SIXTH EUROPEAN ROTORCRAFT AND POWERED LIFT AIRCRAFT FORUM

Paper No. 50

A STUDY OF THE EFFECT OF AFT FUSELAGE SHAPE ON HELICOPTER DRAG

David R. Clark
Analytical Methods, Inc.
Bellevue, Washington, U.S.A.

and

Frank Wilson
Westland Helicopters Limited
Yeovil, Somerset, England

September 16-19, 1980
Bristol, England

THE UNIVERSITY, BRISTOL, BS8 1HR, ENGLAND

ABSTRACT

A study has been carried out where the viscous flow into the base region of a typical helicopter fuselage was explored using an analytic configuration modelling method. The program used was a finite-element, distributed singularity model for the potential flow, with the presence of the viscous effects including the occurrence of regions of separated flow being accounted for iteratively.

A range of aft fuselage shapes were explored with the lateral and vertical transition angles being changed independently. It was found that there was considerable interaction between the pressure field generated by changes in vertical and horizontal cross section and that the pressure gradients experienced by the boundary layer on the surface could be extensively (and favourably) modified by the correct combination of the two effects.

The influence of parameters such as angle of attack and the presence of "real world" configuration features, such as sponsons, has a profound effect on the direction of streamlines entering the base region, and the interaction between the sponson pressure field and the pressure field generated by the fuselage lateral transition can have a significant influence on the extent of the separated flow in the base region and, hence, also on airframe drag.

1. INTRODUCTION

The shape of a mechanism is, to a certain degree, dictated by the function it performs and by the manner in which it performs that function. This is as true for the helicopter as it is for any other machine. Designed preeminently for hover and vertical flight and sustained in most cases by a single rotor, the mass and hence the usable volume must be more or less balanced around the vertical axis of the rotor (conveniently, in a region of low downwash). Requirements for anti-torque and lateral directional control in forward flight dictate some form of auxiliary rotor and vertical surface, generally outside the radius of the rotor. These components are conventionally attached to the fuselage by a slender boom. The boom is slender to minimize hover downloads as the high energy outer regions of the hovering main rotor wake pass over it and also to reduce undesirable side loads in lateral flight. The description of the resulting shape; bulbous fuselage with slender tail boom, fits the whole spectrum of single rotor aircraft now flying, from ultra-light to heavy transport aircraft.

Tandem rotor helicopters, faced with the same vertical drag and side flight constraints, but freed to a certain extent from balance considerations tend toward designs which are, at their simplest level, blunt cylinders between the rotor axes. Again, to minimize vertical drag and sideward flight problems and for system balance, the usable volume is concentrated between the rotors and the overhang outside the rotor axes limited to keep the structure in regions of low downwash.

Whatever the design philosophy, whether single or tandem rotor, the shapes developed with hover, vertical and low-speed forward flight constraints in mind have one feature in common which results in a considerable performance penalty as forward flight speeds increase; that is, the blunt base (tempered somewhat by the tail boom in single rotor machines) which results from the attempt to extend the usable cargo volume as far aft as possible. This blunt base and large aft facing surface creates several problems, especially for the flow along the side of the fuselage. As the section changes towards the base, entering the transition region, the air is initially accelerated and then decelerated at a rate dependent on the precise shape of the individual configuration. If the local pressure gradient is sufficiently steep, the boundary layer will separate, increasing the likelihood of higher drag.

Reviewing the drag breakdown of a typical helicopter with exposed landing gear, as presented in refs. 1 and 2, shows that the drag of the basic fuselage makes up approximately 15% of the total. If the landing gear is retracted (more likely in higher speed machines) the fuselage contribution rises to almost 20%. Since the base drag, controlled by the quality of the flow in, and approaching the aft facing portions of the fuselage, is responsible for as much as 2/3 of this figure, an understanding of the factors controlling base drag is vital to the design of low drag airframes.

Hoerner (ref. 3) presents perhaps the most complete survey of the effect of afterbody shape on base drag. However, the results he summarizes are almost exclusively for bodies of revolution with simple changes in cross section or for square or rectangular prisms with varying amounts of rake in the base region. One conclusion does emerge, however, and that is that the more gradual the change in cross section the better.

Other later work (ref. 2) reviews results on the impact of aft fuselage parameter changes taken from data on a range of representative helicopters. As might be expected, the results confirm the earlier findings that a slimmer, that is a more gradual transition is better. They do, in addition, however, introduce the possibility that, based on their data, combinations of lateral and vertical contractions may be found which offer enhanced drag reduction. Also discussed is the significance of "camber" in afterbody drag, particularly as a function of angle of attack. For large transport helicopters with aft loading doors and a ramplike transition in the vertical plane, this provides important guides towards finding an optimum between ramp angle (and, hence, cargo volume), cruise attitude and an acceptable drag. Reference 2 also discusses in some detail the use of strakes on fuselages designed for aft loading. Taken from earlier work (ref. 4) on fixed wing aircraft, it illustrates the role of the strake in first localizing the separation along the edge of the base region, and then in maintaining (in most cases) attached flow along the ramp centreline.

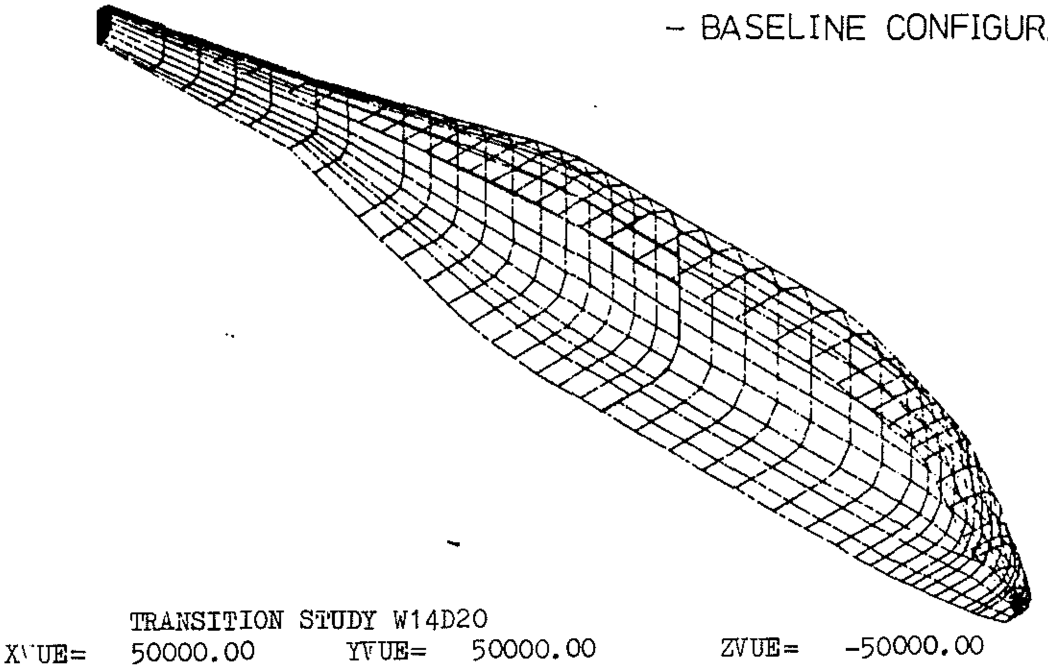
Helicopters are not the only vehicles to employ a ramplike rear closure and many examples of this form are found on automobiles and a considerable amount of research has been done in this area. Typical is ref. 5. Here, a range of simple cylinders with varying slant bases were studied. This work showed that there existed a critical slant angle, close to 45 degrees, where the flow in the base region changed character with a dramatic increase in drag. Starting with a square cut base (0 degrees slant angle in these experiments), the drag increases as the slant angle increases. This appears to be related to an increase in suction on the aft facing surface. At the critical angle, the nature of the flow field changes and thereafter the base suction generally falls, resulting in a reduced drag. This behaviour has been related to the nature of the separated flow field, and, in particular, to the way in which the shear layers springing from the edges of the aft facing surfaces interact. For bluff bases, below the critical ramp angle, the shear layers appear too close to form a "quasi-axisymmetric" (ref. 5) region. Above the critical value, the lateral edge vortices roll up, reattaching the flow along the axis of symmetry. It is this type of flow that is encouraged by addition of strakes on rear loading aircraft configurations.

