N87-11725

# PIAS, A PROGRAM FOR AN ITERATIVE AEROELASTIC SOLUTION

Marjorie E. Manro
Boeing Commercial Airplane Company
Seattle, Washington

# WHAT IS PIAS?

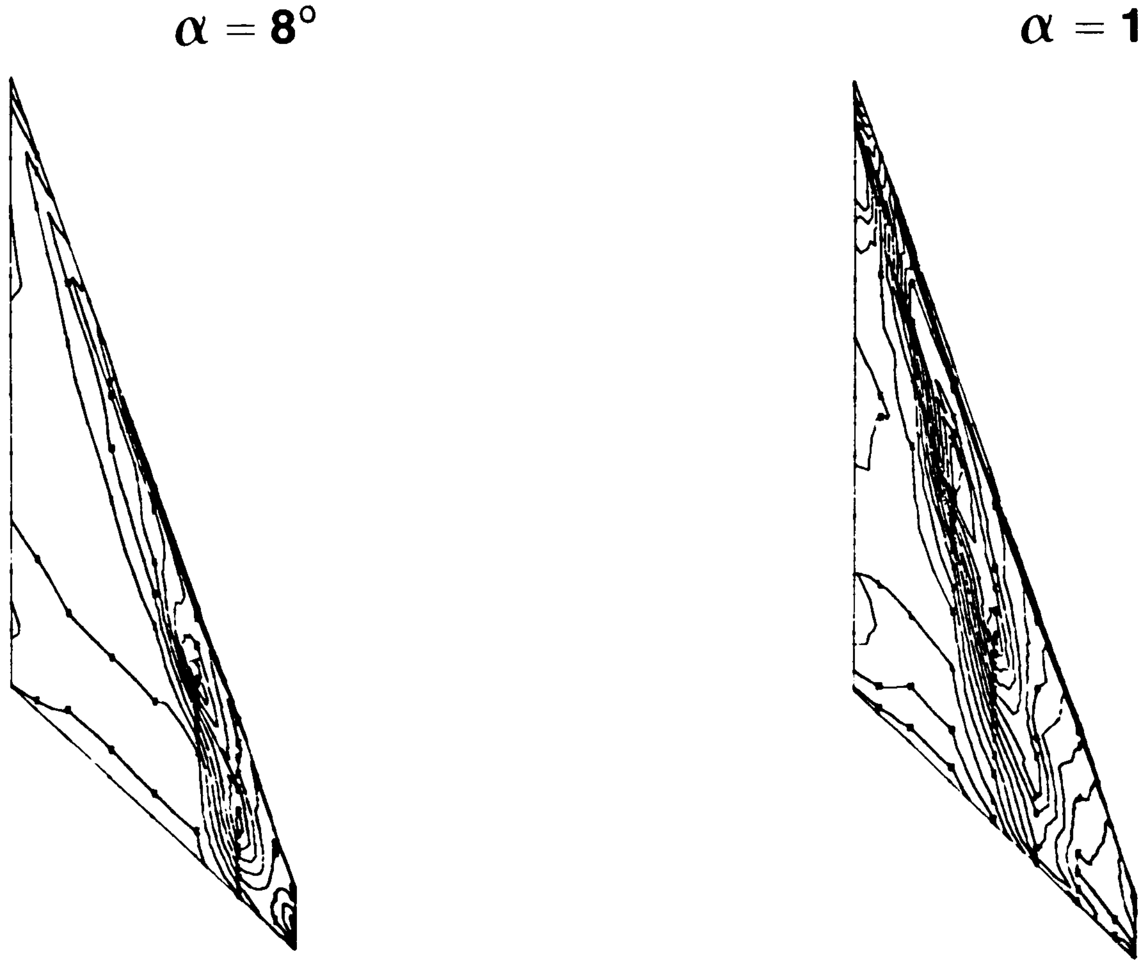
PIAS is the acronym for a Program for an Iterative Aeroelastic Solution. This will be a modular computer program that combines the use of a finite-element structural analysis code with any linear or nonlinear aerodynamic code (fig. 1). At this point in time, PIAS has been designed but the software has not been written. The idea for this development originated with P. J. (Bud) Bobbitt of the NASA Langley Research Center. There was initial interest in an aeroelastic solution for a separation-induced leading-edge vortex. Figures 2 and 3 show some examples of the flow patterns for a low aspect ratio wing and illustrate the need for a nonlinear aeroelastic solution. The development of PIAS by The Boeing Commercial Airplane Company was done under NASA contract NAS1-16740. The engineering and software specifications for PIAS are documented in NASA CR-172200 (ref. 1). The Leading-Edge Vortex Program, which calculates pressure distributions including the effects of a separation-induced leading-edge vortex, uses an iterative solution method. This led to the concept of an iteration cycle on configuration shape external to the aerodynamic code.

