N89-25222

MEETING THE CHALLENGES WITH THE DOUGLAS AIRCRAFT COMPANY AEROELASTIC DESIGN OPTIMIZATION PROGRAM (ADOP)

BRUCE A. ROMMEL
Douglas Aircraft Company, McDonnell Douglas Corporation
Long Beach, California

THE CHALLENGES OF AEROELASTIC DESIGN OPTIMIZATION

Aeroelastic design optimization for commercial aircraft must consider the full range of design loads and aeroelastic constraints. If significant constraints are omitted from the design optimization process, the result may be far from satisfactory and perhaps worse than a nonoptimal design obtained from conventional procedures. Fatigue is a major consideration: As shown in Figure 1, a design which is close to optimum for only a few load conditions may result in a severely short service life. Nearly 5,000 load conditions resulting from variations in speed, weight, maneuvers, and gust loads must be considered when designing a typical commercial aircraft. Typically, service lift goals are on the order of 60,000 flight hours, with 30,000 flights and landings over a service life of 20 years. To achieve these goals the fatigue life is normally set at about twice the number of flight hours and landings of the design service life. Recent experience indicates that these goals may double or even triple with the next generation of commercial aircraft.

To achieve these goals the analysis and design optimization program must be able to handle the large-scale, finite-element models required for detailed stress analysis. On the other hand, to automate the design process, common structural models for static strength, structural dynamics, flutter, and aeroelastic constraints are required. Critical flutter and aeroelastic constraints often arise near the region of transonic flight. A high-speed commercial transport to service the Pacific Basin will cruise at supersonic or even hypersonic speed, resulting in high heat loading conditions. Buckled skin finite elements used for high load conditions in static strength analysis are inappropriate for modal analysis resulting in a model dependency. Future aircraft will undoubtedly use more advanced composite materials to reduce weight and achieve desirable aeroelastic characteristics. It is with these considerations that we are developing an Aeroelastic Design Optimization Program at Douglas Aircraft Company.

CRITICAL LOAD CONDITIONS FOR STATIC STRENGTH (5,000 LOAD CASES)

FATIGUE DESIGN FOR A 20-YEAR SERVICE LIFE

- 60,000 FLIGHT HOURS/FATIGUE LIFE 120,000 HOURS
- 30,000 FLIGHTS/FATIGUE LIFE 60,000 FLIGHTS

LARGE FINITE-ELEMENT MODELS (10,000 - 60,000 DOF)

COMMON MODELS FOR STRENGTH AND FLUTTER DESIGN

DESIGN FOR TRANSONIC/SUPERSONIC TRANSPORTS

Figure 1

ORIGINAL PAGE IS
OF POOR QUALITY

THE PILOT TEST PROBLEM (FIN OR SMALL WING)

Since the earliest days of ADOP development we have used the fin or small wing model to develop our data flows and procedures. This model is small enough so that much of the required data can be calculated by hand for verification. The amount of data is small enough that the procedure may, in many cases, be sight verified. Figure 2 depicts one of the simple wing modes. The mesh shown superimposed over the wire frame model is the aero control point mesh. It is a pseudo mesh generated to show how well the spline between the structural mesh and the aero mesh has fit the data. A Harder spline was used, and the fit was quite good even though the spline had to extrapolate beyond the domain of the structural box. This resulted in a slight cusping of the points farthest from the structural box. In general, the Harder spline will work best when no extrapolation is required and the splined points are near the data points. Even the higher frequency modes were fitted adequately with this spline; however, other spline procedures are being developed for use in ADOP. With this model we developed the animation of mode shapes with solid rendering as well as wire frame displays. The user may rotate during modal animation to better visualize the modes.

This same model was used to develop a stress contours post-processor display.