Previous work, from a study of a range of helicopters, has shown that substantial reductions in drag may be achieved by variations in the rates of taper of the aft fuselage (ref. 2), and has determined with a detailed experimental study (ref. 5) the impact of one of the parameters involved. In the present study, the effect of combining two of the parameters is explored. These parameters are the rates of change of cross section in the vertical and horizontal plane. Particular emphasis is paid to the effect of superimposing the influences of changes in lateral and vertical cross section on the flow approaching the base region and on the tendency of this flow to separate. Further, the influence of the realities of an actual aircraft are considered by including the effect of a sponson and by looking at the results of changes in attitude as reflected in the behaviour of stream properties along streamlines entering the base region.

2. BASIC CONFIGURATIONS STUDIED

To provide a vehicle for the analysis while at the same time making the results more directly applicable to the design process, a baseline was chosen which has a shape typical of helicopters in the mid to upper weight range (7,500 Kgs. and greater). The fuselage was assumed to be approximately rectangular in cross section with rounded corners, with the rounding being of radius greater than 10% of the local section maximum dimension. The transition was straight tapered in both plan and side views to roughly square section tail boom. Figure 1 shows a general view (from below, aft) of the baseline analytic model.

FIG. 1 ANALYTIC MODEL
- BASELINE CONFIGURATION.



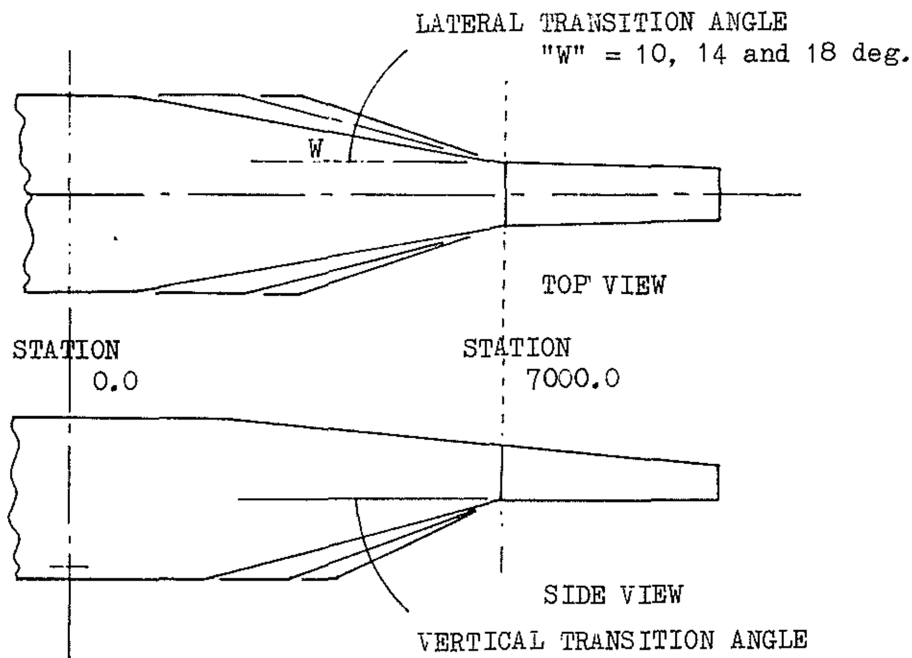


FIG. 2. OUTLINES OF TRANSITION SECTIONS STUDIED.

Throughout the study, the fuselage cross section and tail boom cross section was held constant. The manner, in which the various transition section combinations were generated, is shown in figure 2. Starting from the fuselage station of the tail boom joint, lines were projected forward at varying angles to model varying rates of transition section, until they met the aft projection of the constant fuselage section. This produced a range of ramp angles, angle "D" for the change in vertical section and "W" for the lateral transition angle. The flow around the fuselage and into the base region was studied for lateral transition angles, W, of 10, 14 and 18 degrees, and for vertical transition angles, D, of 15, 20 and 25 degrees. The slope of the upper aft fuselage was held constant throughout.

In the discussion that follows, the configurations will be referred to by their combined lateral and vertical transition angles, e.g. W10D20. The configuration W14D20 was chosen as the baseline since this matched closely the shape of a model for which flow visualization data were available.

3. THE ANALYSIS

The flow over the various transition sections was studied using a finite-element analysis. The procedure initially calculates the potential flow over the body. The direction of the streamline flow is then determined and the boundary layer development along the streamlines calculated. If a region of separated flow is indicated, its boundary is defined and a vortex sheath representing the separated shear layer is constructed and projected downstream. The potential flow solution is then repeated, modifying the boundary conditions to represent boundary layer growth. Experience has shown that for bodies with well defined aft facing surfaces, such as helicopters, two iterations are sufficient for a converged solution.

The program and its development are described in refs. 6 through 8 and other applications to helicopter aerodynamics are detailed in references 9 through 11. The basic program is in widespread use throughout the aerospace industry and the recent experience (refs. 10 and 11), in parallel with an extensive model and full-scale test program supports its use in the present exploratory mode.

4. THE RESULTS

The output from the analysis is available in several forms. The bulk of the data is output for the centroid of each of the panels used to construct the model. The data consists of velocity components, resultant velocity and pressure coefficients. Using post-processing interactive graphics, described in detail in ref. 12, it is possible to "slice" through the configuration and present data plotted along any selected body section. Figure 3 shows such a section taken close to the body centreline on the baseline W14D20 configuration at -10 degrees (nose down) angle of attack. Only lower-surface pressures are plotted. Figure 4 is the corresponding waterline cut taken along a section through the upper fuselage and tail cone. The pressure plots exhibit the typical characteristics of a body at angle of attack with increased suction in regions of curvature and the pressures seeking $C_p = 0.0$ (free stream) in the regions of parallel flow along the sides and the upper and lower surfaces.