- **Program for an Iterative Aeroelastic Solution**
- **Modular computer program to combine:**
  - **Finite-element structural analysis code**
  - **Any linear or nonlinear aeroelastic code**
- **Development:**
  - **Initiated by NASA Langley**
  - **Designed by The Boeing Commercial Airplane Company**
  - **Under NASA contract NAS1-16740**
  - **Reported in NASA CR-172200**
- **Leading-Edge Vortex Program**
  - **Separation-induced leading-edge vortex**
  - **Iterative solution**

Figure 1

## EFFECT OF ANGLE OF ATTACK ON FLOW PATTERN, FLAT WING, M = 0.40

The flow patterns shown in figures 2 and 3 are based on experimental data obtained under several NASA contracts and summarized in references 2 through 4. An extensive data base was acquired for three wings that have the same planform and thickness distribution but different shapes — flat, twisted, and cambered-twisted. Figure 2 shows a comparison of the flow patterns on the planform of the flat wing at two angles of attack at a Mach number of 0.40. The flow pattern is illustrated by lines of constant pressure with the pressure difference between adjacent lines also being a constant. At the moderate angle of attack shown on the left side of the figure, a vortex has developed along the entire leading edge, but attached flow is still apparent on the inboard half of the wing. At the high angle of attack shown on the right side of the figure, the vortex has moved inboard with very little of the flow on the inboard wing still attached.


$\alpha = 8°$

$\alpha = 16°$

Figure 2

## EFFECT OF WING TWIST ON FLOW PATTERN, $M = 0.40$, $\alpha = 8^\circ$

In figure 3, data are shown at Mach number = 0.40 for only one angle of attack, but for two wing shapes. The flow pattern on the left side of the figure — for the flat wing — is the same data as shown at $8^\circ$ angle of attack on the previous figure. The flow pattern on the twisted wing on the right side of the figure is quite different. The vortex has just started at the wing tip at this angle of attack. There is $4.5^\circ$ washout at the tip of the twisted wing and the flow pattern shown here closely resembles the pattern on the flat wing at an angle of attack of 4 degrees. The futility of using a linear method to predict these flow patterns is clearly illustrated in these figures.