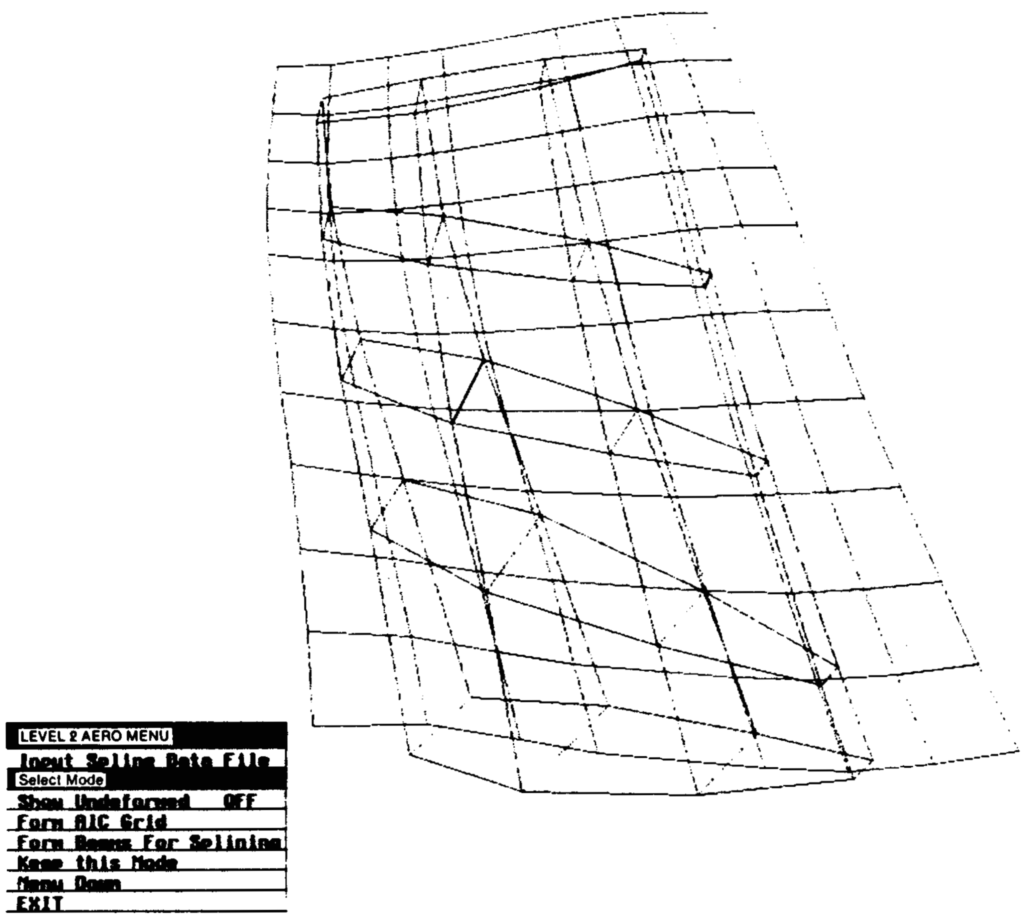

Figure 2

THE BIG TEST PROBLEM

The next test problem developed to test the ADOP program procedures was a complete aircraft model of a high-altitude hypersonic aircraft. Most advanced design study models use 5,000-10,000 DOF. Modal analysis of these models can be completed in a few minutes during a *TSO interactive session on the IBM 3090 computer without resorting to batch-mode processing. Such models can be rotated during animation, even with mirror imaging and solid rendering.

The model shown in Figure 3 was developed by Alan Dodd for an advanced design study. This configuration, which has many interesting design features such as the V-tail, was abandoned as impractical. It makes an ideal study model because no military or commercial trade secrets are revealed in its configuration. It was the first model with which we encountered significant modeling discrepancies with modal display. Some singular modes were developed that showed incorrect element nodal connectivity, even though an interactive graphics system was used to generate the model. These "marble modes" consisted of large deflections of a single node while the rest of the model was relatively stationary. Once these nodes and elements were defined, the modeling problems could be corrected. Subsequently, this condition was discovered in several other models developed for static strength analysis. The ability to compute and display the modes of large-scale, finite-element models has thus become a very valuable diagnostic tool for finite-element structural analysis. This was an unanticipated benefit of ADOP development.

