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A METHOD OF PREDICTING FUSELAGE LOADS IN HOVER

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ABSTRACT

A computer program called DOWNLOAD has been developed as a result of recent interest in a more detailed analysis of fuselage downloads in hover. The fuselage separated flow is modelled using a vortex sheet representation. The rotor flow is generated externally to DOWNLOAD.

The vortex sheet model can predict the separated flow pressure distribution provided the separation point is known. Unfortunately, the poor behaviour of the vorticity vector in the separation region prevents an accurate prediction of the separation line. The causes of this poor behaviour merit further investigation.

DOWNLOAD has been applied to three simple fuselage shapes with a simple triangular representation of the rotor downwash. The predicted download values were in the lower region of the figures usually quoted as a percentage of thrust.

In view of the vortex sheet representation of the complete fuselage surface flow being physically reasonable, this model is probably the most suitable for simulating large separated flows. Further development and refinement of DOWNLOAD is therefore recommended. The work presented here is part of a research programme within the Aerodynamics Department of Westland Helicopters Limited and the University of Southampton into separated flow modelling and panel methods.

NOTATION

C_D	drag coefficient = drag force/Q/area
C_p	pressure coefficient = static pressure difference/Q
ΔH	total pressure difference or correction
P_o	total pressure
p	static pressure
ΔQ	dynamic pressure difference
q	velocity
R	rotor radius
S	distance along surface
$\underset{\sim}{U}$	external velocity vector

$\underset{\sim}{\gamma}$	vorticity vector
ρ	density
θ	angular displacement

1. INTRODUCTION

In recent years, considerable interest has been expressed in a more detailed analysis and prediction of the fuselage download for a hovering helicopter. Consequently, a program, called DOWNLOAD, has been developed in conjunction with the Aerodynamics Department at Westland Helicopters Limited and is based on the commonly used panel method.

DOWNLOAD computes the vorticity field which represents the fuselage surface and its associated separated wakes. The model is a potential flow representation of a real flow phenomenon and is only valid at large Reynolds numbers. Fortunately, most flows of interest to rotorcraft are supercritical.

The two main objectives of DOWNLOAD are: firstly, to predict the fuselage download in hover eventually taking account of the actual details of the varying fuselage cross-sectional shape; secondly to provide a tool for investigating the nature of the interaction of the rotor and fuselage flowfields. The first objective necessitates the generation of the rotor induced velocities on the fuselage surface which will enable the determination of the vorticity sheet representing the fuselage surface and hence the surface pressure distribution and the fuselage drag force or download. The velocities induced by the fuselage in the plane of the rotor can then be generated, if desired, such that a rotor thrust and downwash field can then be computed which allows for the presence of the fuselage. A hovering rotor performance program and DOWNLOAD can thus be run interactively. A method for calculating surface pressures within the rotor wake was also required. Because the position and direction of the attached flow wake is required as input, the program can, in principle, model forward flight regimes at any angle of attack as well as the hover.

The second objective requires that the fundamental laws of aerodynamics be strictly adhered to and thus all empiricism should be avoided. This objective has effectively determined both the type of separated flow model and panel adopted.

Results are presented for the preliminary development of the model and for the rotor flow in hover about simple cylindrical fuselages of three different cross-sections: circular; octagonal (or square with chamfered corners); and 'boat-shaped'. Because the assessment of the fuselage surface flow is only of concern, the rotor flow was represented by a simple triangular downwash field and was generated externally to the program.

2. INITIAL CONSIDERATIONS

The most important feature of DOWNLOAD had to be its capability of representing the various shear flows or wakes occurring by potential flow singularities. There are two shear flows of concern; the rotor downwash field; and the boundary layer separation from the fuselage surface caused by the rotor flow (Figure 1). The solution to both these problems lies in the determination of the difference in total pressure between a point within the rotor or separated flow and a point in the ambient or undisturbed freestream.

2.1 Rotor Flow

Taking the total pressure of the undisturbed freestream as the datum, then the rotor flow has a varying total pressure greater than that of the undisturbed freestream. One complication of any real shear flow such as that of the rotor is the fact that the static pressure will in general vary and differ to that of the ambient due to the presence of the Reynolds stresses. Fortunately, this difference is normally small and the error involved in assuming a constant static pressure throughout the whole flowfield excluding the fuselage will be insignificant.