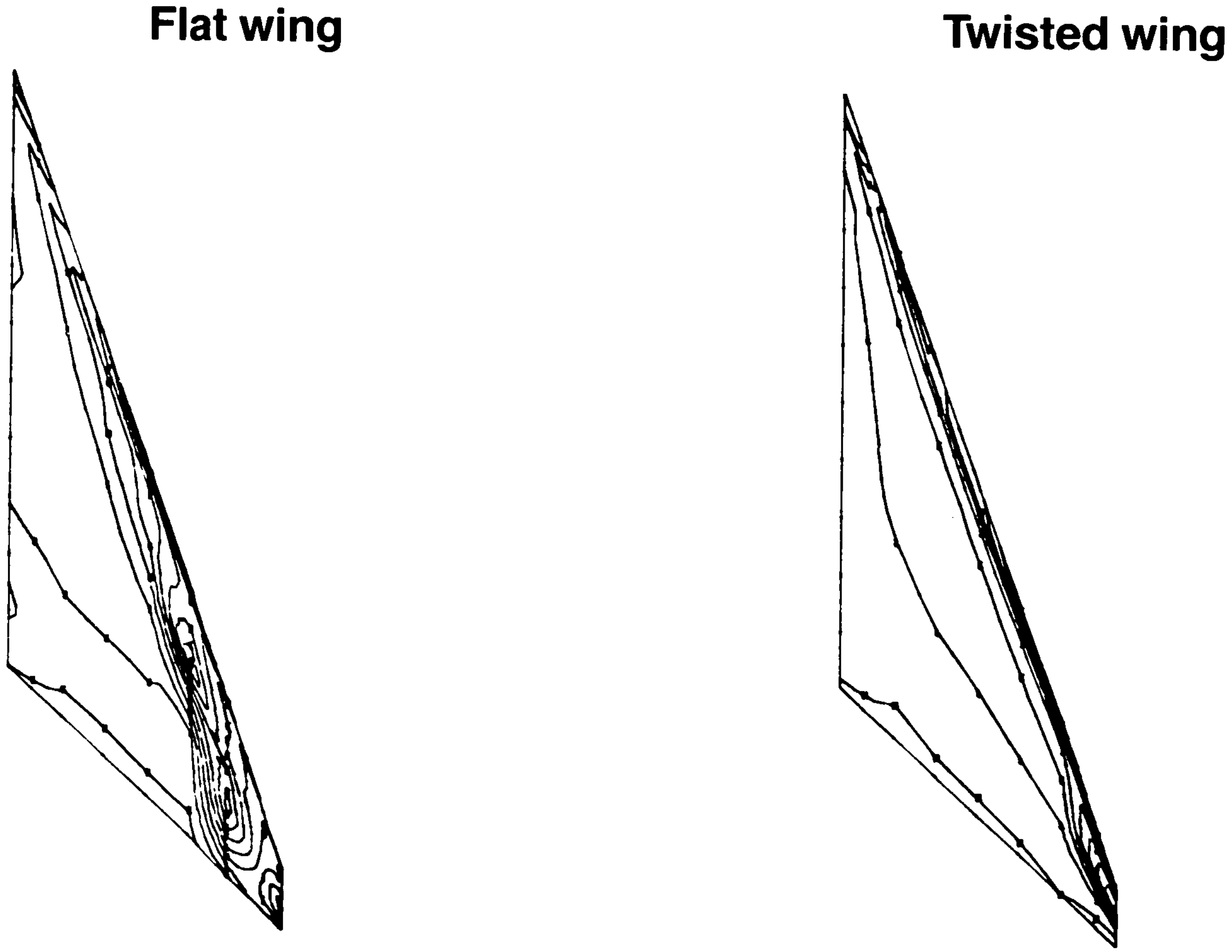


Figure 3

## RATIONALE FOR SELECTING AN ITERATIVE PROCEDURE

A review of the attributes of closed form and iterative solutions was made to confirm the decision to select an iterative procedure (see fig. 4). In a closed form solution, the structural flexibility terms are an integral part of the aerodynamic code. This works well when the aerodynamic solution is linear. If the aerodynamic solution is nonlinear, it is difficult if not impossible to include the flexibility terms in the formulation. In any case, the development would have to be done for each aerodynamic theory. In an iterative solution, the terms for structural flexibility are kept separate from the aerodynamic code. The approach used to obtain aeroelastic loads at a specified design load factor is the alternate execution of two codes: one to calculate the aerodynamic loads on a specific shape and the other to calculate the deflected shape under load. This alternate execution is continued until the wing shape is compatible with the applied loads. The development, applied to one nonlinear aerodynamic program, will address the logic to obtain both convergence to a deformed shape at each angle of attack and convergence to the design load factor. The data management scheme developed for one aerodynamic module will accomodate another theory with minor changes.

- **Closed form solution**
  - **Structural flexibility terms in aerodynamic code**
  - **Straightforward for linear aerodynamic methods**
  - **Difficult for nonlinear aerodynamic methods**
  - **Separate development for <u>each</u> nonlinear aerodynamic theory**

- **Iterative solution**
  - **Structural flexibility terms separate from aerodynamic solution**
  - **Existing structural program can be used to calculate deflected shape under load**
  - **Alternate execution of code to calculate:**
    - **Aerodynamic loads on a specific shape**
    - **Deflected shape under load**
  - **Development for one aerodynamic theory addresses:**
    - **Logic for solution convergence**
    - **Data management**
  - **Other aerodynamic theories**
    - **Should be added easily**
    - **Would require minor changes to data management**

Figure 4

## NEED FOR A GENERAL AEROELASTIC SOLUTION

Having established that the iterative form for an aeroelastic solution was preferred, a review was made to determine the general need for an iterative aeroelastic solution (see fig. 5). Generally, the aircraft configurations that are currently in design exhibit nonlinear flow because of either the physical configuration or the flight domain, or both. The high costs of fuel and increased airline competition due to deregulation have made more efficient aircraft and therefore more realistic design load prediction a necessity. In the past, it has been necessary to augment the use of linear theories with experimental data for structural design. As the costs of wind tunnel testing increase, it is not reasonable to test the many points in the flight envelope that are necessary to support this effort. Many computer programs are being developed that address particular types of nonlinear flow now that computer power is increasing. Both the speed of computations and the available in-core storage have influenced this progress.

