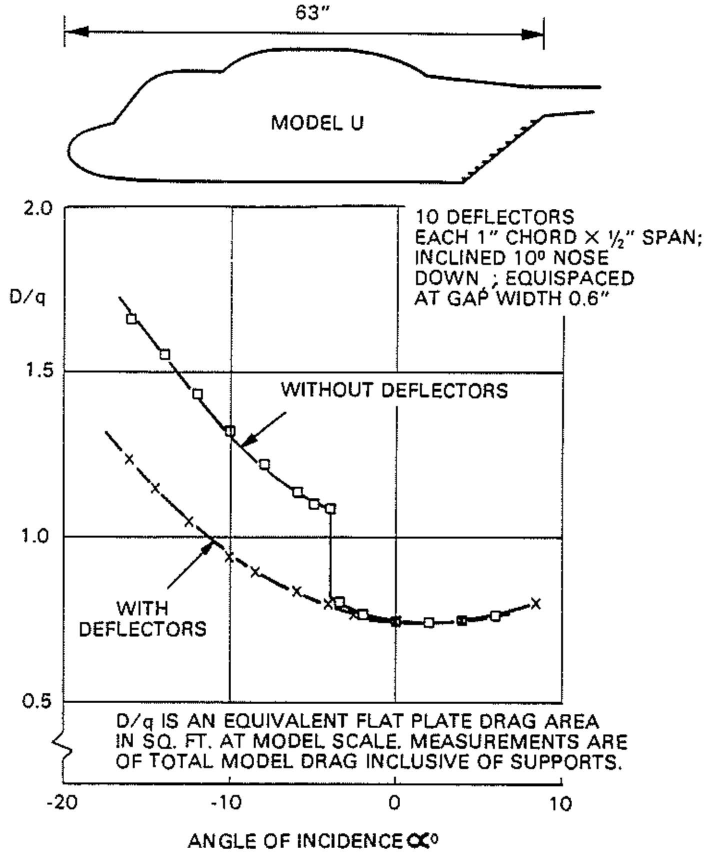


FIG. 7 EFFECT OF DEFLECTORS

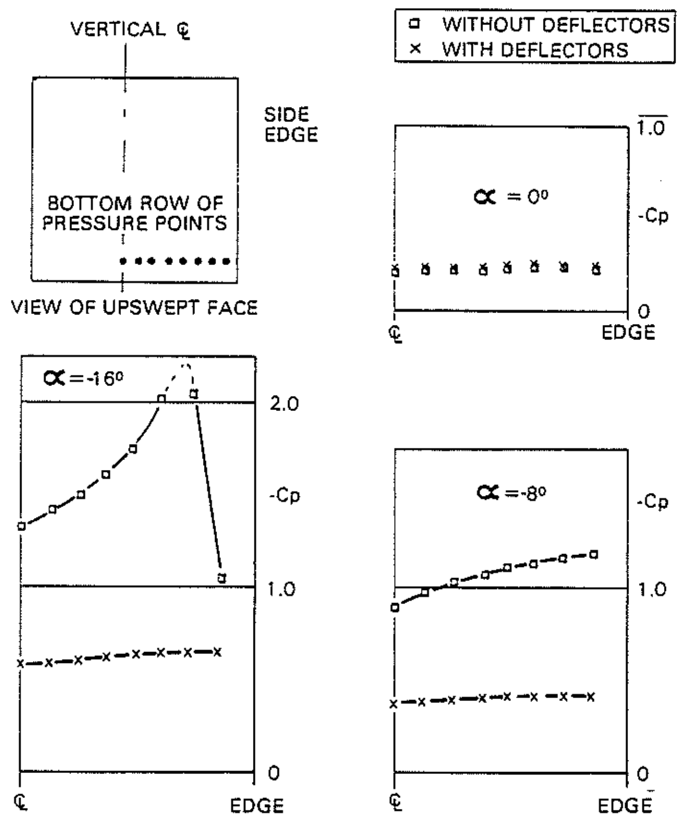


FIG. 8 SAMPLE PRESSURE DISTRIBUTIONS ON UNSWEPT FACE