The difference in total pressure between a point in the rotor flow and a point in the ambient reduces quite simply to a difference in dynamic pressure between the two points (lower left Figure 1). The information required to compute this dynamic pressure difference is readily available from wind tunnel experiments or from rotor performance programs. The difference in total pressure or total pressure correction is generated at each fuselage control point externally to DOWNLOAD along with the components of the rotor downwash which are required for the determination of the fuselage panel strengths.

2.2 Fuselage Separated Flow

Two important considerations determined the method of modelling the separated flow region. Firstly, the potential flow singularities had to be compatible with and suitable for adding to the attached potential flow method already modelled by a panel method. This existing attached flow model utilised a free shear layer representation of the wake modelled by a sheet of vorticity trailing downstream from the trailing edge along the stagnation streamline to infinity. It seemed quite natural, therefore, and consistent to trail this sheet of vorticity from the separation lines and out to infinity. In the attached flow, the sheet of vorticity must be double-sided to meet the fundamental aerodynamic requirement that the body must be closed and hence the sheet modelling the wake and the fuselage surface begins and ends at infinity. In the case of the separated flow, the sheet must begin at infinity, encompass the attached fuselage flow, return to infinity, return to encompass the separated fuselage flow and return once more to infinity, thus keeping the body closed. The vorticity sheet will, as in the attached flow case, trail along the stagnation streamlines from the separation line.

The second consideration follows from the previous section: because the separated flow region will have a total pressure which is lower than that of the attached fuselage flow, this total pressure difference must be able to be computed with ease. This is quite simply achieved by applying the laws of vortex motion (lower right Figure 1) and by making the assumptions that the static pressure within the separated flow region is constant and equal to the ambient and that the total pressure difference across the separated flow region is constant but will vary along the separation line. It is further assumed that the vorticity sheet is converted downstream with a velocity equal to that of the external velocity at separation. The strength of the free vorticity is determined from the bound vorticity vector at separation by subtracting out the vorticity equivalent to the external velocity.

One arbitrary decision required is the angle at which the vorticity sheet leaves the body surface. There is considerable debate as to whether the sheet should leave smoothly or at an angle which is usually the bisector of the angle the separated panel makes with the external flow direction (currently used by DOWNLOAD) and to whether some local curving of the sheet downstream of separation is required or not.

The advantage of the 'free shear layer' approach is that it is conveniently compatible with the panel method approach especially if doublet panels or a vortex lattice is employed. The disadvantage is the occurrence of a local stagnation line at the separation line which is a consequence of the implied application of a Kutta condition at the separation line.

2.3 Separation Criterion

Predicting separation with a simple boundary layer analysis has never been satisfactory. With the complicated flow which DOWNLOAD is attempting to model, a very detailed boundary layer representation incorporating both upstream and downstream influences at separation would be necessary. Many existing methods require large computational resources making them unsuitable for use with panel methods and their prediction of separation is not very reliable. Implicit in the assumption of any potential flow method is that the details of the boundary layer, except the flow displacement which changes the effective surface curvature, are, on the whole, irrelevant.

A very suitable criterion to predict separation is that formulated by Stratford[1]. Strictly speaking, this is an empirical relationship which is based on the significant parameters of the terms in the Navier Stokes equations: namely the first pressure gradient; a pressure ratio based on the peak suction; and the local Reynolds number. A second order correction based on the sign of the second pressure gradient was also included[1]. The criterion is two-dimensional and requires the tracing of the streamlines from just upstream of the separation point, or the trailing edge in attached flow, to the leading edge stagnation point. In order to do this, the surface velocity field must be known from which the above mentioned parameters as well as the distance from the leading edge stagnation point can be computed along the streamline. Stratford's Criterion is ideally suited to incorporation within a panel method program.

2.4 Boundary Layer Analysis

So far, the effect of the boundary layer has only been briefly mentioned in the previous section. The primary influence of the boundary layer will be the displacement of the external flow causing a change in the effective surface curvature which will reduce the peak suction. This in turn will reduce the pressure gradient to separation and change the vorticity value at separation. In terms of predicting the overall download, the boundary layer is of secondary importance. Skin friction drag is only a small percentage of the separation pressure drag when large separations occur.

