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# THE USE OF ANALYTIC TOOLS IN THE DESIGN AND DEVELOPMENT OF ROTORCRAFT

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THE USE OF ANALYTIC TOOLS IN THE DESIGN AND DEVELOPMENT OF ROTORCRAFT*

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SUMMARY

Recent developments in the ability to model helicopter configurations using involved potential flow computer codes are reviewed. Advances in complexity from the basic potential flow solution to solutions with full streamline tracing and viscous flow modeling capability are outlined with particular attention being given to the modeling of separated flow in the base region. The use of large, complex computer programs in a development situation is examined and examples are given of how their reliability and responsiveness may be improved through the use of interactive techniques.

## 1. Introduction

The rotorcraft presently going into service in both the military and civilian markets represent the first real contribution of advanced analytic tools to the design and development process. In these designs--the UH-60A, the YAH-64A, the Sikorsky S-76 and the Bell 222 are typical examples--the full potential of the digital computer has been exploited to support the "cut and try" empirical approach that has been standard since the early days of rotary wing flight. This successful application has been made possible in part by advances in the computing machines themselves, but this alone would not have been enough. It has taken an improved understanding of the basic flow fields (the result of much experimental work) together with the mathematical tools which the new computers make practical, and managements prepared to follow the guidance provided by the output from the programs.

The developing understanding of the rotor flow field, the analytical tools that have been developed to describe them and the results of these analyses have been well documented by others. The work of Harris et al.(1) provides a very good summary of the growth of the sophistication of the analyses from the very simple momentum approaches to the more refined wake modeling methods

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coming available in the late '60's. The more recent work of Landgrebe et al.[2] brings the earlier study up to date and adds the perspective of the design experience that went into today's new aircraft. Of particular note in the context of the present paper is the discussion in Reference 2 of the refinement, one might say streamlining, of the early "free" or "distorted" wake hover performance programs[3,4] where the wake trajectories are calculated using time consuming iterative procedures, the introduction of "prescribed" wake techniques and their evolution into the Circulation Coupled Hover Analysis Program. This provides a good example of the evolution of a program from a research tool, with long cycle times and involved input and output, through an interim program which could be used for design and development work under controlled conditions, to an almost "hands-off" production program. In this, the rigor of the research solution has been preserved while at the same time offering short cycle times. This process has provided management with a very responsive program which is economical to operate and, as Reference 2 indicates, one that can be used with confidence in the results.

Prediction of rotor performance in forward flight is less sensitive to the details of blade/vortex interaction and, consequently, the use of momentum derived inflow continues to be fairly standard for most flight regimes. However, for conditions of high loading, low shaft angles or high advance ratios, all becoming more relevant for today's rotorcraft, wake modeling must provide the basis for the inflow prediction. Fortunately, a simple skewed helical wake provides an adequate model for most performance calculations, but for loads work and especially rotor dynamics, the higher harmonics of inflow must be predicted. This, presently, involves the use of a distorted wake program to calculate the wake development. In this case only the tip vortex has to be calculated (in hover the full wake must be defined) but the calculation is still very involved and time consuming. Hope exists that the wake beneath a rotor in forward flight may be generalized and prescribed in much the same way as it is in hover. The work of Landgrebe and Egolf[5] lays the groundwork for this. Reference 5 describes an involved rotorcraft wake analysis program which would, ultimately, allow for the interaction of all the components of the helicopter in both hover and forward flight. For this to be a practical design tool, wake generalization is essential.

Discussion so far has been concentrated around the rotor system ignoring the other basic element of the system, the fuselage. In fact, until recently, the aerodynamics of the fuselage have been a relatively low priority item in the design process. On military helicopters, the fuselage shape has been designed more by function rather than by any requirement for performance, and for commercial aircraft, esthetics or market appeal has been more important than any aerodynamic requirement. When flight speeds were low or where there was no requirement to perform to challenging specifications against power plant output limits, this practice was tolerable. However, with today's aircraft routinely flying at speeds in excess of 145 knots, airframe drag becomes a dominant consideration and design for low drag vital. When airframe aerodynamics were considered, they were normally handbook designs, strongly based on Hoerner[6], and relying heavily on wind tunnel verification. Even here, a wind tunnel result was no guarantee of a correct answer, since an eventual flight test invariably revealed values, especially where drag is concerned, much larger than those expected. Design by wind tunnel test is not, however, very responsive, and it is undeniably very expensive if a range of configuration options is to be explored. However, in the absence of any adequate analysis, it is the only choice a design team had.

Until very recently, no analysis was available that would adequately represent the airframe of a helicopter and permit calculation of the pitching moment, lift and especially the drag of the whole configuration, or would allow the designer to evaluate the effect of changes in shape on the system forces and moments. Codes which describe the potential flow around general lifting or non-lifting shapes have been available for some time; the work of Hess et al. at McDonnel-Douglas[7,8], the program developed at NSRDC by Dawson et al.[9], the work of the Boeing group[10], and the work of Woodward et al.[11] being typical. For the attached, well behaved flow around slender aircraft shapes, a potential flow code can give quite adequate correlation of lift and pitching moment. However, for an accurate prediction of drag, not only must the attached, viscous flow be represented, but the regions of separated flow have to be identified and modeled.

The first serious attempt to employ potential flow codes on rotorcraft design (as opposed to analysis) was in the design of the inlet for the "Fan in Fin" antitorque system used on the Sikorsky S-67[12,13]. The program used in this application was a modification of the basic Hess code, adapted by NASA Lewis[14] for VSTOL inlet studies. Sikorsky went on from this to develop a full wing and body modeling program, again based on the Hess approach, and used it as the basis for a semi-empirical prediction of rotor head drag[15]. An interesting feature of the Sikorsky program was that an attempt was made to overcome the major drawback in the use of these codes, the preparation of the large amounts of input data describing the shape. This was done using a special pre-processing program which (using low volume generalized input data) developed the detailed paneling description needed by the aerodynamics program. This work is described in Reference 16.

Despite the success of these early programs, they all had one serious shortcoming for helicopter work. That was that although some of them could model the viscous attached flow, none could adequately represent the regions of separated flow, and consequently, the drag of the configurations could not be accurately determined. In this present paper, some of the steps towards filling that gap and providing a drag prediction capability are outlined.

Other reasons for the delay in the acceptance of the involved codes (whether of the rotor or the airframe, the aerodynamics or the dynamics)--and these remarks now apply equally well to any complicated computer model--are the cost of their development, or implementation if it is someone else's code; the length of the debug cycle; their poor response time, mainly due to the large amounts of input that are required; the opportunities for error in transcription, coding and key punching; and, finally, the sometimes overwhelming volumes of output. Most of the output data is rarely if ever used, but it always seems to be shelved "just in case it is needed", creating storage space and data retrieval problems. Of the problems outlined above, the poor response time and the high costs are what have most soured managements on the use of involved analytic tools. This paper will present one approach to the problem and show how, with simple pre- and post-processing programs and the intelligent use of interactive computing techniques, the number crunchers, which are some managements' nightmares, can be turned into responsive, productive programs.