While data presented in this manner along body cuts illustrates how conditions vary over the body, it does not give a true picture of what the flow experiences, except, perhaps, at zero angle of attack. For a truly representative presentation, especially where viscous flow effects are of controlling importance, conditions should be plotted varying along the streamlines.

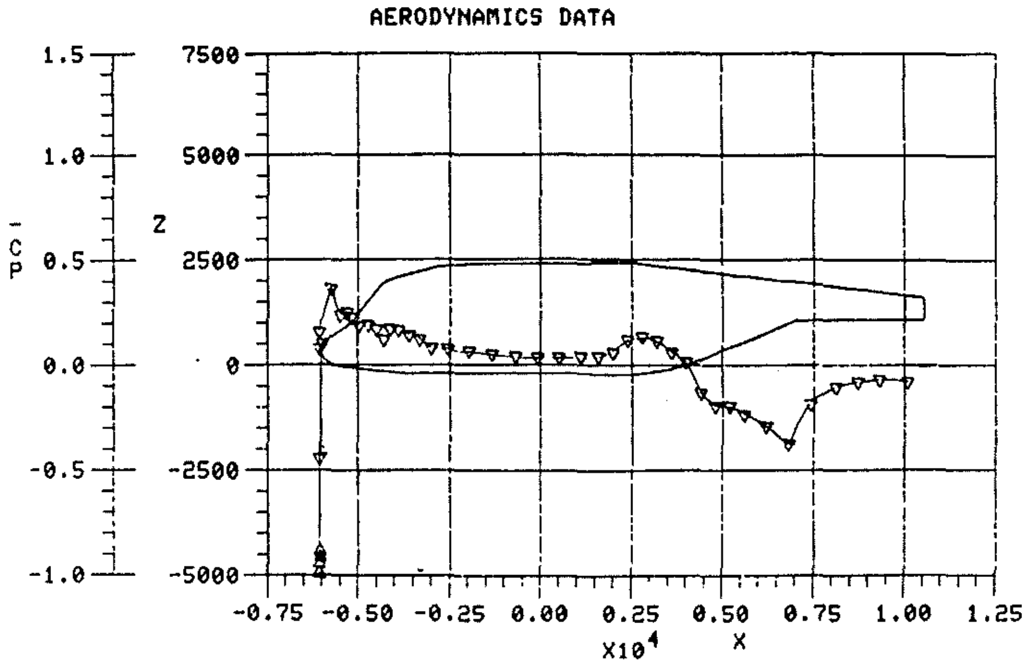


FIG. 3. CALCULATED PRESSURE DISTRIBUTION ALONG LOWER SURFACE CENTRLINE (BUTTLINE 0.0) OF BASELINE CONFIGURATION.

W14D20 ALPHA= -10.0

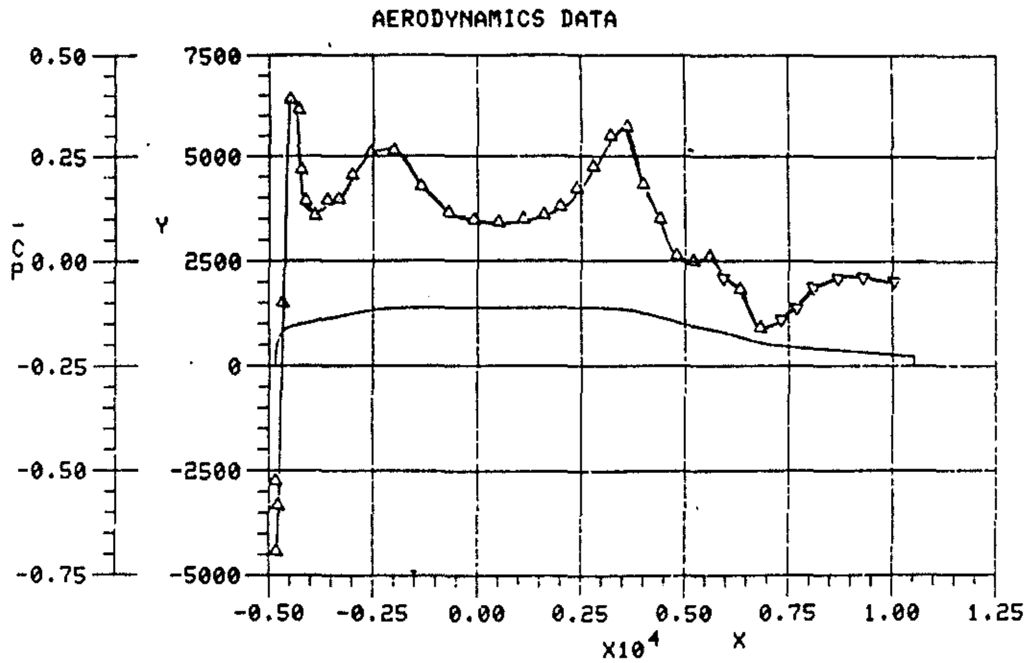


FIG. 4. CALCULATED PRESSURE DISTRIBUTION ALONG WATERLINE 1400.0 ON BASELINE CONFIGURATION.

W14D20 ALPHA= -10.0

This allows the possible influence of upstream history to be assessed as the flow traverses critical regions of the body. A side view of the streamlines on a typical configuration is shown in figure 5, and the pressure distribution along one particular line, streamline 5, is shown in figure 6. The suction peaks at stations 2,000 and 4,000, respectively, reflect the changes as the streamline passes first over the lateral transition and then enters the ramp region. It should be noted here that the calculated streamline trajectories agree very well with measured local flow direction as determined from tuft photographs taken during wind tunnel testing.

After defining the streamline trajectory over the surface of the body, the boundary layer development along the streamline is established. From the integral solution used (ref. 7), all the conventional parameters are available. In an ideal application, separation is assumed to have occurred (in the analysis) when a zero value of local skin friction is calculated. On a practical example, because of uneven surfaces, local irregularities and a bad iteration environment, separation will in all probability occur earlier. Throughout the analysis of the transition section shapes discussed here, a value of the shape factor of H=2 has been taken as an indicator of separation. In this calculation, this was always seen to precede the occurence of zero skin friction by a small distance.

In evaluating the calculated results on the transition sections examined, the success or failure is assessed in terms of the probability of retaining attached flow into the aft facing regions of the vertical transition zone and along the sides through the lateral transition zone. The basis for the comparison between different configurations was the behaviour of a set of streamlines passing through the same points on the mid-section of the fuselage (held constant as the transition sections and other configuration details varied). Although a full set of streamlines were calculated, only results for one streamline will be presented here to illustrate the impact of the changes in aft fuselage shape. Streamline 5 (see fig. 5) has been chosen since, for all the cases, including the full range of angles of attack studied, it passes over the side of the fuselage and enters the ramp region. Finally, it should be noted that when pressure data is plotted along a streamline beyond an indicated separation location, the streamline trajectory is from the initial potential flow calculation.