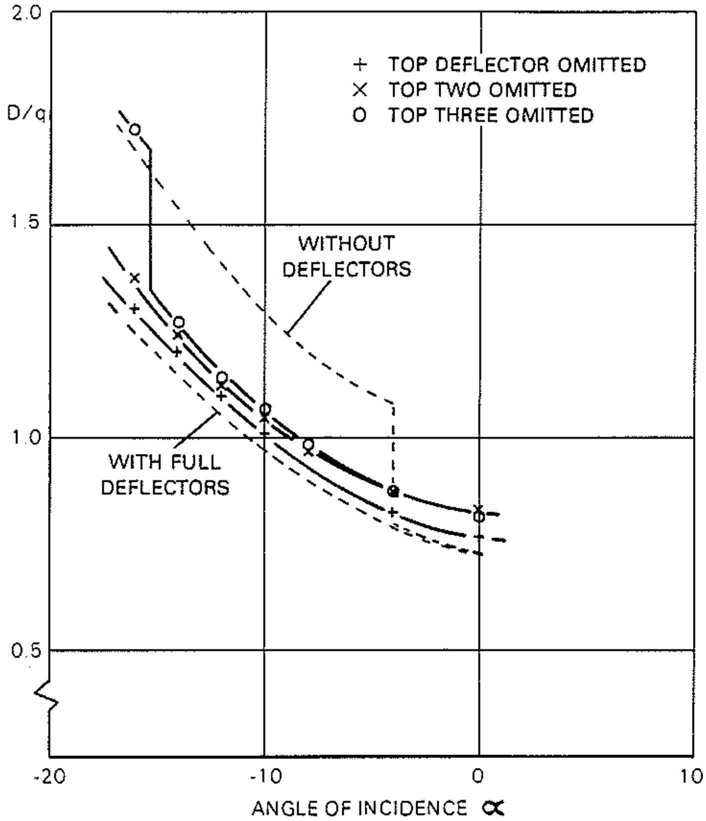


FIG. 9 EFFECT OF OMITTING DEFLECTORS AT TOP OF ROW

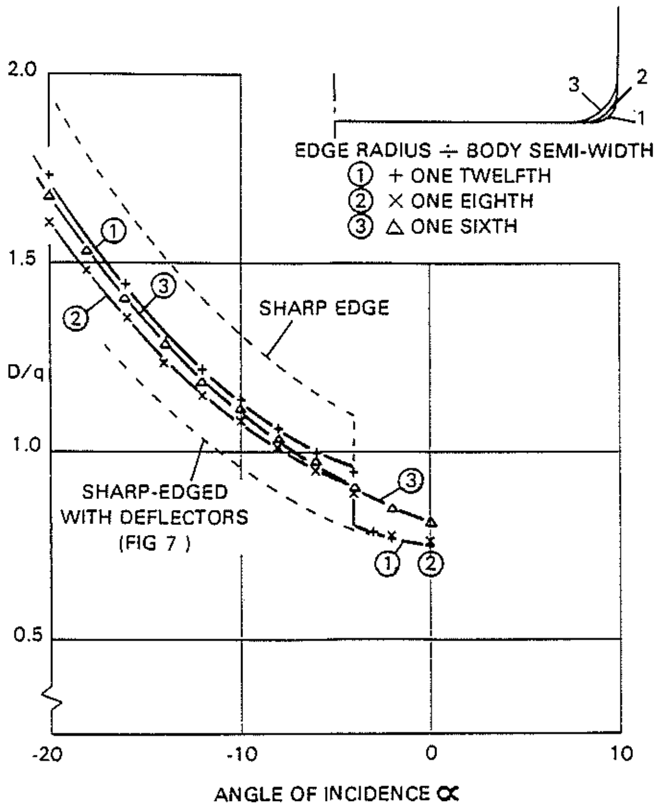
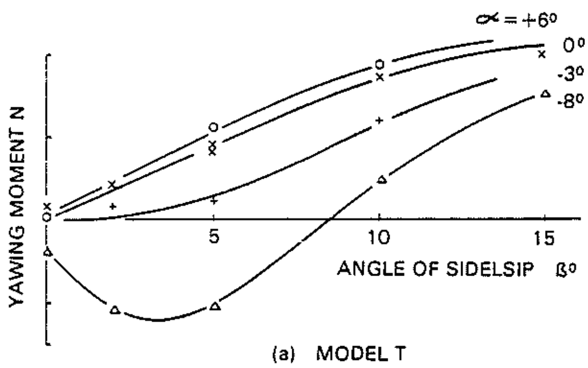