## 2. Recent Developments in Helicopter Configuration Modeling

Because of the nature of the flow field around helicopter fuselages, especially when the influence of the rotor system is added, it is unlikely that practical, tractable, analytical models will be used on a stand-alone basis as a complete replacement for wind tunnel testing. They can, however, and are being used in a supporting role where their flexibility allows a large number of potential candidate configurations to be analysed and the results used to guide the selection of those most likely to succeed in a subsequent test. They can also be used as a guide to the interpretation of flight airloads data, analysing problem conditions and permitting the exploration of alternate solutions before committing to more flight testing.

Before discussing the details of the latest developments, it is appropriate to outline the basic principles that the various approaches to configuration modeling have in common. In all of the methods, the configuration, whether lifting or non-lifting, slender or bluff, is first descretized by being broken down into a series of flat (or almost flat) panels. These panels are then represented in the analysis by some singularity of, at this stage, unknown strength. Various types of singularity can be used, but source or vortex-lattice singularities are most common. The boundary condition of zero flow through the surface of the panels (or some non-zero amount prescribed to account for inlet and exhaust flow) is applied, and with the influence of each singularity at each control point known from the geometry of the panel model, a simple matrix equation for the singularity strengths is obtained.

$$[A_{ij}]\{\sigma_j\} = -\{R_i\} \quad (1)$$

Here $A_{ij}$ is a matrix of the coefficients giving the influence of each panel on every other panel, $\sigma_j$ represents the unknown strengths of the singularities, and $R_i$ the boundary conditions. Determination of the strength of the singularities and ultimately the flow about the body begins with the inversion of the influence coefficient matrix. It would be inappropriate here to go into detail on the mechanics of the solution, since the subject is considered in great detail in the original papers.

The method currently in use at Analytical Methods (AMI) was derived from a code developed by Krauss and Sacher(17), itself a derivative of a program developed by Rubbert and Saaris which in turn stems from the original work of Hess and Smith. The program developed at AMI (designated WBAERO for Wing and Body AEROdynamics program) under contract to the U.S. Army is documented in Reference 18, and uses source singularities for the body. In its earlier versions, it combined source and vortex singularities to form the lifting elements (for the wing, source panels were placed on the wing outer surface and the vortex-lattice placed along the camber line). The basic model, in schematic form, is outlined in Figure 1. WBAERO was used with considerable success in the prediction of loads on aircraft configurations where the flow is attached, and is, in fact, still in wide use in the fixed wing side of the industry.

The key to the prediction of rotorcraft forces and moments is the identification and modeling of regions of separated flow on the characteristically bluff shapes. While the early version of the program, using a modification to the Townsend criterion, predicted separation location adequately, the method used to model the separated flow region was less successful. Figure 2 shows how the separated flow was modeled.

The attached boundary layer on the body displaces the external, potential flow away from the original surface. In other weak interaction viscous/potential flow iteration procedures--Reference 10 is typical--the displacement thickness is added to the body shape and the configuration reconstructed to include the effect of the boundary layer in subsequent iterations. This was considered to be a wasteful approach since the most time consuming part of the procedure, the calculation of the influence of each panel on every other, had to be repeated at every step. Instead, the method adopted by AMI was to treat the presence of the boundary layer by changing the boundary conditions at the surface. A slight outflow was added, effectively pushing the external flow away; the strength of the extra source term was determined directly from the rate of growth of the boundary layer along the surface. By this means the effect of changes in the viscous layer are readily, and from a computational point of view, economically accommodated on successive iterations without having to recalculate influence coefficients.

The same approach was carried over to the modeling of the separated flow.

Unfortunately, unlike the boundary layer solution discussed above, no clear cut rules exist for determining how much effective outflow was needed to displace the stream surface dividing potential and separated flow regions. To get around this, for bluff bodies, the assumption was made that the velocity normal to the surface within the separated flow region was equal to the component of the free stream velocity normal to the surface. A mutually consistent, iterated potential flow/separated flow solution is an intimidating task, and in the interests of producing a working program for helicopter configurations with sharp, aft facing, changes in cross-section, this was deemed to be acceptable, and was at any rate consistent with the outflow assumptions. The success of this approach can be judged from the data presented in the original report[18] and from the example presented in Figure 3 showing a comparison with pressures measured on a model of the BO-105.

Despite the relative success of the method, two major drawbacks were present. They were the empiricisms regarding the separation location and, because of the imposed outflow in the separation region, the inability to predict surface pressures beyond the separation line. This second being the more serious, since without accurate base pressures, a prediction of drag was still out of reach. To overcome this problem, a new model of the separated flow was developed.

At this time, work was also in progress at AMI on a two-dimensional model of flow separation in an investigation of airfoil post stall behavior. For the airfoil problem, a flow model was developed which permitted calculation of the pressures in the separated flow region. The model discussed in detail in Reference 19 is shown in Figure 4. The airfoil is modeled using vorticity panels with the vorticity varying linearly along each panel. The separated wakes from the upper and lower surface separation points is also modeled using vortex panels. In the solution, an initial separation position and wake shape is assumed. The assumption of an initial separation region is not necessary, but helps to reduce computation time. At the point of separation, all the surface vorticity is assumed to go into the vortex sheets which separate the regions in which potential flow is assumed. The separation location, the wake trajectory, the surface singularity strengths, and hence the pressures even in the separated flow region, are calculated iteratively. Apart from the initial prescription of the wake shape, the analysis is completely free from empiricism. This program, designated CLMAX, is in wide use and its success can be judged from the correlation shown in Figure 5.

This type of solution procedure was carried over into three dimensions, and its use on helicopter configurations described in Reference 20. For simplicity, constant strength source panels were retained, and it was found that for three-dimensional shapes, wake relaxation was not required. For this analysis, a full three-dimensional boundary layer calculation was carried out along streamlines traced using the approach suggested by Dawson et al. in Reference 9. The key to tracing a streamline across a body is in being able to identify the neighboring panels at any time so that streamwise and crosswise derivatives can be determined. To do this while still retaining a fairly simple code, a constraint was placed on paneling models. This was that all along the body each column of panels had to have the same number of rows. This assumption of a regular panel grid resulted in considerable reduction of streamline computation effort, but made the task of paneling the configuration somewhat more difficult. The user being restricted to simple, regular bodies, or if complex bodies were required, to inefficient panel densities in some regions of the body.

Despite this, it was now possible, because of the new model of the separated flow region to obtain meaningful pressures all over the body, and a typical output plot is shown in Figure 7. Unfortunately, also evident in the figure is a new problem. Close to the separation point, there exists a sharp excursion in the calculated data which is absent in the experimental data. The reason for the anomaly lies in the type of singularity chosen to model the body. In this case, carrying over from the earlier model, constant source panels were used. Because the separated flow region is constrained to start along the edges of panels, a mis-match exists between potential and viscous flows and, as a result, the pressure spike is produced. The second generation program then has two problem areas: the restrictive, regular paneling scheme and the separation constraint implicit in the use on constant source panels. These are underlined in the schematic in Figure 7.