A simple power law velocity profile was included in the preliminary validation of DOWNLOAD. This had the advantage that already all the required parameters were computed to determine the separation point so that little extra computational resources was required. The surface panels were displaced in accordance with the displacement thickness to the separation line and were then arbitrarily decreased linearly to zero at the trailing edge. This avoids any sudden change in curvature in the separated flow region which would have a major effect on the vorticity solution.

The displacement of the surface panels has the advantage of not introducing other potential flow singularities which cause two problems: firstly there may be a mismatch between the different potential flows; and secondly additional boundary conditions are necessary to solve the system of equations (usually the vorticity is arbitrarily forced to zero at separation). The disadvantage in this method is that the complete set of influence coefficients must be generated for each iteration of the program. However, a model based completely on a sheet of vorticity or doublet panels has much to commend it fundamentally plus the fact that the normal velocity boundary conditions at each panel control point are known and are sufficient to solve for the vorticity vector.

3. STRUCTURE OF DOWNLOAD

The outline of DOWNLOAD is illustrated in Figure 2 and has one iterative loop. This loop consists of the potential flow analysis, streamline tracing and the determination of the separation line. The program has converged when the streamwise position of the separation line does not change by more than 0.5%. The program can be run in many modes: a given number of iterations; prescribed separation; and attached flow only. During each iteration, the separation line becomes the new panel boundary for the panels immediately upstream and downstream of separation.

4. PRELIMINARY RESULTS AND DISCUSSION

The initial validation of DOWNLOAD centred on predicting the flow on the surface of a two-dimensional circular cylinder at a Reynolds number (based on diameter and uniform freestream) of 8×10^6 and correlating the results with those from experiment[2]. Only 10 streamwise panels were employed.

4.1 No Iteration

Applying Stratford's Criterion to the attached flow solution produced a separation angle of 128°. The base pressure was positive but very small. By placing the separation point at 96% of that predicted (i.e. at 123°) the pressure distribution and drag coefficient illustrated in Figure 3 were obtained. The suction peak is overpredicted. The base pressure is overpredicted but offsets the overpredicted suction peak within the integration to give a drag coefficient slightly lower than that quoted in (2). The pressure distribution near separation exhibits a maximum turning point. The value of this maximum depends very much on the proximity of the control point either immediately upstream or downstream of separation. It is a consequence of the local stagnation point occurring in the potential flow at separation mentioned in Section 2.2. Indeed, on closer inspection the vorticity tends to zero at the separation point and the pressure distribution is discontinuous. The combined effect of the overpredicted suction peak and the locally occurring stagnation point is to cause the pressure gradient immediately upstream of separation to be larger than that of the real flow.

The 96% factor mentioned in the previous paragraph is probably just within the experimental error of the original experiment (empirical factor quoted to two decimal places whereas the numerical solution probably requires an accuracy to four decimal places). This is indicative of the suitability of Stratford's Criterion for predicting accurately the separation point.

The results presented in Figure 3 were felt to be sufficiently encouraging that other cross-sectional shapes were tested. An octagonal (or square section with chamfered corners) shape (Figure 4) and a 'boat-shape' (Figure 5) were chosen.

No experimental data for the supercritical flow about square sections or square 'with rounded corners' sections could be found and only a very rough estimate of the drag coefficient was able to be obtained from (2) (Figure 4). Separation was predicted at about midway between cd: the chamfered corner delaying separation to beyond corner c, the separation point for a square section. The large suction peak at separation is probably overpredicted and results in part from the ill-conditioning of the influence coefficient matrix (see next section).

The 'boat-shaped' section (Figure 5) was an attempt at filling in the base suction region and reducing the drag coefficient compared to Figure 4. The closure angle was much too large and the flow separated from the corner c as may be expected from the real flow situation and again illustrating the capabilities of Stratford's Criterion in predicting separation accurately. The suction peak at separation is again apparent.

This seemed an appropriate stage to assess the effect of the inclusion of the boundary layer analysis on the solution for the circular cylinder. As can be seen from the pressure distribution in Figure 6, the displacement of the surface panels had minimal effect on the peak suction, increased the base pressure giving a lower drag force and removed the maximum turning point in the pressure distribution at separation.

The boundary layer displacement was then arbitrarily increased by a factor of 2 and 3 to see whether the peak suction could be reduced or not. The separation point was fixed at 123°. Figure 6 illustrates that for a factor of 3, the peak suction is reduced to a value that lies within the range of data of (2). At the same time, the base pressure is increased and the prescribed separation point is now too far downstream. The reduction in suction peak combined with the apparent removal of the maximum turning point at separation provides an improved pressure gradient value upstream of separation.