---

*Time-Sharing Option

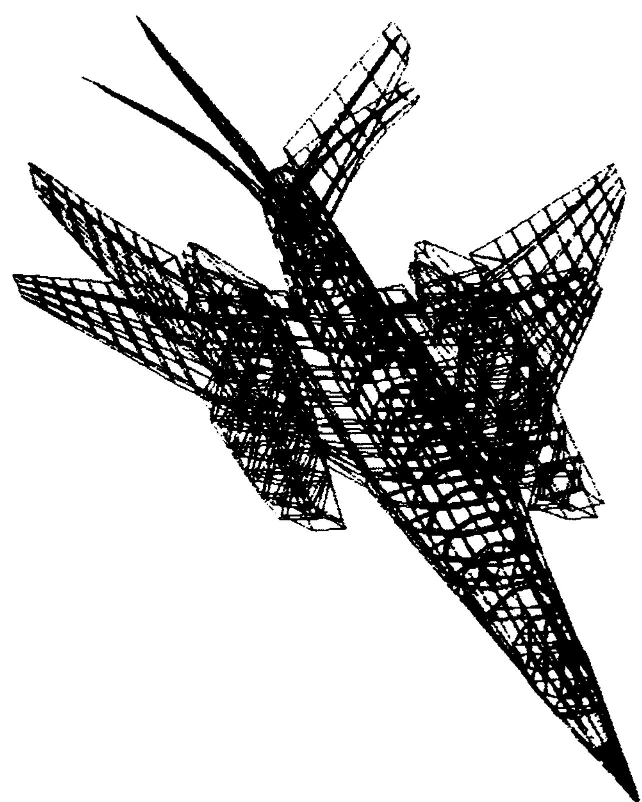

Figure 3

[redacted]

LARGE SCALE VERIFICATION MODEL (MD-80 SERIES)

When we started ADOP development, models like the one in Figure 4 - originally developed during the detailed design development of the MD-80 - were considered too large for use in any aeroelastic design optimization procedure. However, after we had developed procedures for weight and balance and large-scale modal analysis, we were challenged to test our procedures against real results from real aircraft. Since we don't do ground vibration tests on paper airplanes, we found ourselves translating this model, computing its weights, and calculating its modes. This model uses about 30,000 DOF and about 10 modes can be computed in about 1.5 hours on the IBM 3090 computer. Modal animation displays can be achieved, but view selection is much slower than for the smaller models. We divided the model into bays for weights analysis. When we translate the finite-element model we have only the finite-element weight. Other weights are determined by our semi-empirical weights program. This program computes the total bay weights and moment of inertia. From this data we compute the tear weight difference between the finite-element model and the bay weight. This is accomplished by dividing the model into bays with our IMAGES interactive graphics program. The tear weight is then distributed to the surface elements in each bay as a nonstructural mass. Major masses may be excluded from this distribution and lumped directly to one or more nodes using the IMAGES system. Passenger floor loading is assigned to the model using the IMAGES system.