Both these problems are overcome in the third generation version of the program now nearing completion. The way this is done is outlined in Figure 8. In the new program, designated Program DRAG, the constant source panels have been replaced by vorticity panels, where the vorticity is varied from front to rear, allowing the separation line to cut across panels. The streamline tracing problems have been overcome by building the body up with patches of panels, the regular structure being retained within each patch. The only additional data required at input being the patch joint information describing the neighbors. A typical body panelled using this scheme is shown in Figure 9. Documentation on this version of the program is in preparation for release later this year. Development of all three versions of the program has been supported by the U.S. Army, AMRDL (now AVRADCOM) at Ft. Eustis, Virginia.

An interim version of the program, with the improved streamline capability but still with body source panels, has been used by AMI in several development studies over the past year. One of these has been of special interest since it has exercised the program in a way typical of that found in many engineering departments. AMI has been working under subcontract to Hughes Helicopters on a study funded by AVRADCOM, Ft. Eustis, to carry out an analysis of two helicopters, one a typical utility transport aircraft, the other a typical attack helicopter. After analysing the baseline shapes, three modifications of increasing scope are to be designed and tested. The program involves work on both pylon and hub. The analysis was used to explore a range of potential shapes before committing to hardware. This is an essential feature when, as in this case, some of the models to be tested are large (80% full scale). Figures 10 and 11 show the baseline configurations and Figure 12 the attack helicopter mounted on the ground plane for the large scale wind tunnel test. A feature of added interest in Figure 12 is the analytical model developed to represent the hub and shaft. Because of the complexity of the hub, a detailed representation is impractical. To get around this, a model was developed which, regulating the inflow and outflow from the forward and aft facing panels, simulates the drag of the hub as an effective momentum deficit. For studies of the body aerodynamics, the drag of the hub and shaft is assumed known as a function of frontal area. Reference 15 provides a useful summary of this type of data. Not shown in Figure 12 is the representation of the efflux from the power plants and the other exhaust and inlet flows which can be modeled with the program. A wind tunnel, any shape, can also be modeled by the program if it is required.

Another study currently under way at AMI involves the X-Wing helicopter/aircraft. The aircraft, currently under development by Lockheed Aircraft for the U.S. Navy, has been wind tunnel tested and the data on an early configuration indicated regions of separated flow around the hub/pylon/wing root joint. This could lead to drag rise problems when the aircraft reaches its 300 kt design goal and AMI has been using the programs described above to explore ways of reducing the extent of the separated flow. Figure 13 shows the aircraft in the wings-stopped configuration and Figure 14 presents some typical data. This figure is interesting in that it gives a good example of how rotorhead fairings do not necessarily solve all of a helicopter's drag problems. As the flow approaches the rotor head, it is decelerated. This is followed by a rapid and very marked acceleration over the fairing followed by a strong deceleration. This deceleration and its accompanying unfavorable pressure gradient are more than the boundary layer can tolerate, and separation occurs. On a more conventional helicopter with a more prominent rotor head, these problems are intensified.

## 3. The Use of Involved Analytic Tools in Helicopter Design and Development

The programs described in the section above dealt with fuselage aerodynamics using finite-element models of the airframe. As such, they would seem to have little in common with the rotor aerodynamics or dynamics programs that are available or the structural dynamics methods now in widespread use in the industry, but this is not true. They are all large numerical solutions to involved mathematical models, all demanding most of the capacity of the computing machines currently available, and all requiring long development and debug times (or if the code is obtained from some government agency, familiarization). This involves a considerable investment on the part of a management wanting to upgrade its capability. It is not surprising then when managements are reluctant to commit to a particular code having been oversold in the past on programs which in critical situations have failed to be responsive. The most common problem is a data deck that is too large, involving long data assembly times, and opening up the possibility of key punch errors, perhaps the most frequent cause of computer program crashes. At the other end of the run, so much data is generated, on page after page of output, that the process of producing something in a format meaningful to the decision makers often takes not hours but days. An unacceptable situation in the press of a competitive development flight test program where quick decisions are a must.

Figure 15 is a schematic of a program which falls into this category, and again the example is a fuselage aerodynamics code, but it could just as well be NASTRAN, Normal Modes or C-81. Aside from the usual data transcription errors and key punch errors, all of which force a "return to go" situation, there is the problem in logistics. In the typical medium sized company, the flow diagram in Figure 15 involves as many as 10 hand-offs of information. The engineer transcribes (codes) the data and hands it to a key punch operator who, sometime later, hands back cards. The engineer then assembles the deck and hands it to the computer operator, and so on. By the time the data, in intelligible form, is handed to a decision maker, the problem may be past solution. The scenario above can be even more involved in a large organization where an internal delivery service is involved and at each hand-off, especially where punched cards are involved, the risk of a dropped deck increases. For low volume programs, whose input/output volumes are small, this type of arrangement may be acceptable, but for large scale problem solving, it is completely out of the question. What in a research situation may be tolerable cannot hope to succeed where there is the pressure of a production or development problem.

Happily, there is a solution to the dilemma, and that lies in the use of interactive computing techniques, particularly in the preprocessing of data and in the post run analysis of the output. The latest generation of machines offer the capability of interactive manipulation of mass storage data in one part of the system, batch operation for the problem solving, and back to interactive for the data analysis. This final phase is particularly rewarding if interactive graphics is available.

Figure 16 is a schematic of the system set up by AMI to handle large configuration modeling problems. The procedure, first outlined in Reference 21, is split into three phases, the common element in each case being the interactive terminal. The raw data, aircraft cross-section drawings, are digitized on line using a digitizer board and the input data deck, now on a computer file, is assembled. This file is then read by a data preview program which has identical read commands to the main program, catching punch errors in a short, responsive (on-line) program. At the same time, the input data may be plotted. Together these take care of the punch and data transcription errors which used to be the major cause of crashes in the main program. With this data deck/file checked, the operator can then submit his batch job directly to the computer from the terminal; no punched cards to be dropped. After the batch job is complete, he simply reactivates the terminal and begins interrogating his output file. With a properly constructed post processing program he has the flexibility to plot almost anything against anything else, and can go straight to the key items of information and produce data in graphic form. For rotor problems where there are huge volumes of data, especially in forward flight, this capability is priceless. With the engineer dealing directly with the computer, his productivity has gone up tremendously, and the system response time (here the system is the problem solving system, not the computer itself) has improved by at least an order of magnitude.

Figures 17 through 22 are taken from an operating session using the pre- and post-processing interactive programs that have been developed for the WBAERO family of programs and are copies made direct from the screen of the computer terminal. In order to arrive at the display given in Figure 17, the data deck must have been successfully read. Failure to read the deck would have produced a diagnostic which would indicate the line number of the error. Having reached this stage, the operator has the option of plotting all or selected parts of his input data. This permits him to verify the integrity of the input profiles. In the present case of building a mathematical model of a geometric shape, the end profiles of adjoining sections must match. Comparison of these profiles is provided as a special capability in the example shown. In the example of Figure 17, the operator chose to plot all the input sections and the plot, done on line, is shown in the next figure, Figure 18. A badly transcribed point would have shown up clearly in this view. Having verified his input, the operator then submits the program, as a batch job, from the terminal and goes back to some other task. Later, following execution of the job, he logs on and prepares to review his output.