FIG. 10 EFFECT OF ROUNDING SIDE AND BOTTOM EDGES OF UPSWEPT FACE



(a) MODEL T

(b) COMPARATIVE RESULTS FOR BASIC MODEL (FIG. 1)

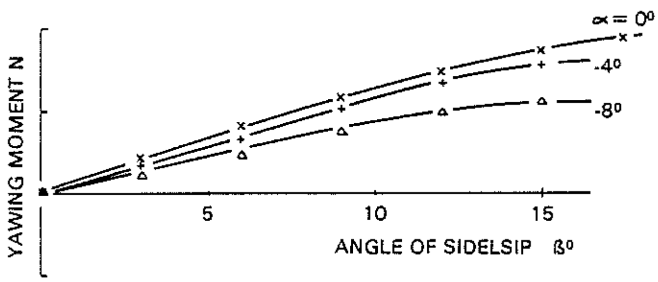


FIG. 11 YAWING MOMENT DUE TO SIDESLIP, FIN OFF

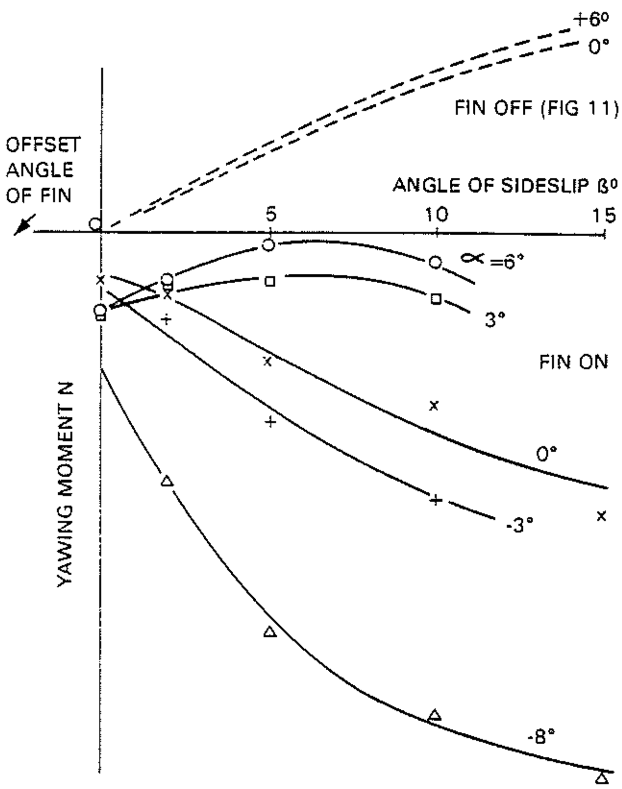


FIG. 12 YAWING MOMENT DUE TO SIDESLIP, MODEL T

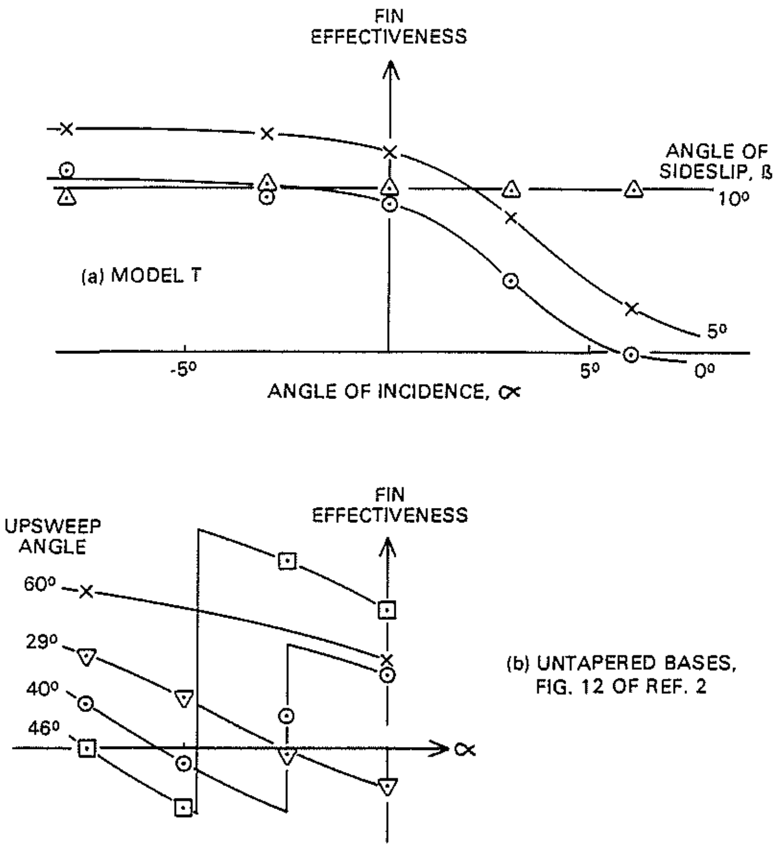


FIG. 13 FIN EFFECTIVENESS (DEFINED AS dN/dß FIN ON MINUS FIN OFF AT CONSTANT ß)