Obviously, the incorporation of a boundary layer analysis is desirable and should improve the behaviour and prediction of the model. The problem is choosing a suitable and compatible boundary layer representation for use with a panel method and which is cheap on computational resources. This is currently being pursued.

4.2 Iterative Scheme

Because Stratford's Criterion depends upon the local pressure gradient and Reynolds number, an iterative scheme must be employed to determine the solution to the vorticity sheet. The separation point must move upstream as a consequence of the fact that the pressure gradient will be discontinuous in the potential flow model at separation. In the real flow, it is meaningless to trace streamlines in the separated flow region. Unfortunately, there are many problems arising which prevent convergence to a fine tolerance (certainly to no less than about a 5% difference in the streamwise position of the separation point).

The first difficulty is that associated with the local stagnation point at separation occurring in the potential flow model. Because the vorticity tends to zero, large crossflows are generated immediately upstream of separation causing starting problems for the streamline tracing algorithm. Normally streamline tracing starts at the control point immediately upstream of separation to avoid this difficulty. Depending on the position of the separation line in relation to the original panel geometry determines the size of this panel and hence distance of the control point upstream of the separation line (upper half Figure 7). In addition to this, the pressure gradient at separation will be greater than that of the real flow as mentioned in 4.1.

Attempts to obtain a fine tolerance on convergence are also frustrated by the very ill-conditioned influence coefficient matrix. The computation of a new panel geometry at separation (upper half Figure 7) can lead to a very small panel and a very large panel either side of separation being created. This makes the influence coefficient matrix even more ill-conditioned and the vorticity solution becomes badly behaved (typically a minimum turning point in the pressure distribution of the same order of magnitude as the peak suction appears prior to separation). Attempts to obtain an accurate solution even on a high precision ICL 2970 using the most sophisticated algorithms for solving ill-conditioned matrices have failed. The only method of obtaining an accurate solution is to perform residual iteration using a fast algorithm such as an orthogonalisation technique which, in itself, is inaccurate because it has no control over the round off errors due to the very nature of this type of algorithm. One consequence of residual iteration is the need to store, or to regenerate each iteration, the influence coefficient matrix. On real machines and small virtual machines, storage will require a spare alien hard disc. For 200 panels, each iteration takes about 44 CPU sec on the ICL 2970 and convergence, using an accelerator, is achieved to within 0.5% within 4 iterations. This problem is currently being investigated.

The lengthwise vorticity component at separation is also badly behaved and can give magnitudes many times greater than that of the streamwise vorticity component anywhere on the surface. Whether this is connected with the above mentioned ill-conditioning problem is not known yet.

The question of at which angle the separated sheet should leave the surface requires further investigation. The magnitude of the maximum turning point in the pressure distribution at separation may also depend on the angle at which or smoothness with which the separated sheet leaves the surface (Figure 7 lower half). This smoothness may be aided by an appropriate boundary layer analysis as discussed in the previous section.

The final solution depends on the correct prediction of separation. The base pressure is very sensitive to the position of the separation point. The base pressure calculated by the model correlates well with experiment when the separation point is known. Stratford's Criterion seems to be very capable of predicting separation accurately but depends on the vorticity, pressure and pressure gradient calculated by the potential flow model. The model itself is physically very reasonable but obviously needs further development in the region prior to separation.

5. INCORPORATION OF ROTOR DOWNWASH

The main aim of the development of DOWNWASH so far has concentrated on the solution to the fuselage surface flow. The rotor downwash field and its associated total pressure difference variation can either be experimentally or numerically generated data and is alien to DOWNLOAD.

The results discussed in the following sections were obtained using a simple triangular rotor downwash for two disc loadings: 5 lb/ft^2 and 10 lb/ft^2. Three fuselage sections were investigated (Figure 8): circular; octagonal; and 'boat-shaped'. Because the external velocity field is not uniform, the flow at any one lengthwise station is not characteristic of the overall flow about the fuselage and it is not possible to present any one meaningful pressure distribution typifying the flow. Consequently attention is focussed on the separation line and the overall download value.