- **Current aircraft exhibit nonlinear flow**
  - **Physical configuration**
  - **Flight domain**
- **More realistic design load prediction is required for efficient aircraft**
  - **High fuel costs**
  - **Airline competition due to deregulation**
- **Linear systems are inadequate without experimental augmentation**
- **Costs of wind tunnel testing are increasing**
- **Many theories for nonlinear aerodynamics are being developed**
- **More computer power is available**
  - **Faster**
  - **More in-core storage**

Figure 5

## ITERATION LEVELS

The basic flow of the proposed interative solution is shown in figure 6. The initial input includes the aerodynamic model, the structural and mass models, the flight condition description, and execution parameters for the solution. These parameters include the maximum number of iterative cycles, the acceptable tolerance on the change in deflection between cycles, and the acceptable tolerance on the design load factor. There are two levels of iteration. The outer level consists of solutions at several angles of attack. This approach is necessary because of the nonlinear nature of the solution. The procedure for determining the values of successive angles of attack is shown later. The inner level of iteration continues for each angle of attack until a wing shape is obtained that is compatible with the calculated airload. The acceptable tolerance on deflection may be less stringent for the initial stages of the solution than for the final solution. The aerodynamic and structural modules shown in this cycle are separate programs and the only requirement is that a specified minimum amount of data is written to a file for communication with PIAS. The other calculations and the interpolations are provided by new code that will also control the solution sequence.