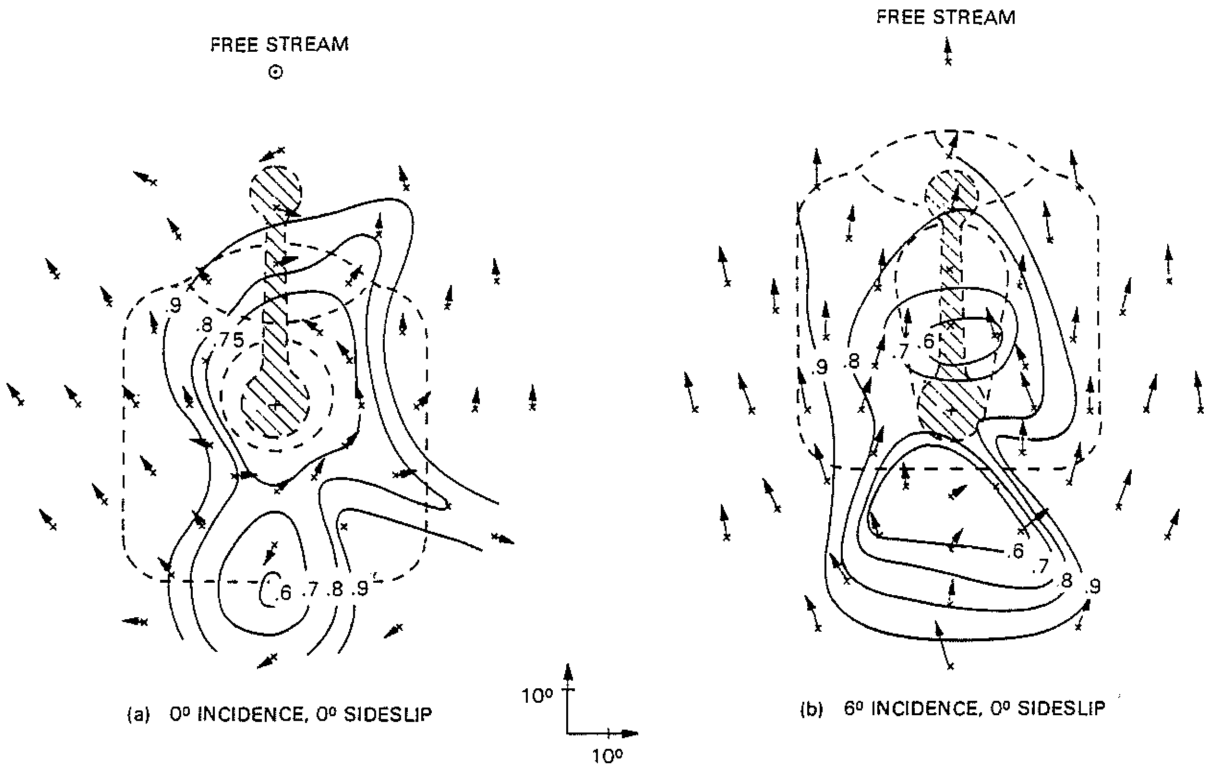