The terminal display reproduced in Figure 19 gives the options that he has available when producing graphic output. From the WBAERO family of programs (this includes Program DRAG), he can plot data from either the Geometry, Aerodynamics, Streamline or Boundary Layer segments of the output. Examples of plots from the geometry package were given in Figures 10 through 13. Here, the operator can choose his view point at will, is able to plot all or part of the body and can include or delete hidden lines. Knowing in this case what the shape looks like, the operator has chosen the Aerodynamics routine and is provided with another set of options, Figure 20. He has complete freedom to plot any of the available parameters against any other and for a three-dimensional problem such as a helicopter fuselage, he can choose to plot any of his dependent variables, pressure and local velocity against either axis at a selected station, buttline or waterline cut. With this capability, he can very quickly determine the effect of configuration changes without the labor of plotting and cross-plotting by hand. Contour plots are also available, a feature that is very costly, in terms of effort, using manual plotting. Figure 21 provides an example of the type of plot that is available from the aerodynamics routine. In the streamline and boundary layer options, similar choices are available. The user can plot any one, a number of, or all streamlines and can plot any of the streamline parameters against each other. This is particularly useful in studies of separated flows where boundary layer parameters, before separation, can be plotted against the flow variables or the local surface curvatures, and based on this information, steps taken to modify the surface and prevent the separation. Examples of plots from the streamline option are given in Figure 22.

Even if the user does not desire graphic output, he has the capability to enter the output file produced by his batch job and extract just the data that he requires. The mass storage system of the computer allows him to store large volumes of data for later retrieval through his terminal without the awkward and space consuming stacks of printed output.

The system described above is operational on the CDC cyber network with the graphics capability supplied by Tektronix software at a Tektronix 4000 series terminal. Similar capabilities should be possible using other operating systems.

## 4. Conclusions and Recommendations

With the refinement of the WBAERO configuration modeling program into the DRAG version, the involved potential flow aerodyamics codes have reached the level of development where they can join the sophisticated rotor aerodynamics, dynamics and the airframe programs in a very detailed description of the elements of the helicopter. The application of these programs is already widespread, but before they can be used effectively in a development or production, as opposed to a research environment, their responsiveness and reliability has to be improved. This can only come about through the use of interactive computing techniques, the use of on-line computer graphics and exploitation of the computer's mass-storage capability. One such system has been outlined here. Certainly, before the next round of problems to be solved, those involving the interaction of the elements of the system can be attacked, interactive techniques will have to be exploited on a larger scale. This is especially true of the Second Generation Comprehensive Helicopter Analysis System being planned by the U.S. Army AVRADCOM at Ft. Eustis.

The present study has provided good experience in what is required to make a large computer program effective in a development role. Based on this experience, guidelines have emerged that should be applied to any new codes under consideration for the future. These programs should be

* Simple (to operate)
* Direct
* Accessible
* Responsive

Simplicity is essential for effective operation, with the input preparation/output analysis being such that it can be handled by a junior engineer with minimum supervision. This provides a challenge for the program developers. Direct and Accessible may be linked together since in order for the system to be effective, the impact of changes to the input must be immediately evident in the output, and this can only occur if the engineer operates the program. In too many organizations, the computer codes are prepared and executed by an intermediary, a computer analyst who acts much like a priest at the Delphic Oracle. Finally, the programs must be responsive, providing prompt answers, if the investment in time and effort (and money) is to be repaid with a rapid turnaround under the pressure of a product development situation. It is felt that the system developed at Analtyical Methods and outlined in this paper provides such a capability.

## 5. Acknowledgements

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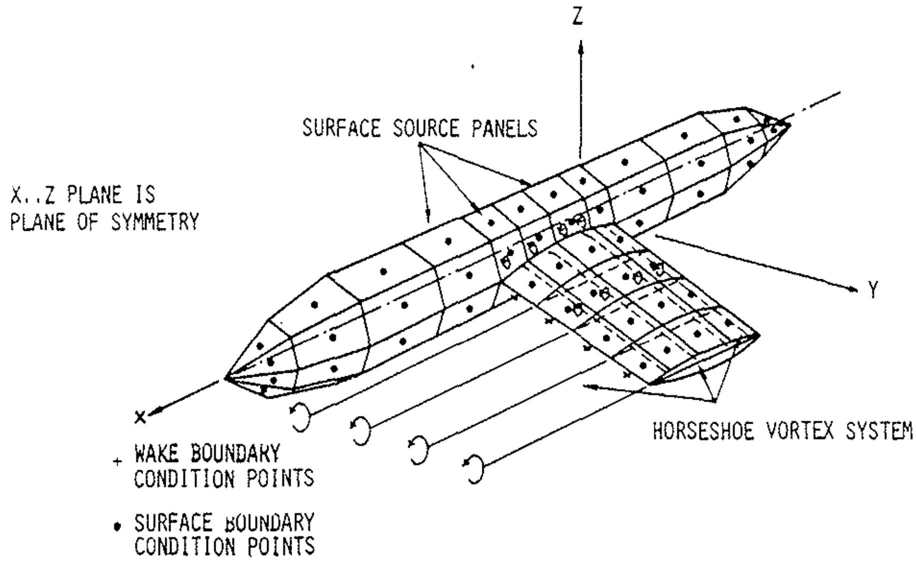


Fig. 1. Schematic of Source and Vortex Panel Potential Flow Model.

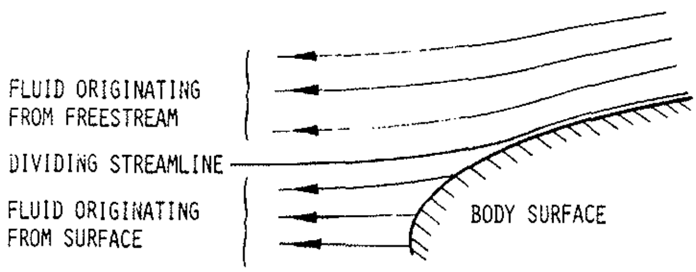


Fig. 2. Modeling of Potential Flow to Account for Separated Regions.