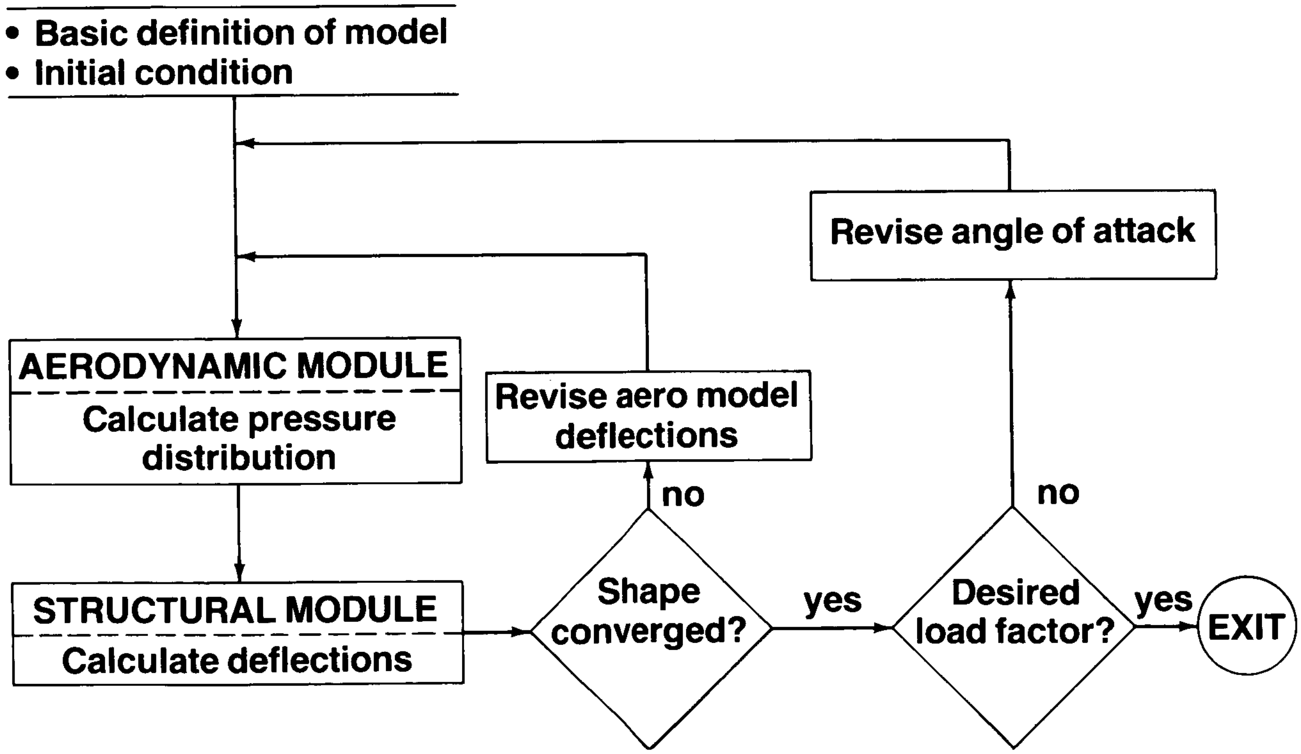


Figure 6

## SPECIFIC PROBLEMS ADDRESSED

The major problems that need to be solved before a viable aeroelastic solution is possible are shown in figure 7. The first of these is the difference between the grid used in the aerodynamic module and the model for structure and mass. Generally, the aerodynamic grid is tailored to be densest in areas where high pressure gradients are expected; the structural model is densest in regions of high stress/strain gradients. Usually, the mass model is compatable with the structural model. The pressure values calculated by the aerodynamic code are typically located at panel centroids. The code for structural analysis requires loads at the structural nodes, and for a realistic analysis the summation of these loads must represent the total load and distribution as obtained from the aerodynamic program. The conversion of one type of data to the other type is a required function. Code that is external to the functions already available in the aerodynamic and structural programs is needed to make additional calculations, to initiate execution of the existing codes as required by the algorithm, to determine when convergence within specified tolerances is achieved, and to manage the data flow and storage. The data management plan must allow for the changing nature of the data during the solution, as well as for the required checkpoint-restart capability. The design of PIAS stressed retention of adequate data so that the solution could be easily restarted from several points in the cycle. In addition to a continuous execution to the desired load factor, it is expected that the user will sometimes wish to pause periodically to review the results at selected steps in the cycle. There will also be times when a situation will be encountered for which a course of action was not defined.

- **Difference in aerodynamic and structural grids**
  - **Aerodynamic grid — dense in regions of high pressure gradients**
  - **Structural grid — dense in regions of high stress/strain gradients**

- **Code is required to provide:**
  - **Additional calculations**
  - **Data conversion**
  - **Selective execution of existing codes**
  - **Control of solution convergence**
    - **Configuration shape within specified tolerance**
    - **Load factor within specified tolerance**
  - **Data management**

- **Checkpoint-restart procedures**
  - **Planned pauses during solution**
  - **Restart after a situation is encountered for which a course of action was not defined**

Figure 7

## DESIGN OF PIAS

The elements incorporated into the design of PIAS are shown in figure 8. The Leading-Edge Vortex (LEV) Program is used for the aerodynamic module. The output is pressure distributions at the centroids of panels representing the configuration surface. The LEV Program has the capability to calculate loads for either attached flow or for a separation-induced vortex. The ATLAS Integrated Structural Analysis and Design System is used for calculating the deformed shape of the wing under the combined effect of airload and inertia loads. ATLAS is a system of modules with a variety of capabilities. The ATLAS surface spline interpolation module uses the method of Desmarais (ref. 5). A sample of the results of an interpolation using this method is shown in figure 9. A recent development for potential enhancement of ATLAS uses the surface spline interpolation module to perform an exact integration of the pressure distribution over discrete areas of the wing to obtain forces and moments. From these forces and moments, equivalent nodal loads are calculated that represent the total load. The Execution Control Monitor (ECM) will direct the execution of these programs, including control of solution convergence. The ECM will also provide a data management scheme to transfer the data between the aerodynamic and structural modules. The few additional calculations that are required for an aeroelastic solution — but not for the aerodynamic and structural modules individually — are part of the function of the ECM. These calculations determine the vertical load factor, the revised angle of attack, and the origin of the vortex when using the separated-flow option of the LEV Program for the aerodynamic module.

- **Combine existing codes into an aeroelastic solution**
  - **Leading-Edge Vortex (LEV) Program**
    - **Separation-induced leading-edge vortex**
    - **Attached flow**
  - **ATLAS**
    - **Structural and mass modeling**
    - **Calculate structural deflection due to airload and inertia loads**
    - **Surface spline interpolation**
    - **Calculate equivalent nodal loads**

- **Execution Control Monitor (ECM)**
  - **Direct the overall aeroelastic solution process**
  - **Control of solution convergence**
  - **Data management**
    - **Transfer of data**
    - **Retention of results at each solution step for restart**
  - **Provide additional calculations**
    - **Load factor, $n_z = C_L q S/W$**
    - **Revised angle of attack**
    - **Origin of vortex for separated-flow option of LEV**

Figure 8

## RESULTS OF SURFACE SPLINE INTERPOLATION

The upper left portion of figure 9 shows an isometric drawing of an experimental upper surface pressure distribution on an arrow wing. The arrows show the locations of the measured data and, as indicated, the orifices were arranged in seven streamwise rows. Progressing from the inboard to the outboard section, the location of the peak pressure is a little farther aft at each spanwise section. In the lower right hand portion of this figure, an isometric drawing of the interpolated pressures is shown. The output points are arranged in rows that are perpendicular to the centerline of the model. The location of the peak pressures follows the same pattern as shown in the input distribution. In this case, the extrapolation in the wing tip area seems to be quite good, even though extrapolation is not recommended with this method.