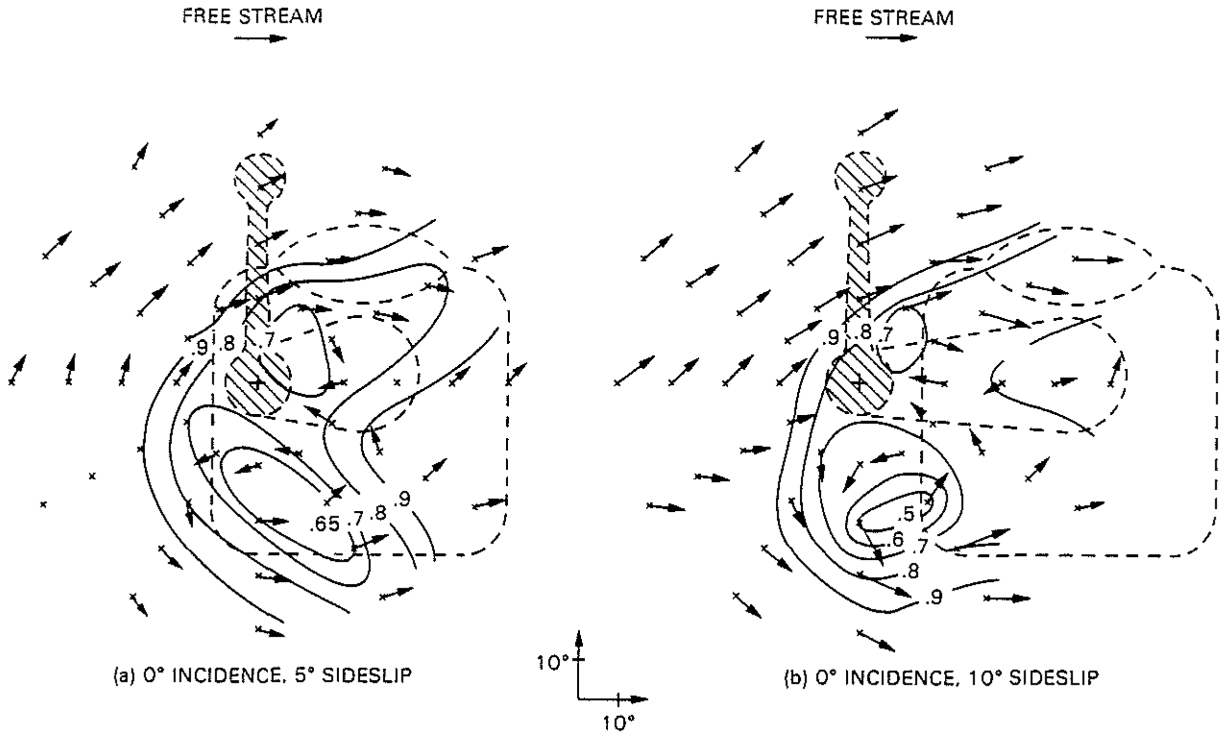