Figure 9 illustrates the separation line and download value for the circular section. The flow at the separation point furthest upstream at a disc loading of 5 lb/ft^2 is supercritical so that the model is valid at this point. The line of separation reflects the form of the downwash distribution i.e. separation occurs furthest downstream where the local Reynolds number is greatest in the rotor tip flow. The overall download predicted is 131 lbs at a disc loading of 5 lb/ft^2 and, for a typical rotor thrust associated with this size of fuselage, this represents about .5 to .7% of the thrust. Similarly, for a disc loading of 10 lb/ft^2, the download is 261 lbs and represents about 1.0-1.3% of the thrust. These figures should be regarded as minima since the circular cylinder probably represents the ideal fuselage shape.

A typical helicopter fuselage drag coefficient in uniform flow is about 1.8 times that of the circular cylinder and applying this factor brings the quoted values up to about 1-1.2% and 2-2.5% respectively. This latter value is in approximate agreement with that obtained from a fuselage element approach[3]. Figures 10 and 11 show the corresponding results for the octagonal and 'boat-shaped' section respectively. The download at a disc loading of 5 lb/ft^2 for the octagonal section was computed to be 306 lbs and for the 'boat-shaped' section 446 lbs or about 1.2-1.5% and 1.8-2.2% of thrust. The download at a disc loading of 10 lb/ft^2 for the octagonal section was computed to be 652 lbs and for the 'boat-shaped' section 947 lbs or 2.6-3.3% and 3.8-4.7% of rotor thrust.

The downloads predicted are of the correct magnitude but on the low side. Overall, it is felt that these download values are sufficiently encouraging to warrant further development and refinement of DOWNLOAD.

6. FUTURE DEVELOPMENT

In addition to the various numerical studies specifically mentioned in previous sections, consideration is being given to a higher order representation of the doublet panels and a more direct solution to the integral equations. The present method of solution fits a cubic spline to the panel strengths and, consequently, the vorticity is known only at each control point. Much computational effort is expended in generating the vorticity field by interpolation in, for instance, the streamline tracing routine. A direct solution to the vorticity is desirable. Unfortunately, for the same number of panels, the influence coefficient matrix is much larger and introduces extra problems in addition to the ill-conditioning already mentioned when inverting the matrix. The method of (4) is currently being assessed on the basis of whether a better overall behaved solution for little extra computational resources can be achieved.

A carefully designed experimental programme to suit the software is required to validate DOWNLOAD. In particular, some simple rotor/fuselage wind tunnel tests to provide information on the nature of the rotor/fuselage interaction and to provide data for correlation with the results from DOWNLOAD are also needed.

CONCLUSIONS

The vortex sheet representation of separated flow is a reasonable model and can predict the base pressures with reasonable accuracy provided the separation point is known.

The accurate prediction of separation is prevented by several factors which cause the vorticity solution to be badly behaved at separation. Alleviation of these problems should enable a reasonably accurate separation line to be computed using Stratford's Criterion. In this context, a simple and fast boundary layer displacement calculation is probably desirable.

The overall downloads computed for simple fuselage shapes are in the lower region of those figures usually quoted as a percentage of thrust.

The vortex sheet representation of the complete fuselage surface flow is physically reasonable and probably the most suitable for simulating the large separated flows which occur on fuselage surfaces. Further development and refinement of DOWNLOAD is recommended.

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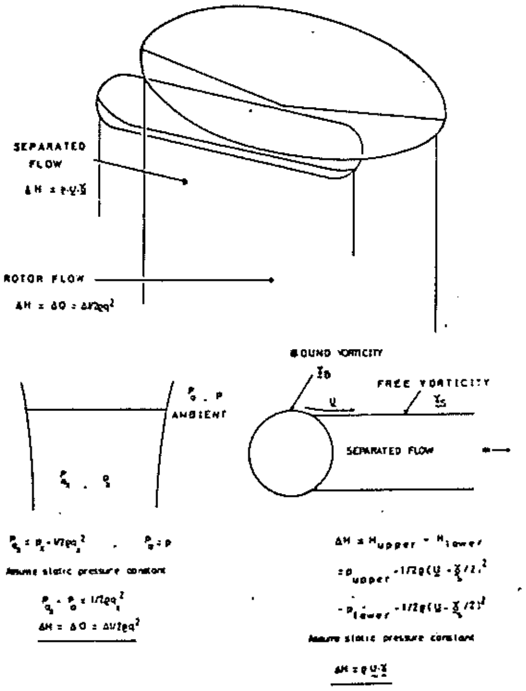