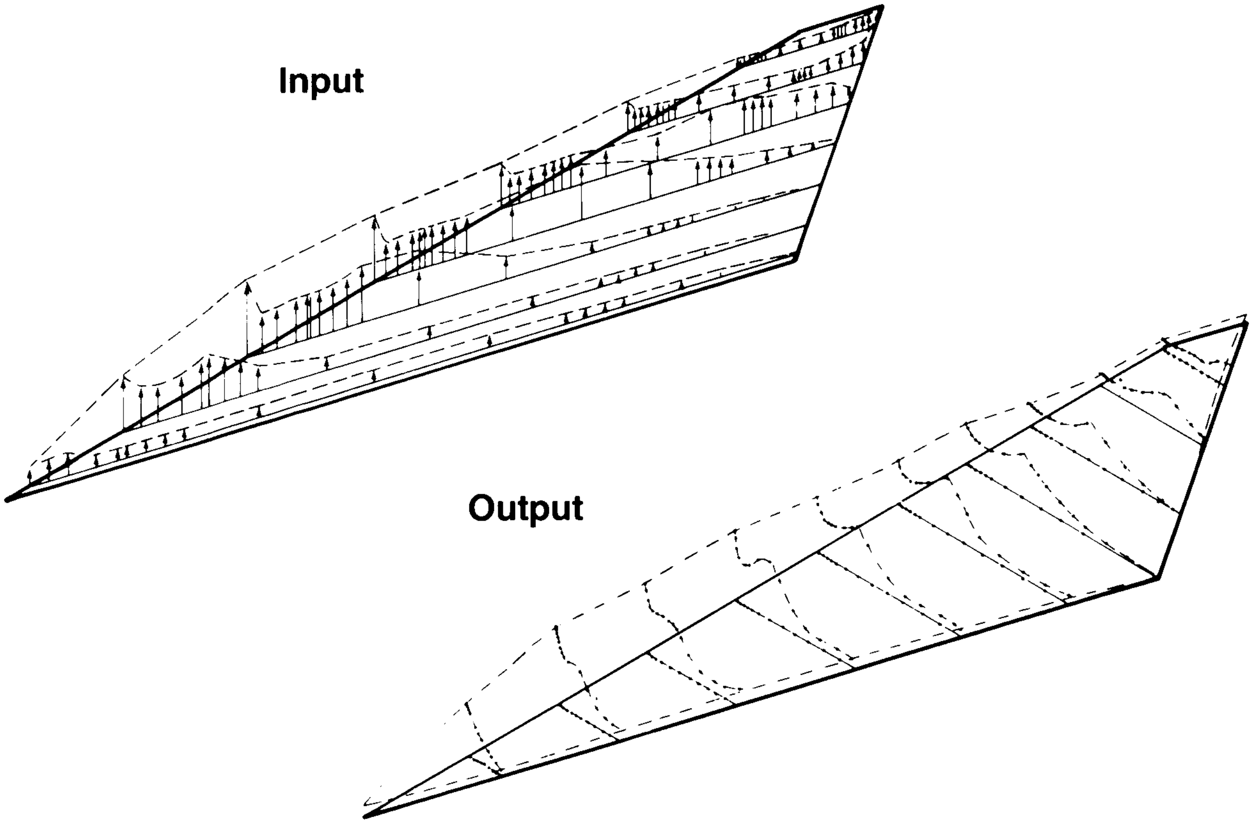


Figure 9

## ATLAS INTEGRATED STRUCTURAL ANALYSIS AND DESIGN SYSTEM

As shown in figure 10, ATLAS is based on the stiffness finite-element structural analysis method. The extensive library of structural finite elements allows modeling of configurations from the simple to the complex for both metalic and advanced composite structures. Capabilities are also provided for modeling structural, nonstructural, fuel, and payload mass distributions with the library of mass finite elements or by concentrated masses. Automatic grid generation from minimum user input simplifies both structural and mass modeling. A number of other features that are needed for the iterative process, as well as some that will make the process easier for the user, are available in ATLAS. The capability for using a combination of local coordinate systems — rectangular, cylindrical, and spherical — allows the aerodynamic and structural grids to be in different systems. The surface spline interpolation method and calculation of equivalent nodal loads, as previously described, are necessary to obtain the deflection of the wing at the structural nodes. The surface spline interpolation method will be used to calculate the modifications to the aerodynamic grid for the next execution of the aerodynamic code. There is the capability in ATLAS to have a control program which can be a combination of FORTRAN code, calls to execute other modules of ATLAS, and calls to execute codes that are not a part of ATLAS. This capability provides a convenient framework for developing the Execution Control Monitor (ECM).