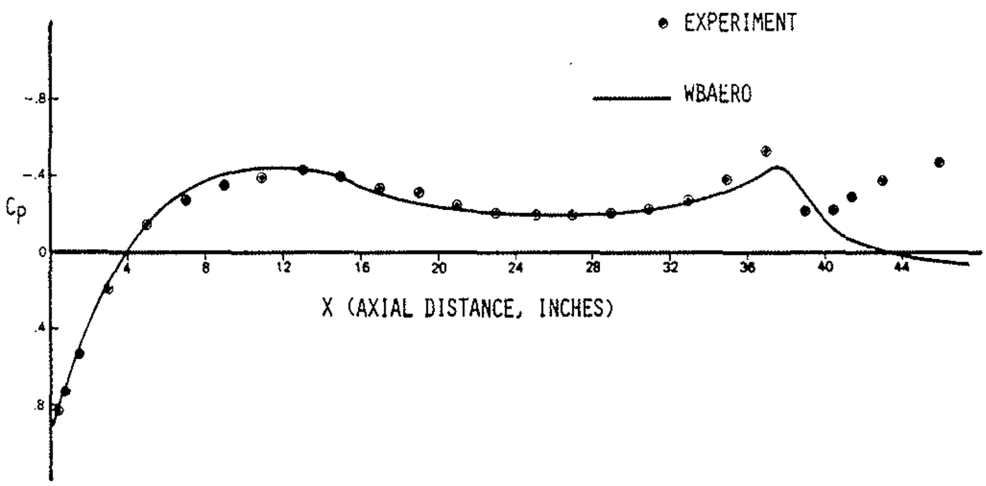


Fig. 3. Pressure Distribution Along Top Centerline of BO105 Calculated Using WBAERO. 0° Pitch, 10° Yaw.

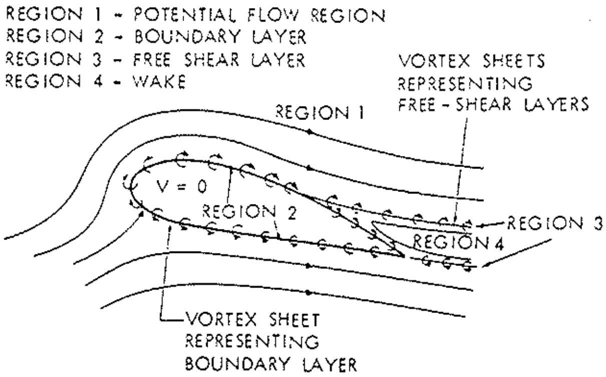


Fig. 4. Improved Model of Separated Flow Region Used in CLMAX Program.

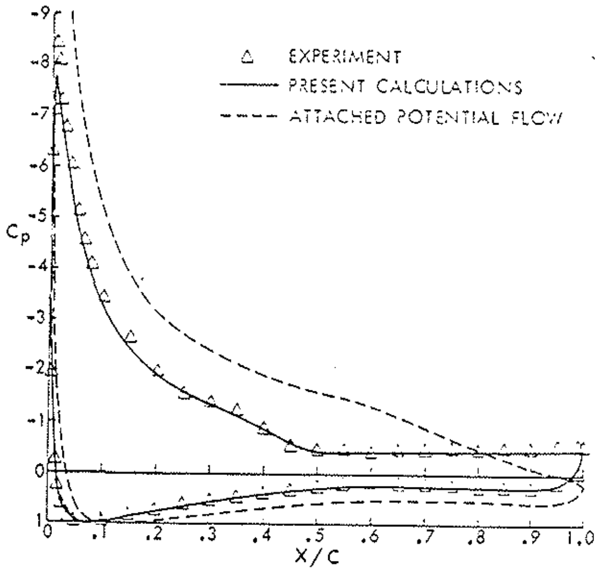


Fig. 5. Typical Correlation of Post Stall Airfoil Pressure Distribution Using CLMAX Program.

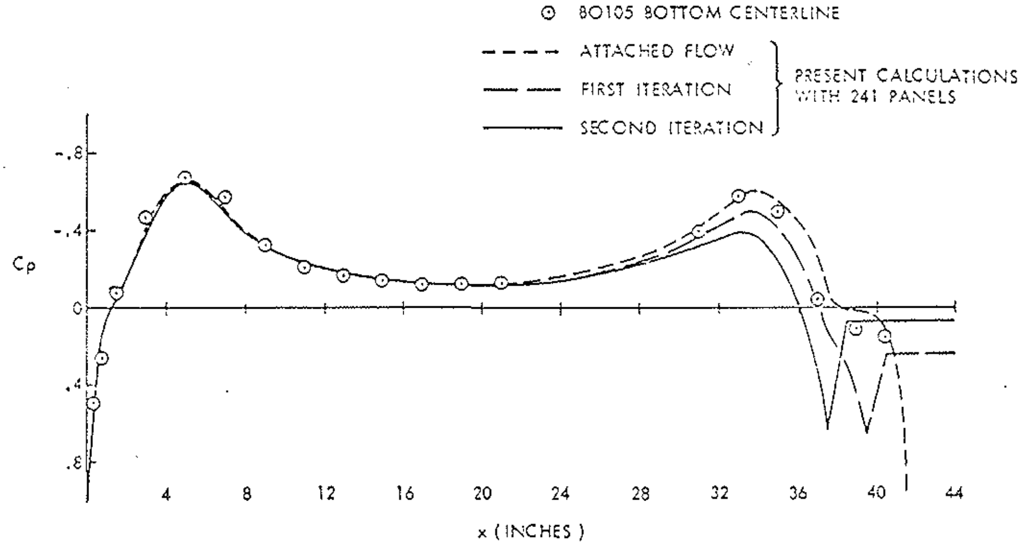


Fig. 6. Pressure Distribution Along Bottom Centerline of BO105 Calculated Using Iterim Program with Constant Source Panels. 0° Pitch, 0° Yaw.

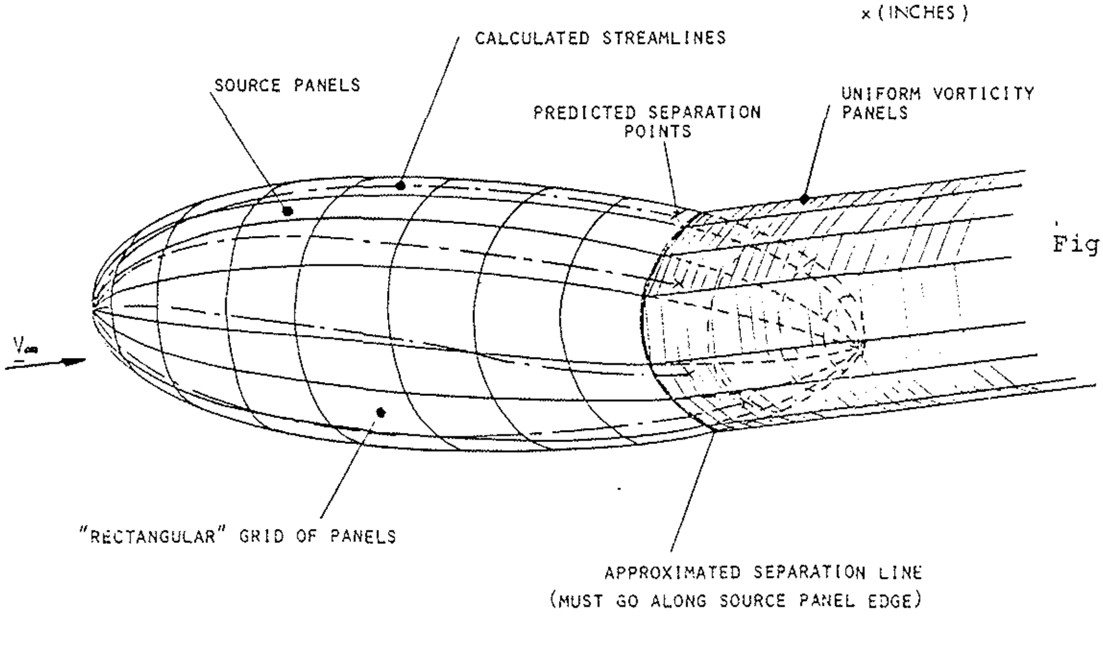


Fig. 7. Schematic of Interim Model for Modeling Separated Flow on Bodies.