5. DISCUSSION OF THE CALCULATED RESULTS

Figure 7 presents the effect on the Cp along a typical streamline created by moving the lateral transition location with a fixed vertical transition. In figures 8 and 9, the effect of changing vertical transition location is presented at two values of lateral transition location. All of the data is calculated for an angle of attack of -10 degrees (nose down). The most notable feature in figure 7 as the vertical transition is moved aft is the way in which the changes in cross section augment the effect of each other. For the most forward position, W10, the passage over first the lateral section change and then the entry into the ramp region are distinct. When lateral and vertical transitions coincide, W14, the suction peaks augment each other, raising the maximum suction level and increasing length of the run through a region of unfavourable gradient. With the lateral transition at its maximum aft position, W18, the peak suction and the extent of the unfavourable pressure gradient are at their maximum. This is reflected in an earlier separation.

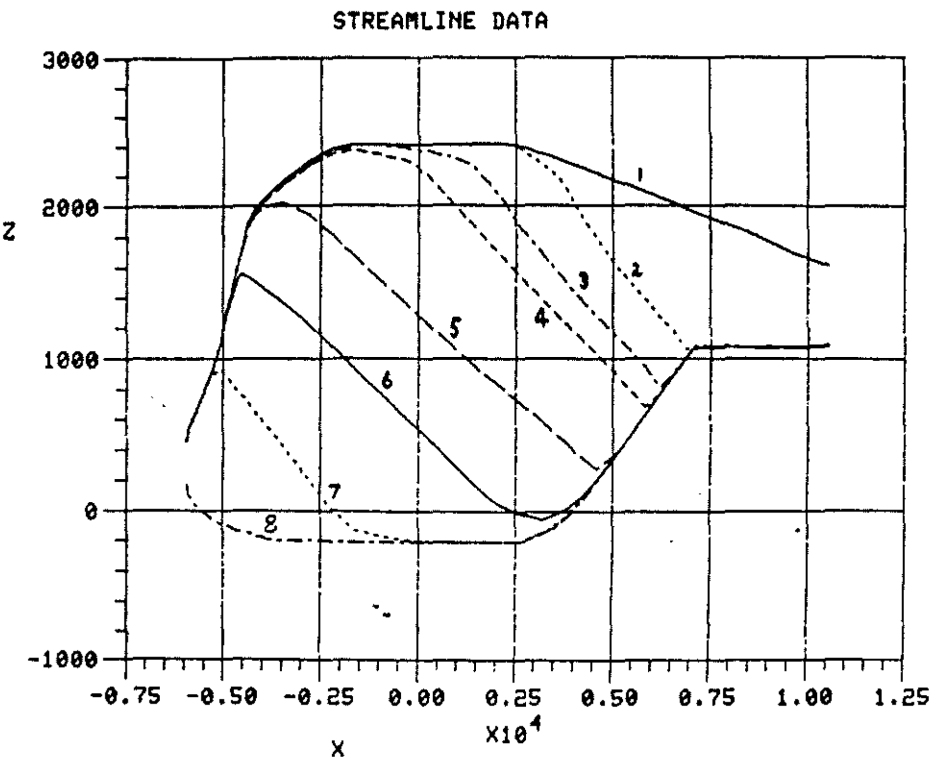


FIG. 5. TYPICAL CALCULATED STREAMLINE PATTERN ,SIDEVIEW. (NOTE EXPANDED VERTICAL SCALE)

TRANSITION STUDY W1OD2O

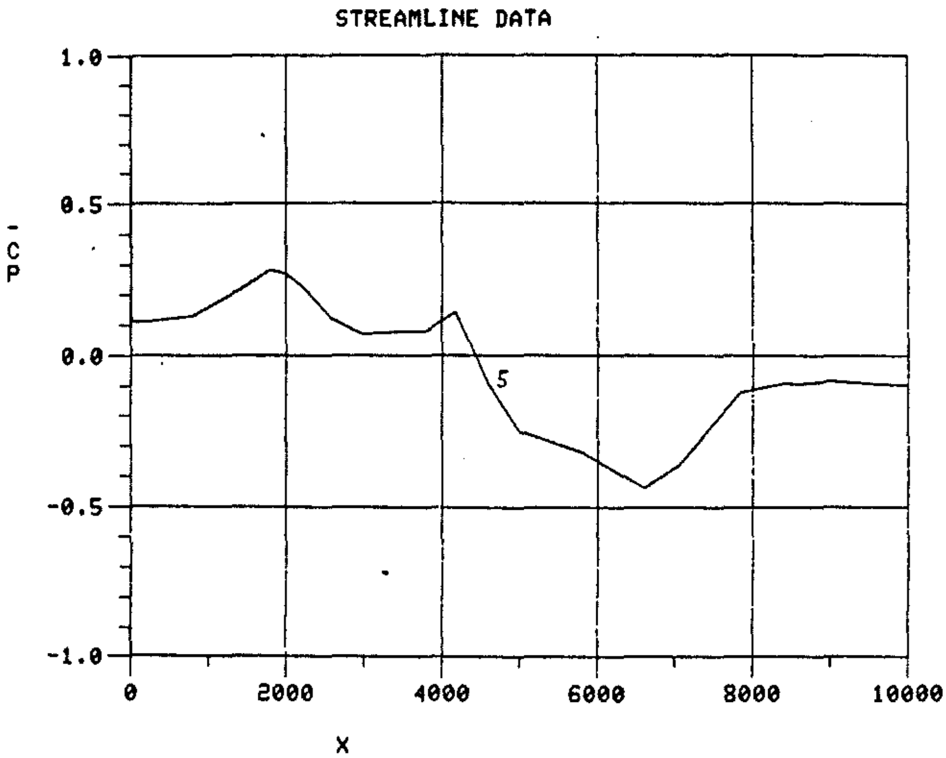


FIG. 6 PRESSURE DISTRIBUTION ALONG TYPICAL STREAMLINE.