FIGURE 1

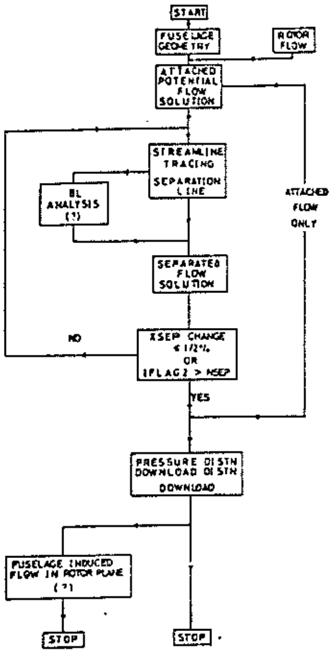


FIGURE 2

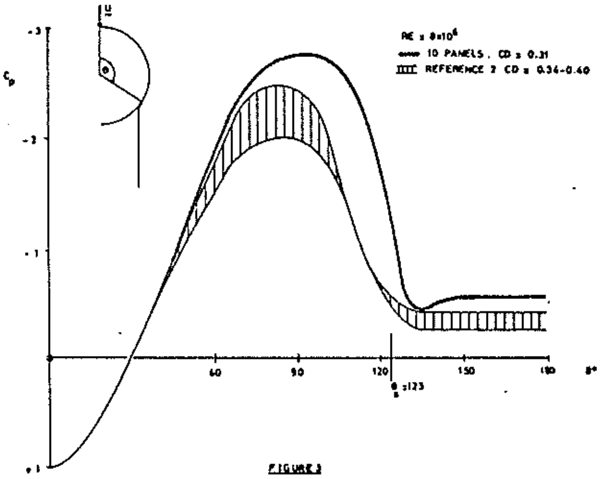


FIGURE 3

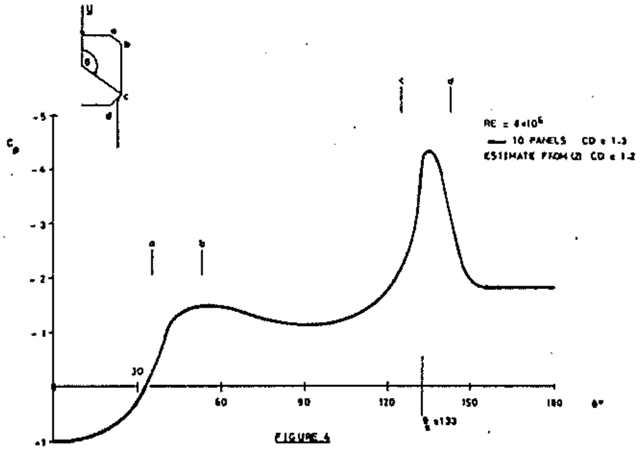


FIGURE 4

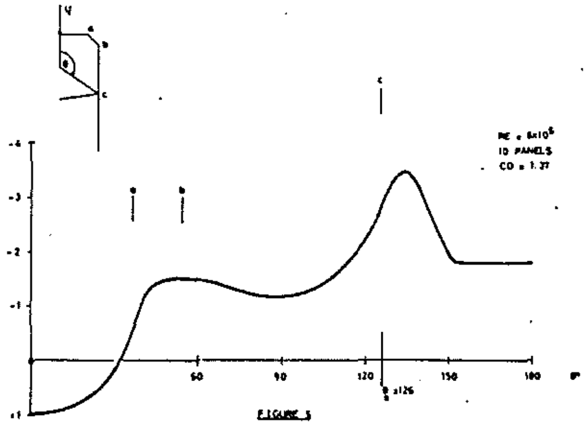


FIGURE 5

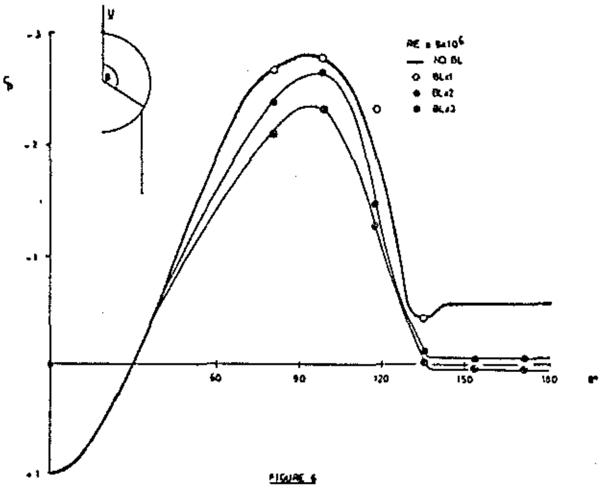


FIGURE 6

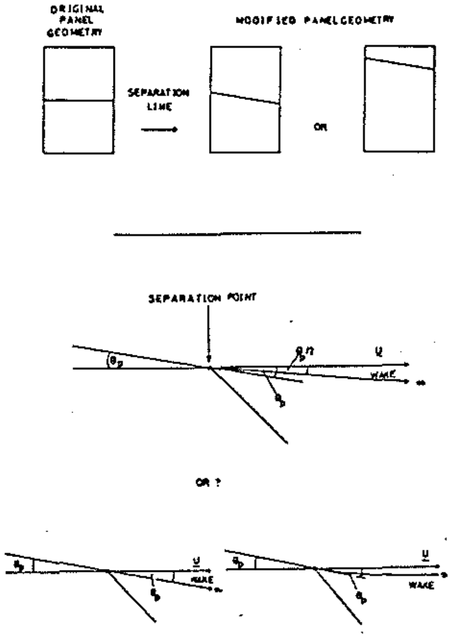
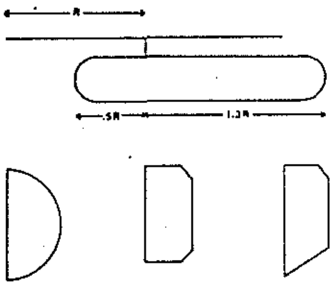
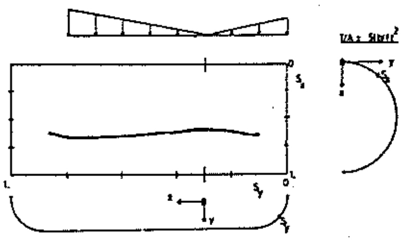


FIGURE 7

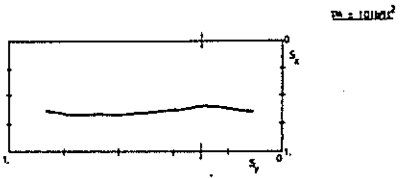