- **Stiffness finite-element structural analysis method**

- **Structural modeling**
  - **Library of structural finite elements**
  - **Simple to complex configurations**
  - **Metallic and advanced composite structures**

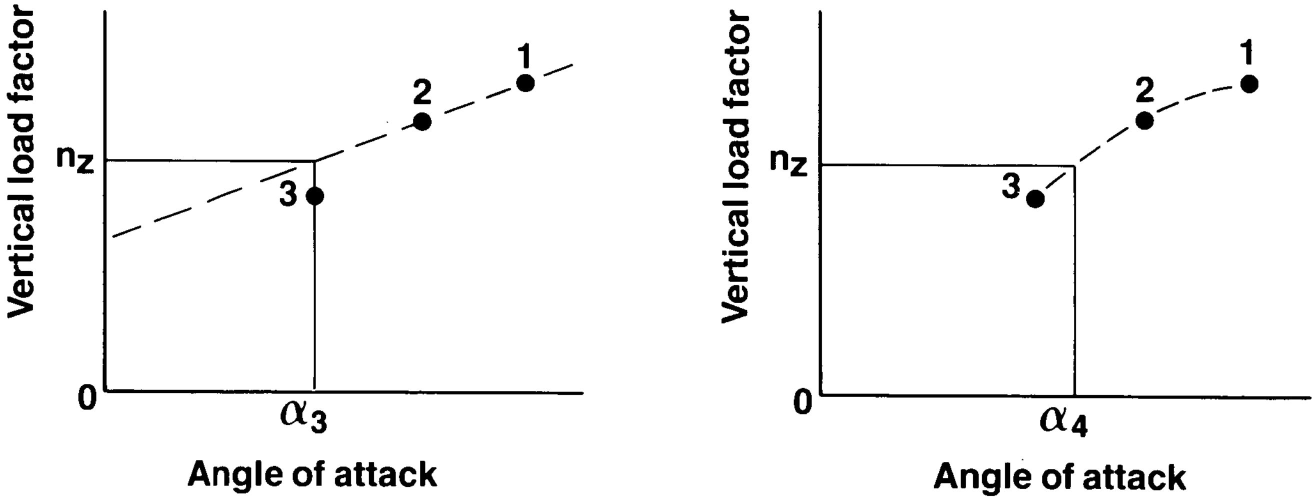
- **Mass modeling**
  - **Library of mass finite elements or concentrated masses**
  - **Structural, nonstructural, fuel, and payload mass distributions**

- **Additional features**
  - **Automatic grid generation - minimum input**
  - **Capability to use a combination of local coordinate systems**
  - **Surface spline interpolation, calculation of equivalent nodal loads**
  - **Data management**
  - **Execution control modules**
    - **Perform problem-specific calculations**
    - **Execute selected modules of ATLAS**
    - **Execute other programs**

Figure 10

## DETERMINATION OF SECOND ANGLE OF ATTACK

As stated earlier, the ECM will calculate the revised angle of attack. A basic premise of this development is that the vertical load factor is not a linear function of the angle of attack $\alpha$. It is expected that solutions for four angles of attack will be necessary to achieve the design load factor $n_z$. The user specifies the first angle of attack for each case; the load factor for this angle of attack is then calculated from the predicted pressure distribution and is shown in figure 11 as a solid circle, labeled 1. The second angle of attack may be selected to correspond to the design load factor by temporarily assuming a linear variation between zero and the first calculated point as shown on the left, or the user may specify $\alpha_2$ directly as shown on the right. The load factor for the second point is obtained from the pressure distribution at this angle of attack and is shown as the solid circle labeled 2. It is clear that the assumption of linearity is only a convenience for estimating the next angle of attack to try.



**Third angle of attack** **Fourth angle of attack**

Figure 11

## DETERMINATION OF THIRD AND FOURTH ANGLES OF ATTACK

Again assuming a linear variation of load factor with angle of attack, these first two points are used to find the angle of attack for the design load factor by linear interpolation (or extrapolation) as shown in the left part of figure 12. The load factor is calculated using the pressure distribution from the third solution and is shown as a solid circle labeled 3. A curve fit through these three points is used to get the fourth angle of attack, which should be the final one. The logic in PIAS is such that as soon as the calculated load factor is within the user-specified tolerance for the desired load factor, the solution will stop.