TRANSITION STUDY W1OD2O ALPHA= -10.0

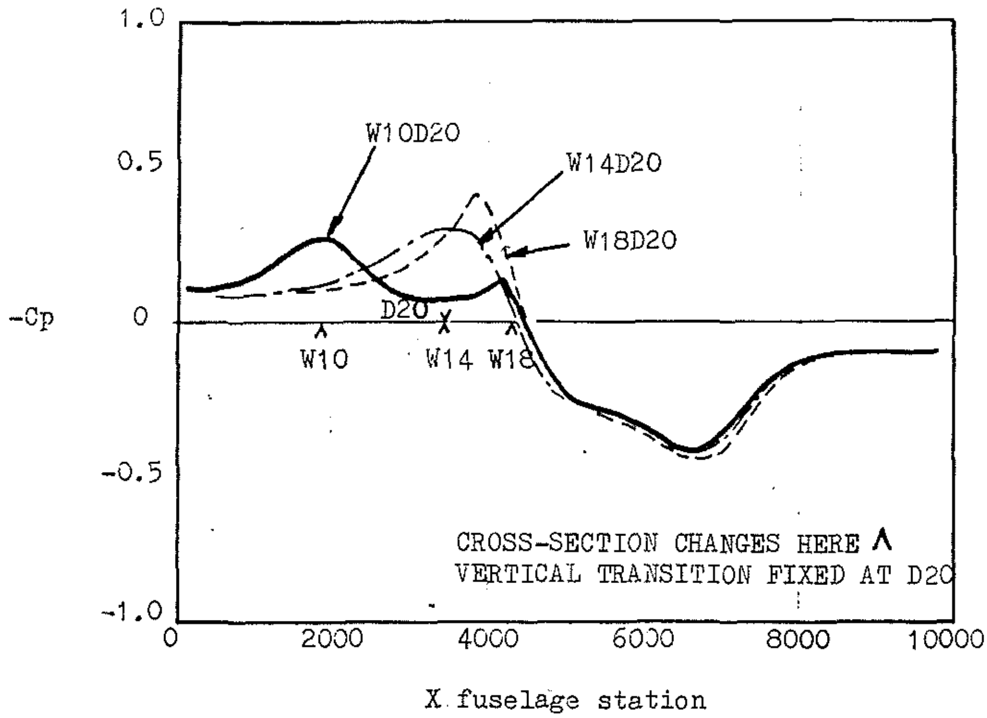


FIG. 7 EFFECT OF VARYING LATERAL TRANSITION ANGLE ON PRESSURE DISTRIBUTION ALONG STREAMLINE 5. -VERTICAL TRANSITION ANGLE = 20°

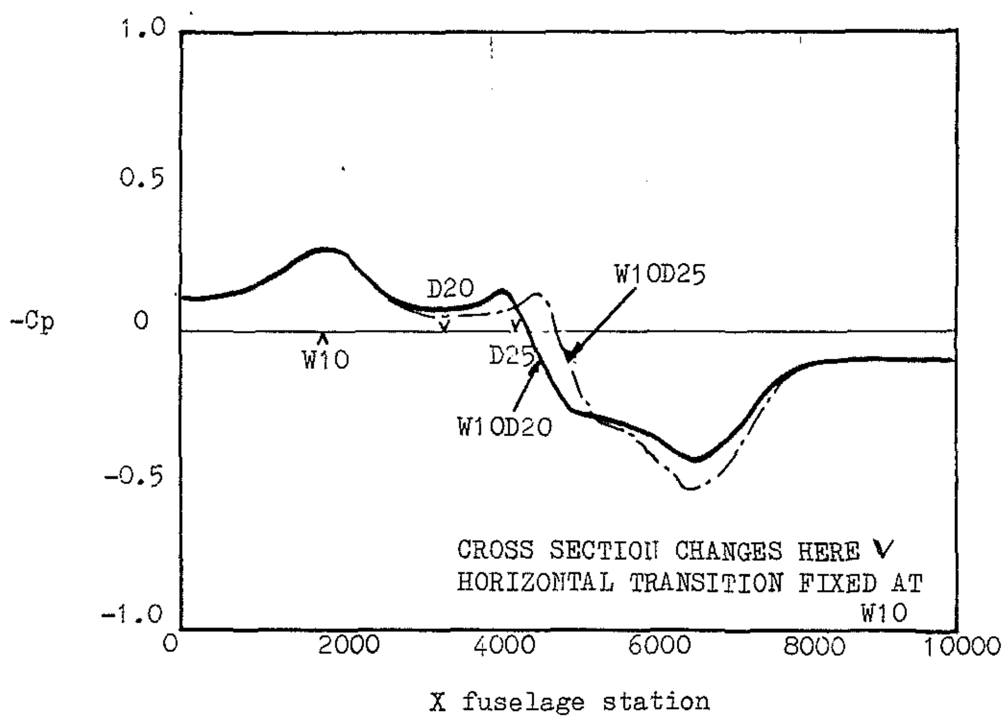


FIG. 8 EFFECT OF VARYING VERTICAL TRANSITION ANGLE ON PRESSURE DISTRIBUTION ALONG STREAMLINE 5. -LATERAL TRANSITION ANGLE = 10°

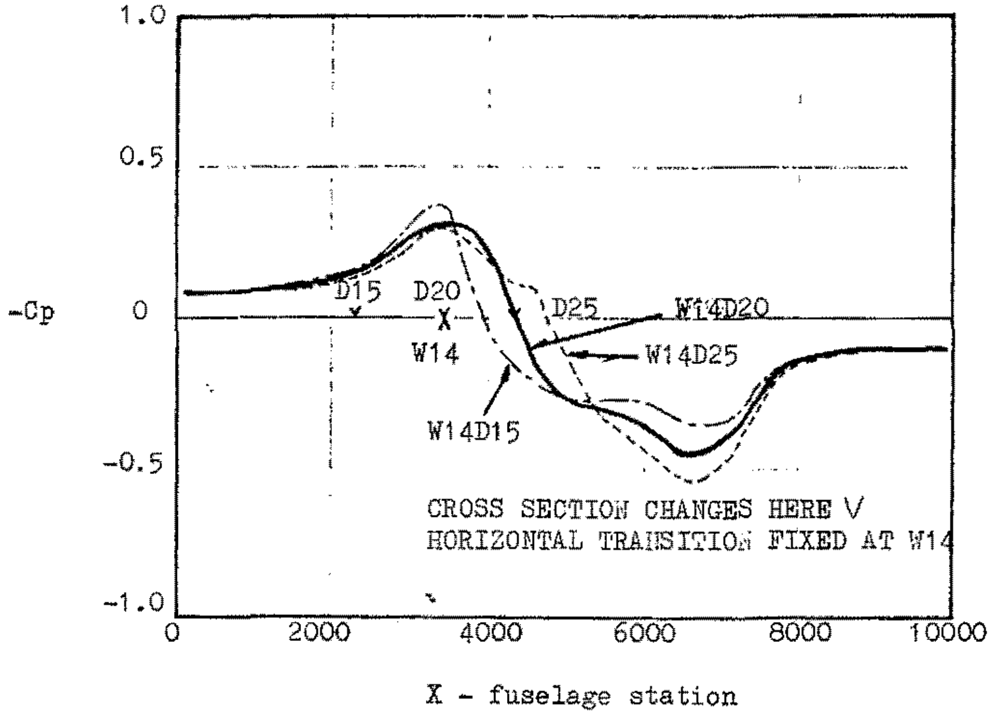


FIG. 9. EFFECT OF VARYING VERTICAL TRANSITION ANGLE ON PRESSURE DISTRIBUTION ALONG STREAMLINE 5. -LATERAL TRANSITION ANGLE = 14°