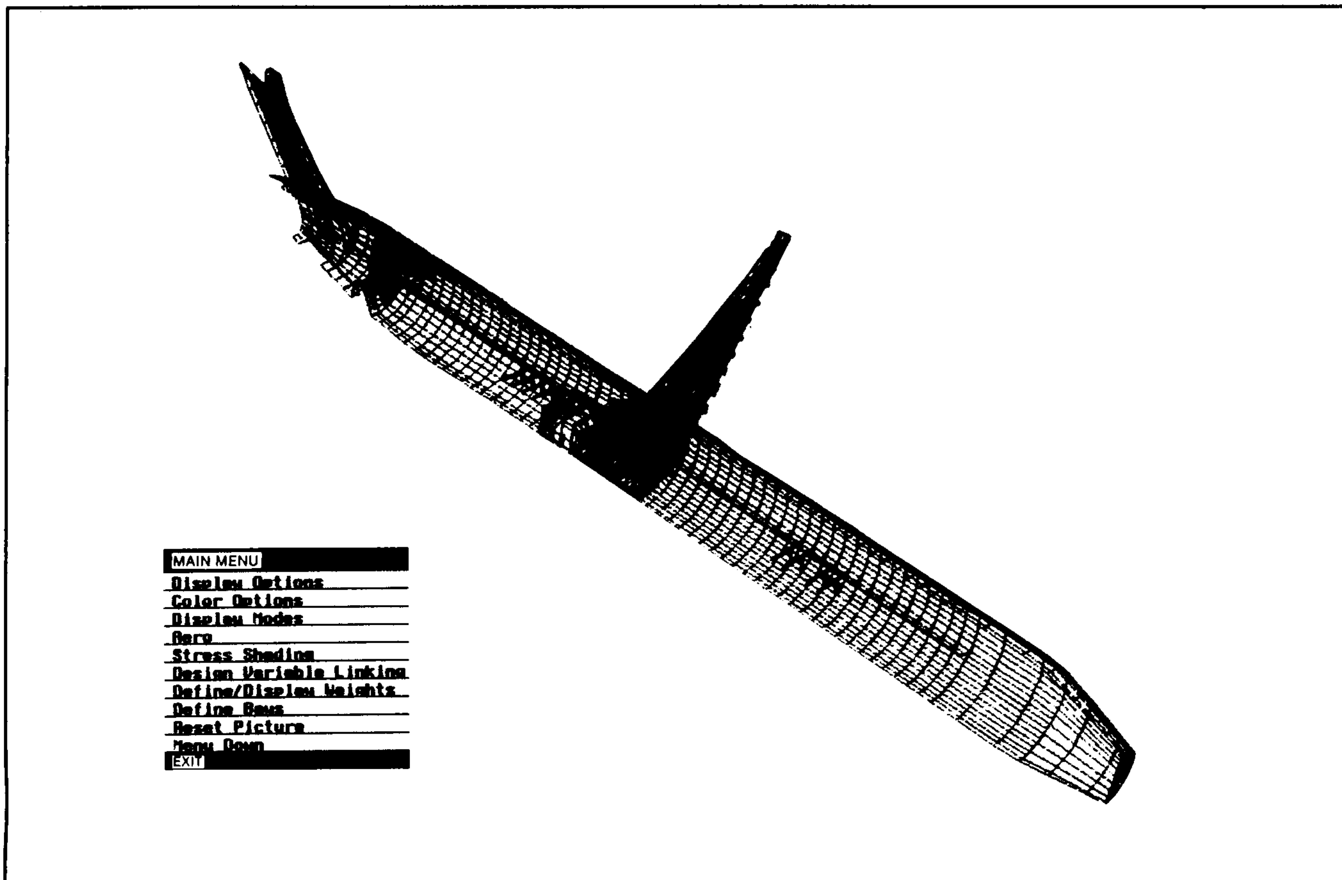

Figure 4

FLAP MODEL

In one of our first major ADOP applications we computed the modes of a flap model for an aircraft that we currently have under design and development (Figure 5). The widespread availability of computer graphics for finite element modeling has resulted in the development of very large structural models. This inboard flap model uses 35,523 DOF which is larger than the entire MD-83 model. With our first attempt at modal analysis of this model, we discovered numerous singularities. Many were traceable to an incompatible programming assumption: that all models should be able to take a general inertia loading at each node. Many of the bar elements in this model had section properties defined in only one direction. Furthermore, many dummy bar elements had been introduced as a modeling convenience that did not represent any real structure.

These fictitious structural elements and numerous boundary condition errors were the source of most of our problems. ADOP detects joint instability by considering the internal load paths resulting from all elements connected to each joint. Two approaches to automatic joint instability correction (NASTRAN Auto SPC) have been used in other programs. In one approach light stability springs are attached to the unstable nodes. In the other approach the unstable nodes are treated as skew nodes and the global DOF for these nodes are rotated so that the singular directions can be grounded out. In ADOP we had taken the the spring approach. This model showed us that this was a bad approach. As a result, ADOP was significantly reprogrammed to use the skew node approach. This corrected most of the problems. A modal analysis with ADOP was then performed and the modes reviewed with the IMAGES system. As a result, this fly-away vane deflection was discovered in some of the modes, as was an error in the model's boundary conditions. These errors were corrected and the modes recomputed.