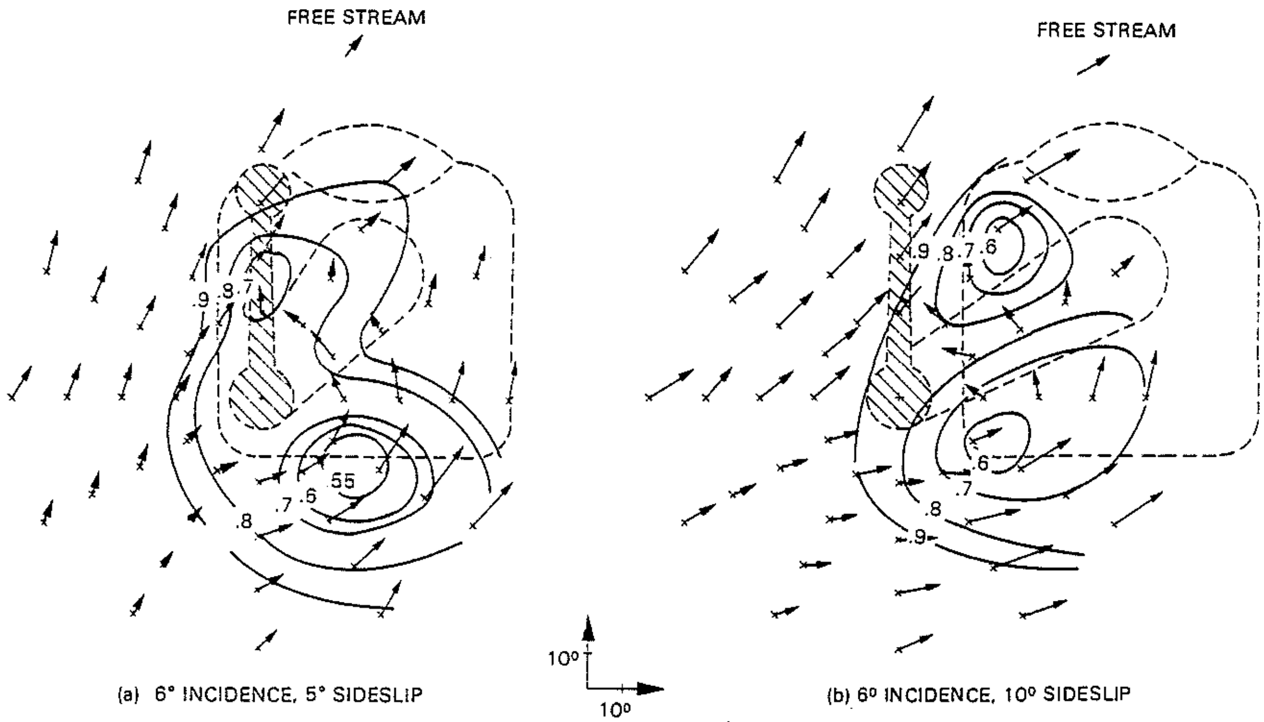
FIG. 14. WAKE SURVEYS AT 0° SIDESLIP



(a) 0° INCIDENCE, 5° SIDESLIP

(b) 0° INCIDENCE, 10° SIDESLIP

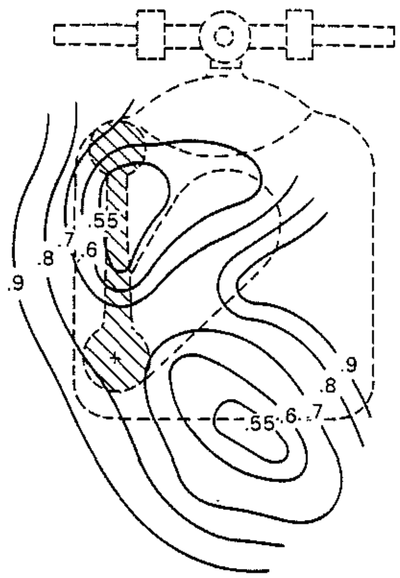
FIG. 15 WAKE SURVEYS AT 0° INCIDENCE



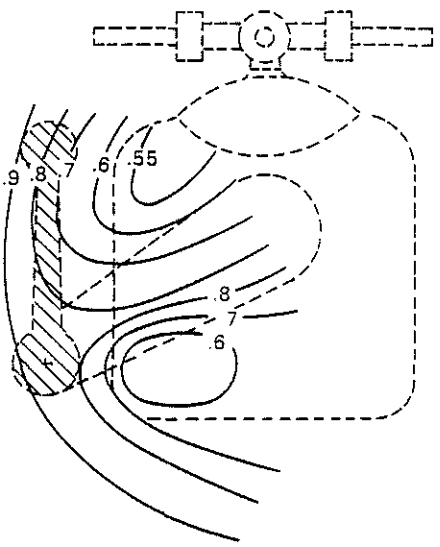
(a) 6° INCIDENCE, 5° SIDESLIP

(b) 6° INCIDENCE, 10° SIDESLIP

FIG. 16 WAKE SURVEYS AT 6° INCIDENCE



(a) 6º INCIDENCE, 5º SIDESLIP



(b) 6º INCIDENCE, 10º SIDESLIP

FIG. 17 WAKE SURVEYS IN PRESENCE OF SIMULATED ROTORHEAD