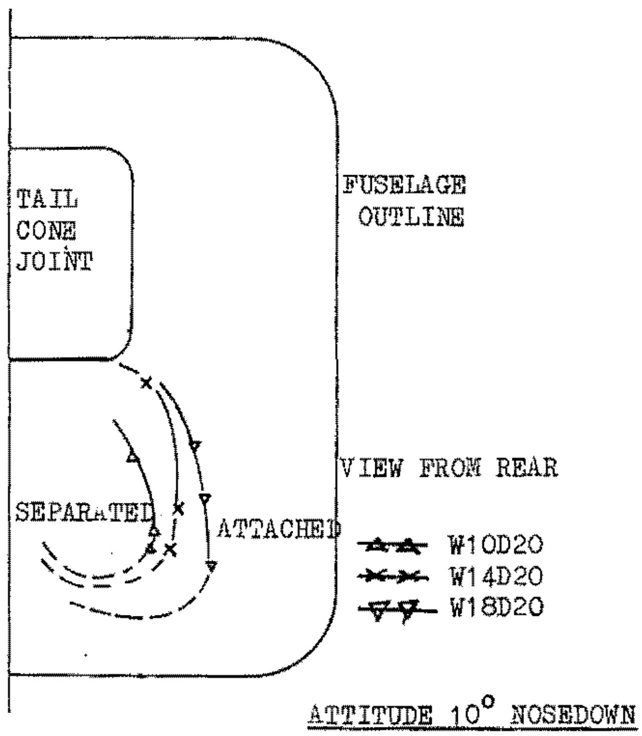


FIG. 10. PREDICTED SEPARATION CONTOURS - VERTICAL TRANSITION FIXED - LATERAL TRANSITION VARYING

With lateral transition fixed, at W10 in figure 8 and W14 in figure 9, and the vertical transition moving aft, that is with the ramp steepening, similar results are found. As before, when the transition regions are well separated,(W10D20 and W10D25 in figure 8), their effects are clearly distinguishable. Again, as in figure 7, when the vertical change precedes or is coincident with the lateral change, the effects tend to coalesce, strengthening the suction peak and increasing the length of the run under an unfavourable pressure gradient (compare cases W18D20 and W14D15, respectively, from figures 7 and 8). When the vertical change is aft of the lateral change, W14D25 in figure 9, the same reinforcement is not found and the small separation of the effects creates a region of relief from the unfavourable gradient as well as considerably reducing the steepness of the initial gradient. Of all the shapes summarised in figure 9, the best from a practical point of view, the one with the largest cabin volume and the "boxiest" shape as a result of the combination of transition angles, also appears from the streamline pressure data to offer the best chance of minimizing separation and reducing drag. This is confirmed by the calculated separation profiles.

The discussion above is based on the behaviour of one typical streamline. A proper evaluation of the success or failure of a configuration can only be based on the amount of separated flow in the base region. These data are presented in figures 10 and 11, and confirm the preliminary conclusion reached above; that is, that when the change in vertical cross section occurs forward of or is coincident with the change in lateral cross section, the chances of separated flow, and hence, increased drag, appear to be higher than if the vertical change is aft of the lateral transition.

Before going on, it should be noted that in all cases the vertical transition angle has a relatively weak effect on the pressure gradient into the base region. It does affect flow along the lower surface into the ramp area, increasing the suction peak around the lower edge of the ramp. However, since the bulk of the flow entering the region below the tail boom comes not along the bottom of the fuselage and up the ramp, but along the fuselage sides, entering the base region moving horizontally and towards the centreline, the effect of changes in vertical section angle would be minimal. This is confirmed by data on the typical streamline for configurations W10D20 over a range of angles of attack presented in figure 12. After the first suction peak at the lateral transition, the second break in shape is where the streamline turns onto the aft facing surface of the ramp. This occurs later at an angle of attack of -6 degrees, since the streamline traverses a path further up the side of the fuselage as a result of the relatively more nose-up attitude. Despite this, the pressure gradients in the ramp region, after the break, are very similar. At 0 degrees, the streamline does not enter the base region, and instead passes aft along the side of the tail cone.

In a practical application the actual value of drag would depend very much on the quality of the surface and especially on the nature of the corner. In the calculations, a generous radius was assumed and in many cases flow was found to traverse the corner without separating. On a real aircraft, particularly one with aft ramp doors, a sharp corner is almost unavoidable and (with or without strakes (ref. 3)) an edge separation is virtually certain.

The data presented above and the discussion so far have related to idealized shapes. One of the most frequent departures from the streamlined shapes on real world machines is the addition of sponsons for landing gear or stores carriage. The presence of sponsons low on the aft fuselage will have a significant effect on the flow entering the ramp region. To explore this, two sponson configurations were studied. Again, starting with configuration W14D20 as a base, sponsons typical of current practice were added as pictured in figure 13.