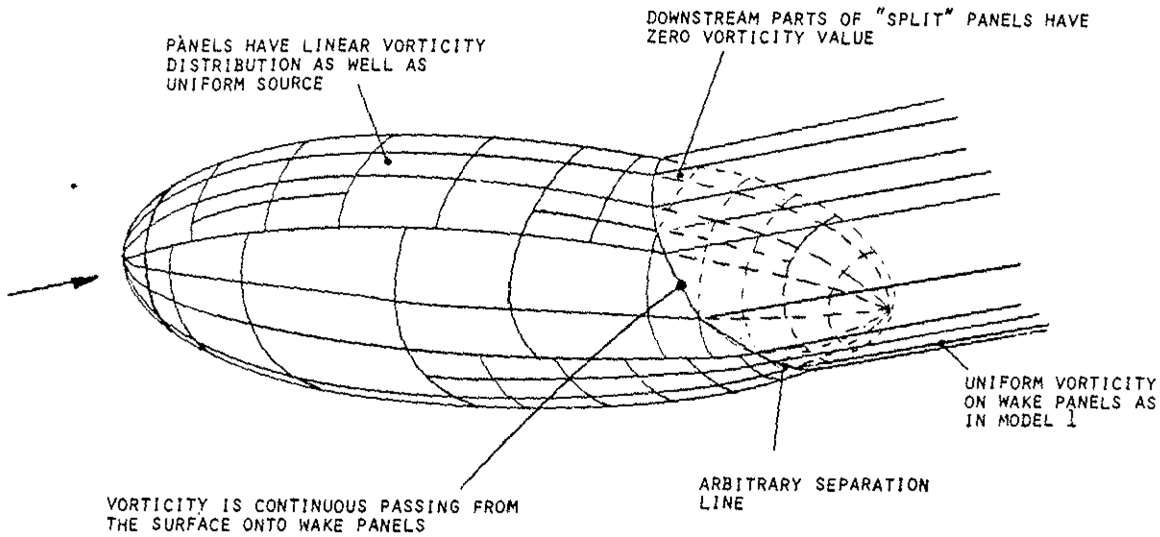


Fig. 8. Schematic of Program DRAG Model.

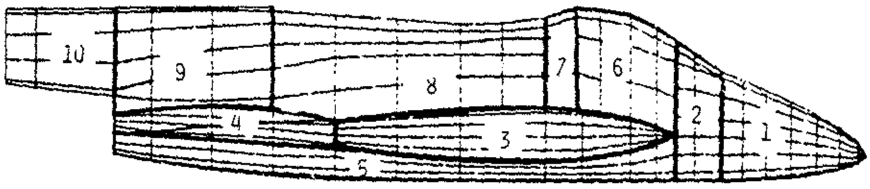


Fig. 9. Typical Example of Multi-Patch Body Paneling.

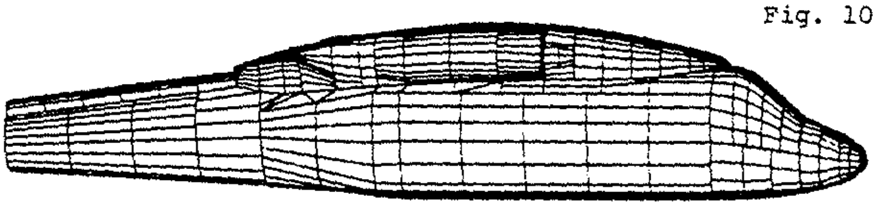

Fig. 10. Baseline Utility Transport Helicopter Paneled for Hub/Pylon Drag Study.

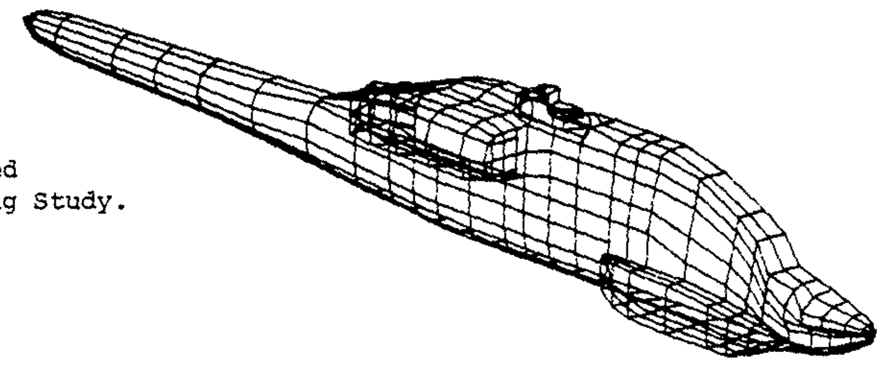

Fig. 11. Baseline Attack Helicopter Paneled for Hub/Pylon Drag Study.

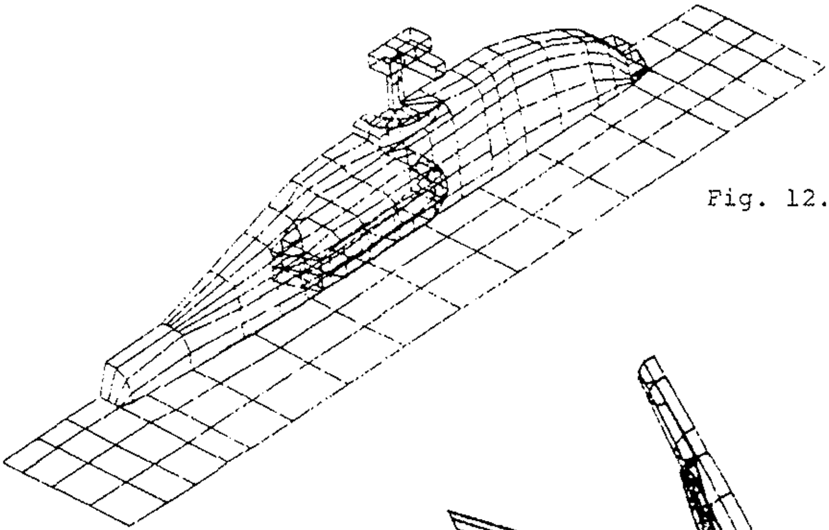

Fig. 12. Partial Attack Helicopter Model on Wind Tunnel Ground Plane.