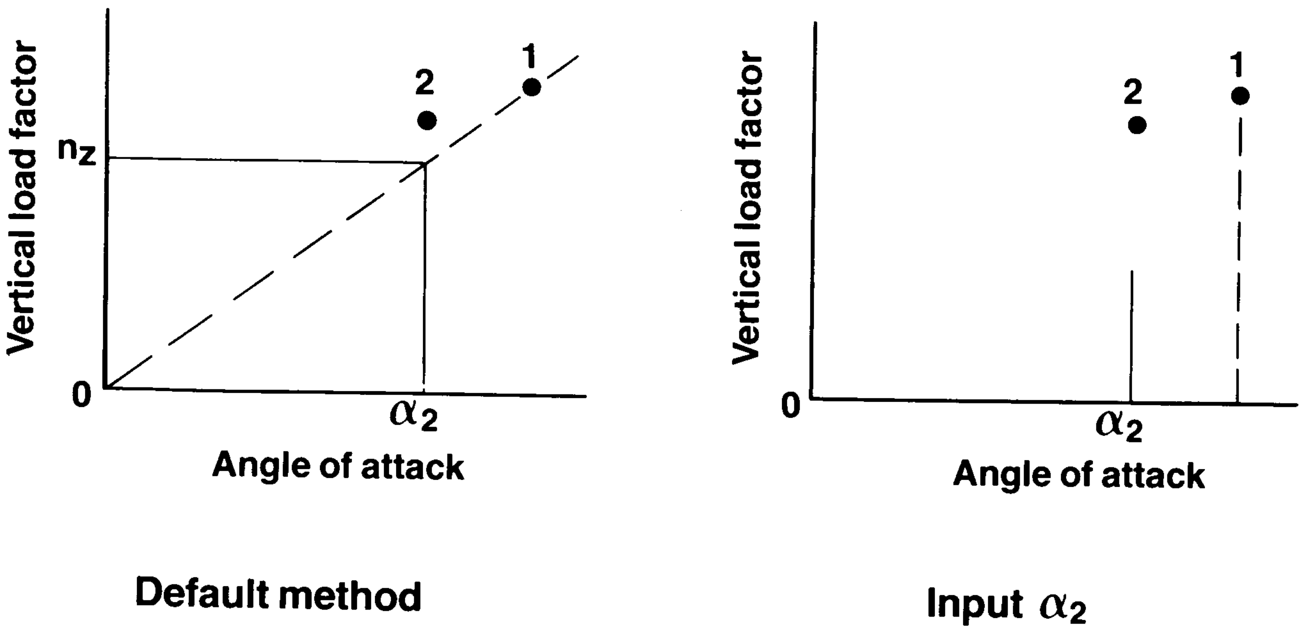


Figure 12

## ADDED CAPABILITIES

As the specification for PIAS was developed, some unexpected uses became apparent as listed in figure 13. The initial goal was to be able to calculate design load pressure distributions for a specific load factor. By stopping the solution after convergence on the wing shape at the first angle of attack, it will be possible to analyze flexible wind tunnel models for expected test conditions. The little-used capability to represent cases with attached flow in the LEV Program will allow analyses of a configuration that exhibits this phenomenon through part or all of its flight envelope. With the capabilities of ATLAS, it will be possible to calculate the internal stresses for the design load case. In addition, once the structure and mass of the aircraft are modeled, the user can take advantage of other ATLAS capabilities such as the vibration and flutter analyses and automated structural resizing. In respect to adding other aerodynamic codes to PIAS, it is interestng to note that advances are being made in nonlinear transonic codes — full potential and Euler — and in nonlinear supersonic codes.

- **Loads for wing with shape converged at a specific angle of attack**
- **Attached flow**
- **Internal stresses**
- **Other ATLAS capabilities**
    - **Vibration analysis**
    - **Flutter analysis**
    - **Automated structural resizing**
- **Nonlinear transonic codes**
    - **Full potential**
    - **Euler**
- **Nonlinear supersonic codes**

Figure 13

# REFERENCES

1. Manro, Marjorie E.; Donahue, Michael J.; Dreisbach, Rodney L.; and Bussoletti, John E.: Specification for a Program for an Iterative Aeroelastic Solution (PIAS). NASA CR-172200, 1983.

2. Manro, Marjorie E.; Manning, Kenneth J. R.; Hallstaff, Thomas H.; and Rogers, John T.: Transonic Pressure Measurements and Comparison of Theory to Experiment for an Arrow-Wing Configuration, Summary Report. NASA CR-2610, 1976.

3. Manro, Marjorie E.: Supersonic Pressure Measurements and Comparison of Theory to Experiment for an Arrow-Wing Configuration. NASA CR-145046, 1976.

4. Manro, Marjorie E.: Transonic Pressure Measurements and Comparisons of Theory to Experiment for Three Arrow-Wing Configurations, Summary Report. NASA CR-3434, 1982.

5. Harder, R. L.; and Desmarais, R. N.: Interpolation Using Surface Splines. Journal of Aircraft, vol. 9, no. 2, Feb. 1972, pp. 189-191.