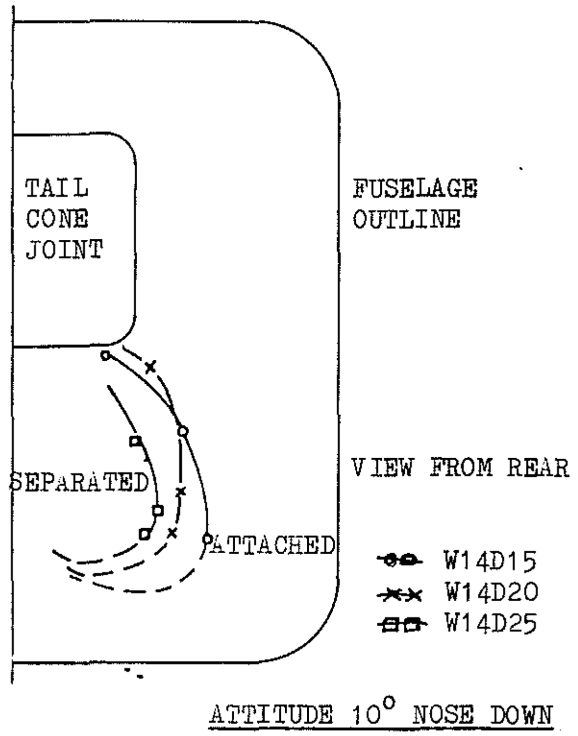


FIG. 11. PREDICTED SEPARATION CONTOURS - LATERAL TRANSITION FIXED - VERTICAL TRANSITION VARYING

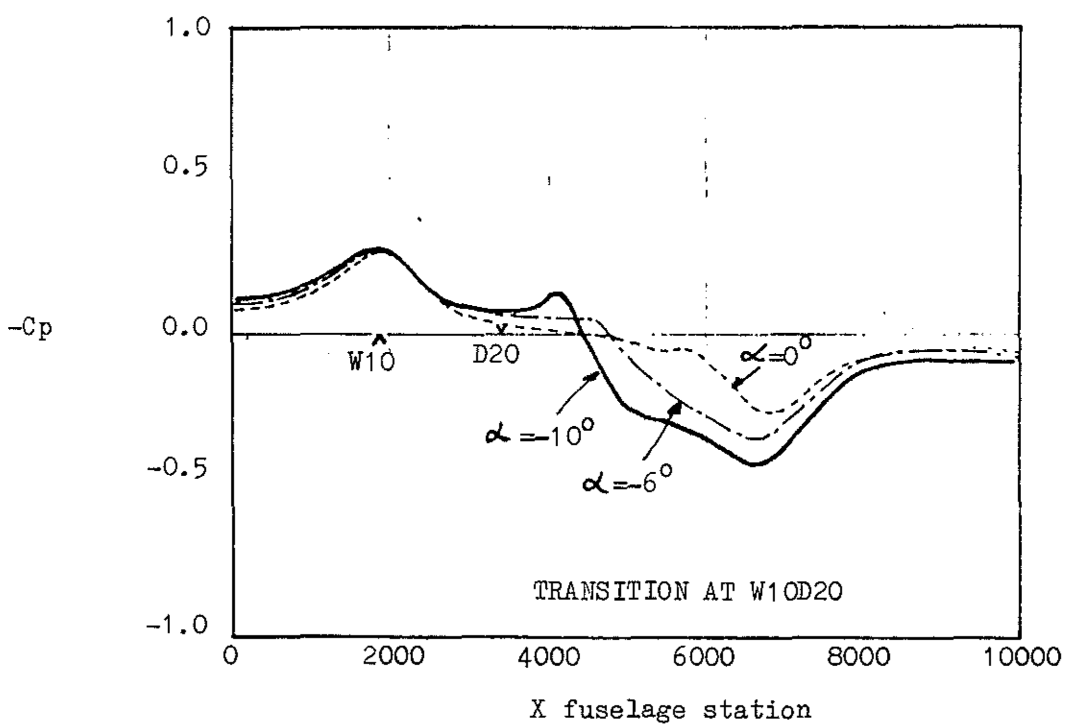


FIG. 12. EFFECT OF PITCH ATTITUDE ON PRESSURE DISTRIBUTION ALONG STREAMLINE 5. -TRANSITION FIXED.

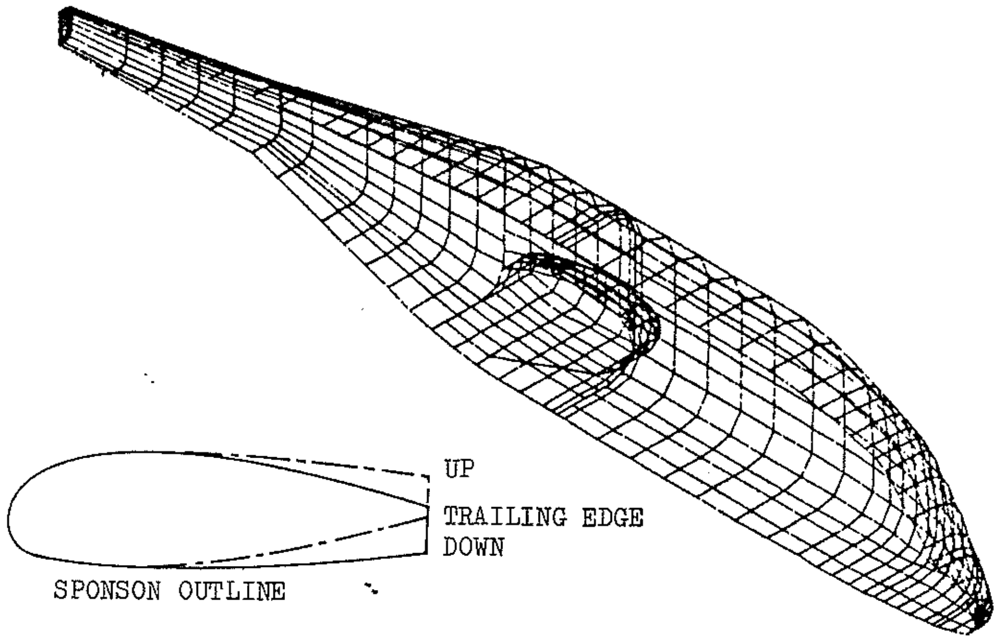


FIG. 13. ANALYTIC MODEL OF CONFIGURATION WITH SPONSONS.

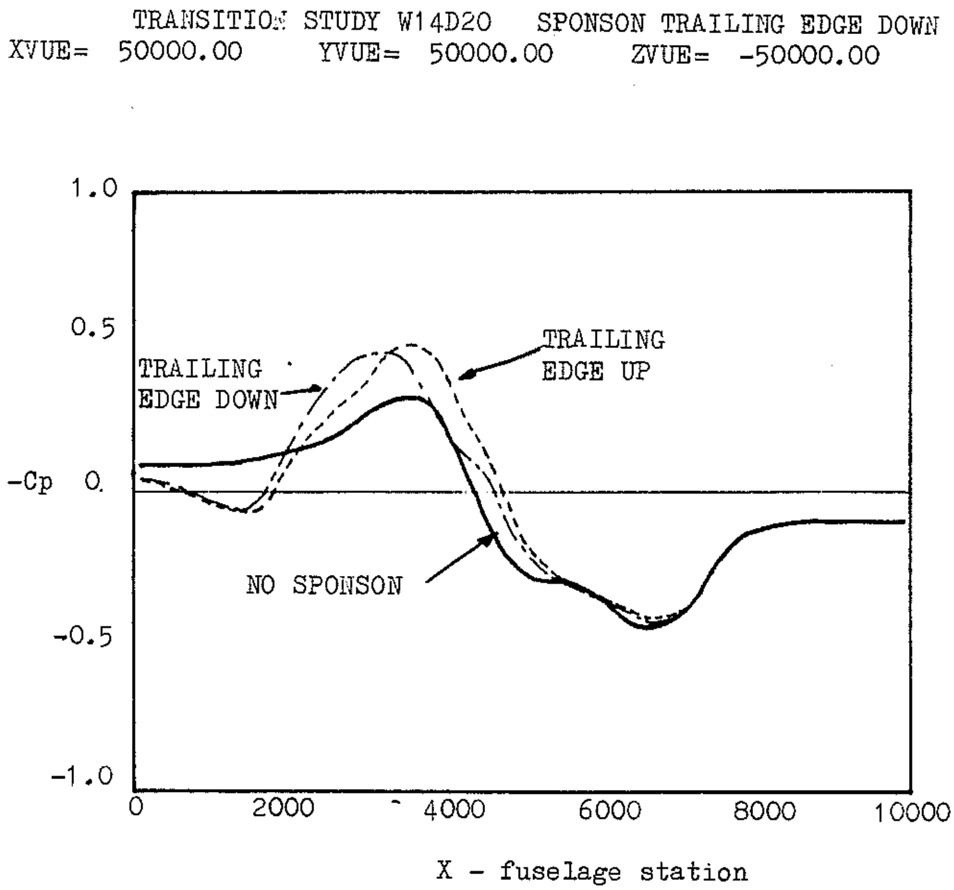


FIG. 14. EFFECT OF SPONSON ON STREAMLINE 5 PRESSURE DISTRIBUTION.

This shows an aft view of the analytic model with (inset) the cross sections of the different sponsons examined. These were a conventional trailing-edge -down form, and an alternative shape with the trailing edge raised. In each case the base of the sponson was cropped square. The lower surface of the trailing-edge-down sponson reflected the curve of the fuselage lower surface.

Results from both sponsons are summarised in figure 14. Plotted at the same scale as the earlier pressure plots, this figure for the same streamline as earlier shows that the main influence of the sponson comes from the blockage it creates rather than from any lifting effect. The small lift-induced changes are indicated by the differences between trailing-edge-down and up curves. The figure is dominated by the thickness effects and, in particular, by the increased suction as the flow passes over the upper surface. Accompanying this and shown in figure 14 is the substantial deflection of the streamline from its original path. The heightened suction peak and increased run in an unfavourable pressure gradient can only degrade the chances for attached flow. Added to this is the effect of the separated flow in the base region of the sponson tending to be fed into the ramp region by the lateral component of the local flow velocity. Again, the calculated effect of the sponson on the local streamline flow correlates well with observed tuft behaviour during wind tunnel testing.