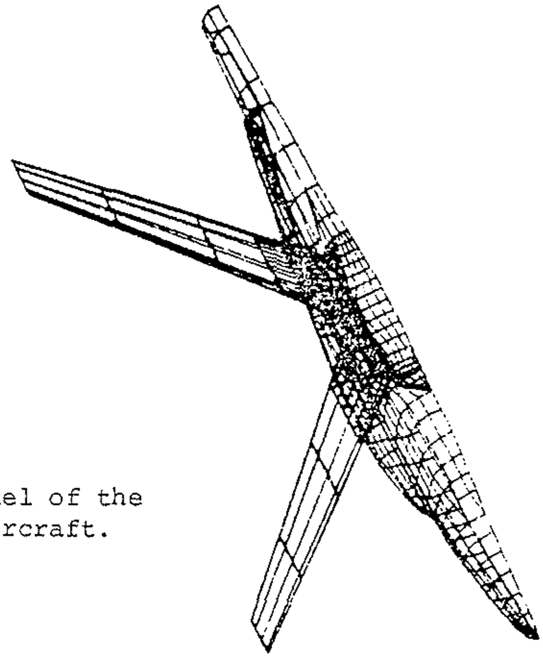

Fig. 13. Panel Model of the X-Wing Aircraft.

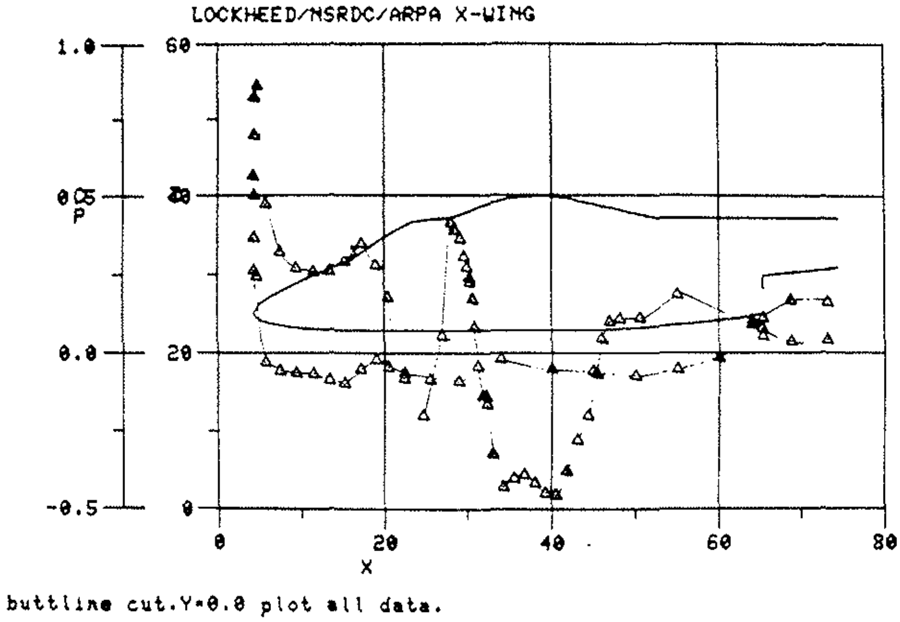


Fig. 14. Typical Output for Data from Program DRAG.

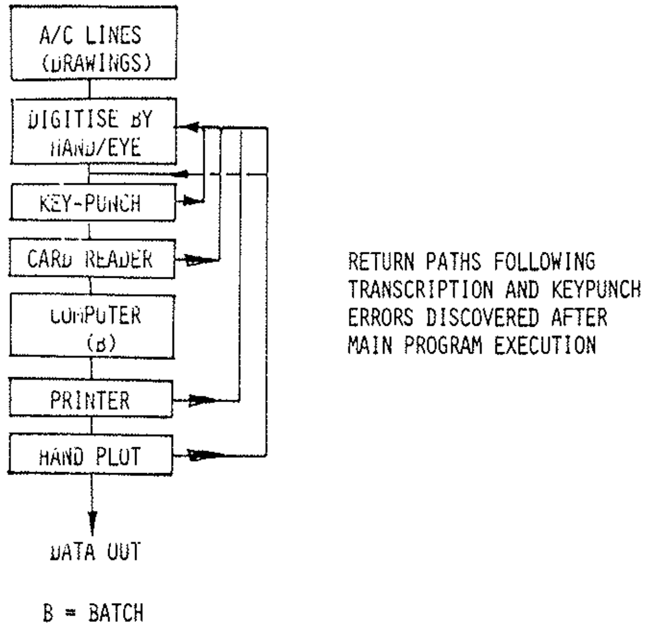


Fig. 15. Block Diagram for Serial Operation of an Involved Batch Mode Computer Program.

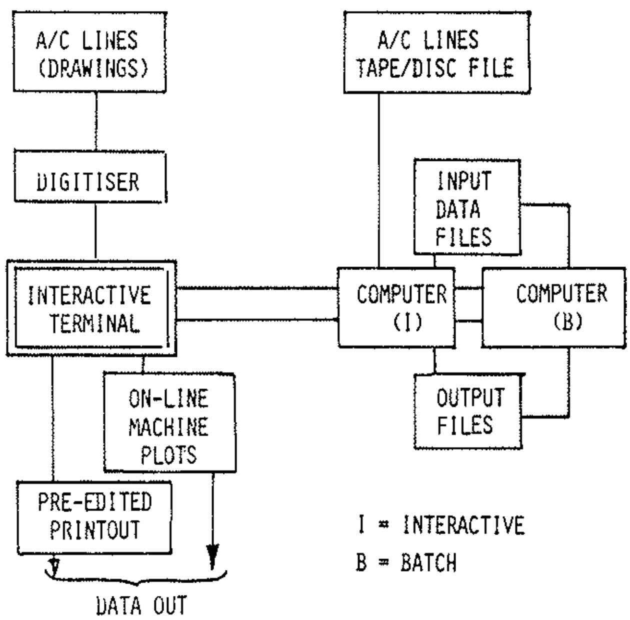


Fig. 16. Block Diagram of the Interactive Operation of Involved Configuration Modeling Porgrams.

```
                THIS PROGRAM PLOTS SHAPES FROM INPUT DATA DECK
                                  OF THE
                         ***   WBAERO PROGRAM   ***


     INPUT CAN BE FULL WBAERO DATA SET OR PARTIAL,STARTING AT CARD 7


     KEY IN BAUD RATE AND RETURN
 ? 300


     YOU HAVE THE FOLLOWING PLOT OPTIONS
          1    PLOT ALL SECTIONS
          2    PLOT ALL SECTIONS IN A DESIGNATED BLOCK
          3    PLOT ANY DESIGNATED SINGLE SECTION
          4    COMPARE UP TO 10 DESIGNATED SECTIONS
          5    TERMINATE!

     KEY IN DESIRED OPTION AND RETURN!
 ? 2

     WHAT BLOCK DO YOU WISH TO PLOT?
     KEY IN BLOCK NUMBER AND RETURN!
 ? 1
```

Fig. 17. Operation of Interactive Input Data Review Program.