CROSS SECTIONAL AREA = 0.062R²

FIGURE 8

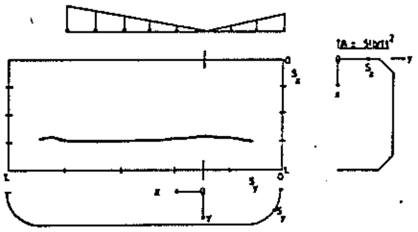


DOWNLOAD = 131 lbs → 0.5-0.7% THRUST

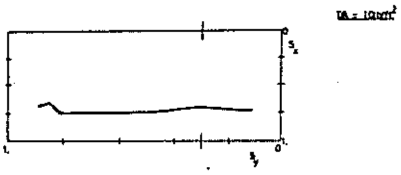


DOWNLOAD = 261 lbs → 1-1.3% THRUST

FIGURE 9

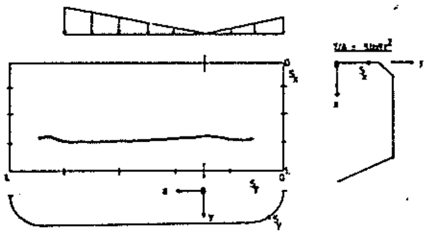


DOWNLOAD = 306 lbs → 1.2-1.5% THRUST

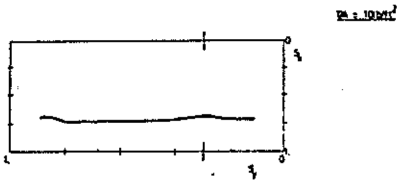


DOWNLOAD = 652 lbs → 2.6-3.3% THRUST

FIGURE 10



DOWNLOAD = 446 lbs → 1.8-2.2% THRUST



DOWNLOAD = 947 lbs → 3.8-4.7% THRUST

FIGURE 11