Although the present study only examined two simple sponson configurations, one general observation can be made. That is, that the addition of any protuberance in the lower aft fuselage region that (inevitably) decelerates then accelerates the local flow, merely by its presence, will invariably degrade the flow quality and increase drag.

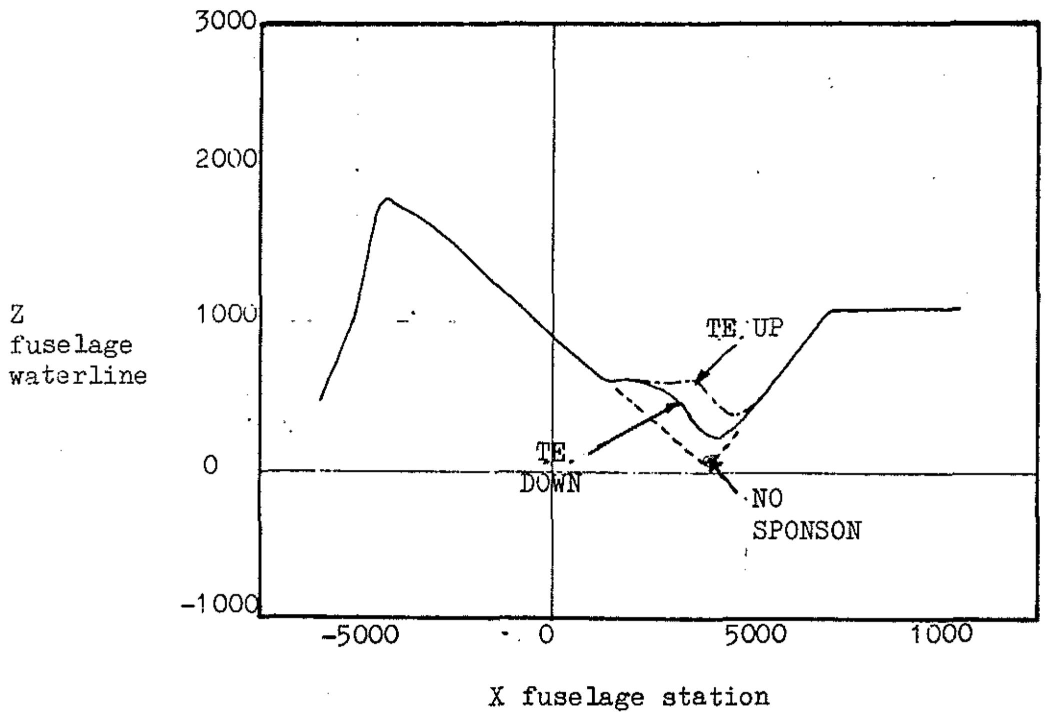


FIG. 15. EFFECT OF SPONSON ON PATH OF STREAMLINE 5.

6. CONCLUSIONS

Based on a study of the calculated results and guided by the assumption that there exists a strong correlation between drag and the extent of separated flow, the following conclusions may be drawn.

*When considering the influence of transition parameter, changes in cross section in the horizontal plane, lateral transition appears to have the strongest effect in determining flow quality ~~in the base region~~.

*Changes in cross section in the vertical plane have a relatively weak effect in determining separation. Varying the ramp angle changes peak suction values only slightly.

*Chances for lower drag are increased if the lateral transition occurs forward of the vertical transition.

*The presence of sponson and any other bluff configuration features in the vicinity of the changes in vertical or horizontal cross section will almost certainly aggravate any flow separation and drag problem if one exists or trigger separation if the flow is still attached.

7. RECOMMENDATIONS

The review of the data presented above also suggest some additional work which should be done to further clarify the picture of the flow into the base region. These recommendations fall into two areas relating to improvements to the analytic model and to further areas of study.

*While the analysis models the shear layer bounding regions of separated flow, no attempt was made to relax or deform this in any way. Since test data shows that, at least for sharp corner-type separations, the sheets of vorticity springing from the separation line roll up to form strong vortices, the roll-up should be modelled in the analysis and the sensitivity of the calculated results to vortex roll-up should be established. Work on the analysis to carry out the wake relaxation is now in progress.

*Since one of the main features of the streamline pressure distributions is the suction peak generated turning the corner from the fuselage side onto the lower surface of the aft facing ramp, the effect of that radius should be investigated.

*The effect of the blend radius on the fuselage sides and lower surface at the transition locations should be studied.

*Interaction between the flow field on the upper deck, the aft pylon and along the fuselage sides should be explored.

*The effect of main rotor-induced effects, minimal at very high speed, but significant at advance ratios where at least the upper fuselage is immersed, should be studied.

8. ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of Westland Helicopters, Ltd. throughout the period of this study.

9. REFERENCES

1. Williams, R.M. and Montana, P.S., "A comprehensive plan for helicopter drag reduction", paper from the special report presented by the AD HOC committee on rotorcraft drag to the american helicopter 31st annual national forum, Washington, D.C., May 1975.

2. Keys, C. and Wiesner, R., "Guidelines for reducing helicopter parasite drag", paper from the special report presented by the AD HOC committee on rotorcraft drag to the american helicopter 31st annual national forum, Washington, D.C., May 1975.

3. Hoerner, S.F. fluid dynamic drag, published by the author, 1965.

4. McCluney, B., "Improving the Belfast", Flight International, August. 1967.

5. Morel, T., "Effect of base slant on the flow in the near wake of an axisymmetric cylinder", Aeronautical Quarterly, Royal Aeronautical Society, London, May 1980.

6. Woodward, F., Dvorak, F., and Geller, E., "A computer program for three-dimensional lifting bodies in subsonic inviscid flow", USAA-MRDL-TR-78-18, April 1974.

7. Dvorak, F., Maskew, B., and Woodward, F., "Investigation of three-dimensional separation on fuselage configurations", USAAMRDL-TR-77-4, 1979.

8. Clark, D.R., Dvorak, F., Maskew, B., Summa, J.M., and Woodward, F., "Helicopter flow field analysis", USARTL-TR-79-4, 1979.

9. Clark, D.R. and Leitner, R.T., "Application of a configuration modelling technique to the design and analysis of X-wing aircraft configurations", paper presented to the 5th European Rotorcraft and Powered Lift Forum, Amsterdam, the Netherlands, September 1979.

10. Logan, A.H., Marthe, R., Clark, D.R. and Phelps, A., "An integrated analytical and experimental investigation of helicopter hub drag", presented at the 35th annual national forum of the American Helicopter Society, Washington, D.C., preprint no. 79-5, May 1979.

11. Logan, A.H., Prouty, R.W. and Clark, D.R., "Wind tunnel tests of large and small scale rotor hubs and pylons, volume 1-"data analysis and summary", USARTL-TR, to be published in 1980.

12. Clark, D.R., "The use of analytic tools in the design and development of rotorcraft", presented at the Fourth European Rotorcraft and Powered Lift Aircraft Forum, Stresa, Italy, September 1978.