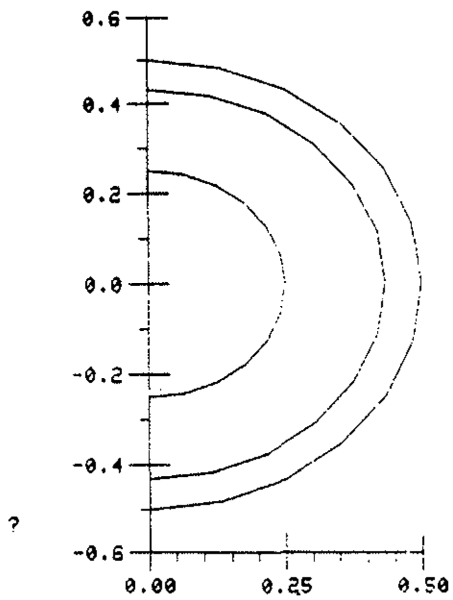


Fig. 18. Typical Plot Generated During Input Data Review.

```
              THIS PROGRAM PERMITS PLOTTING OF OUTPUT DATA FROM

                      THE WBAERO FAMILY OF PROGRAMS


      YOU HAVE THE FOLLOWING PLOT OPTIONS

                1  GEOMETERY
                     ELEVATIONS OR PERSPECTIVE VIEWS OF BODY
                2  AERODYNAMICS
                     PLOTS OF PRESSURE AND VELOCITY DISTRIBUTIONS ON BODY
                3  STREAMLINES
                     PLOTS OF FLOW PROPERTIES AND BODY CURVATURES
                4  BOUNDARY LAYER
                     PLOTS OF BOUNDARYLAYER PROPERTIES ALONG STREAMLINES

      KEY IN SELECTED OPTION AND RETURN.(EG. 2RETURN)
? 2
```

Fig. 19. Operation of Interactive Output Data Review Program.

```
     THIS IS THE AERODYNAMICS LINE PLOTS PACKAGE.

     SELECT PARAMETERS TO BE PLOTTED FROM MENU BELOW.
     DATA CAN BE PLOTTED VS.X,Y, OR Z(AS APPROPRIATE)

     SECTIONS                 PARAMETERS              AXES

     1  STATIONS              1  VX                   1  X
     2  BUTTLINES             2  VY                   2  Y
     3  WATERLINES            3  VZ                   3  Z
                              4  V RES
                              5  CP

     KEY IN SELECTION: SECTION,PARAMETER,AXIS.(EG.1,5,2)
? 2,5,1

     YOU HAVE SELECTED A BUTTLINE(Y) CUT. KEY IN VALUE.
? 0.02

     DO YOU WISH TO SUPERIMPOSE PLOT ON SECTION OUTLINE?
     ANSWER YES OR NO.
? yes
```

Fig. 20. Aerodynamic Plot Options Available During Output Data Review.

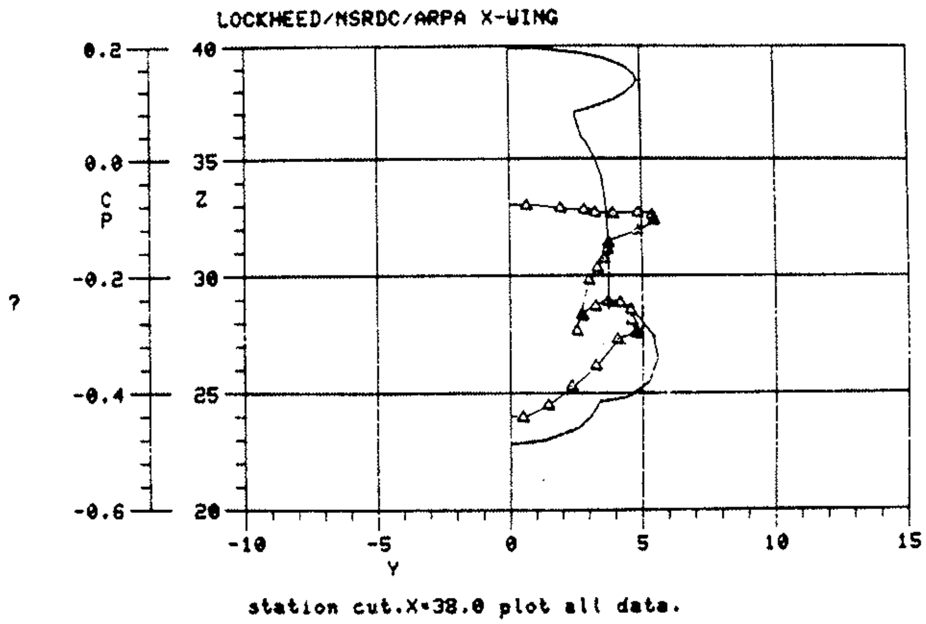


Fig. 21. Typical Aerodynamics Output Data Plot. X-Wing Body Station Cut.

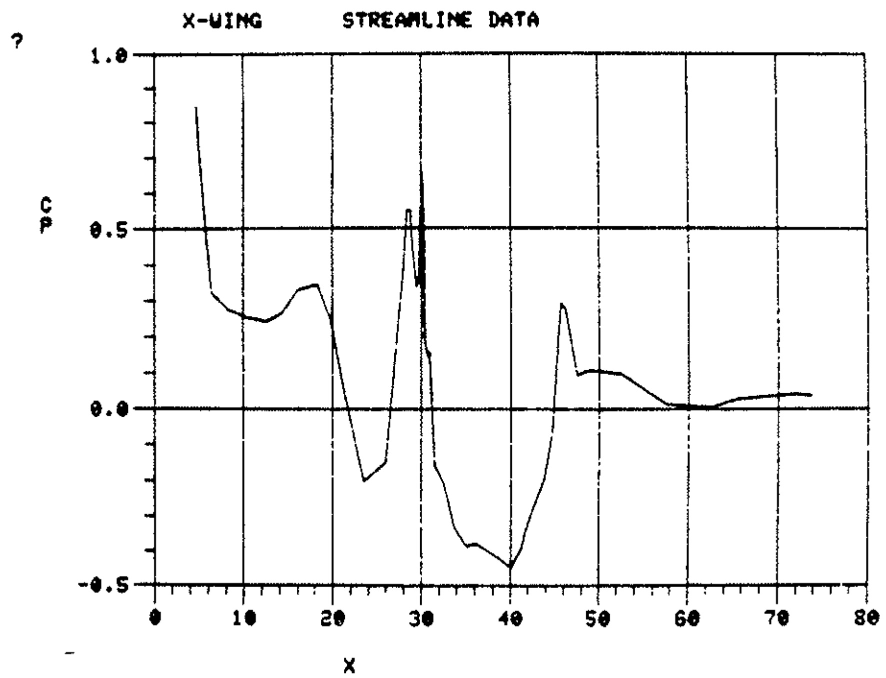


Fig. 22. Typical Streamline Output Data Plot. X-Wing Top Centerline Potential Flow Streamline.