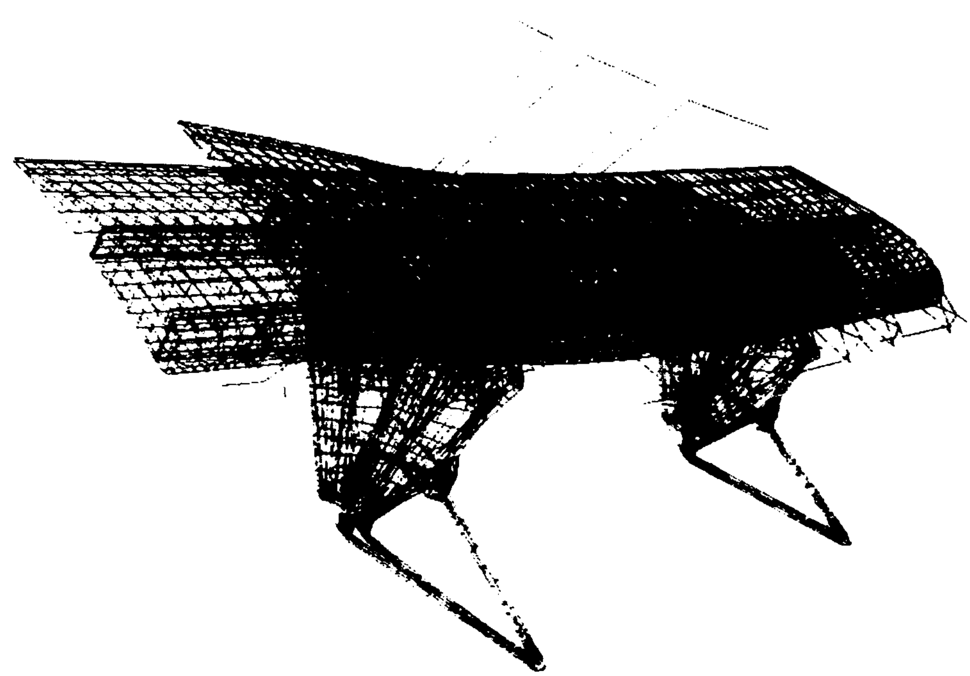

Figure 5

FLAP MODEL TIMING RESULTS

The modal analysis extracted eight modes. One of these is shown in Figure 6. ADOP's front-end processes include model translation from NASTRAN or CASD model files, joint instability identification and correction, equation count, node and element resequencing to minimize the wavefront and envelope size, and the generation of mass and stiffness matrix derivatives (scaled element arrays). These expensive front-end processes result in a well-structured data base for the numerically intensive modal analysis. ADOP uses an adaptive shift subspace iteration procedure for modal analysis. The actual modal analysis of this model was accomplished in 79.26 CPU minutes on the IBM 3090 computer, and 9.70 CPU minutes on the CRAY XMP-18. This speed-up factor of 8.2 is close to the maximum expected computational ratio for these single-CPU machines. Front processes were much lower, resulting in a speed-up factor of only about 2.3 between the CRAY XMP-18 and the IBM 3090. The modes extracted with ADOP were compared with the modes extracted with NASTRAN, resulting in errors of about one percent for all modes. The NASTRAN results were computed with both the Guyan reduction and Householder Givens in superelement procedures and with the NASTRAN block Lanczos procedure. The NASTRAN block Lanczos required 127.14 CPU minutes on the IBM 3090. Direct comparisons between the NASTRAN and ADOP run times are difficult to make because NASTRAN performed more shifts and computed more modes than did ADOP. Block Lanczos should be faster than subspace iteration, but the very efficient implementation of adaptive subspace in ADOP makes it very competitive with NASTRAN Block Lanczos.

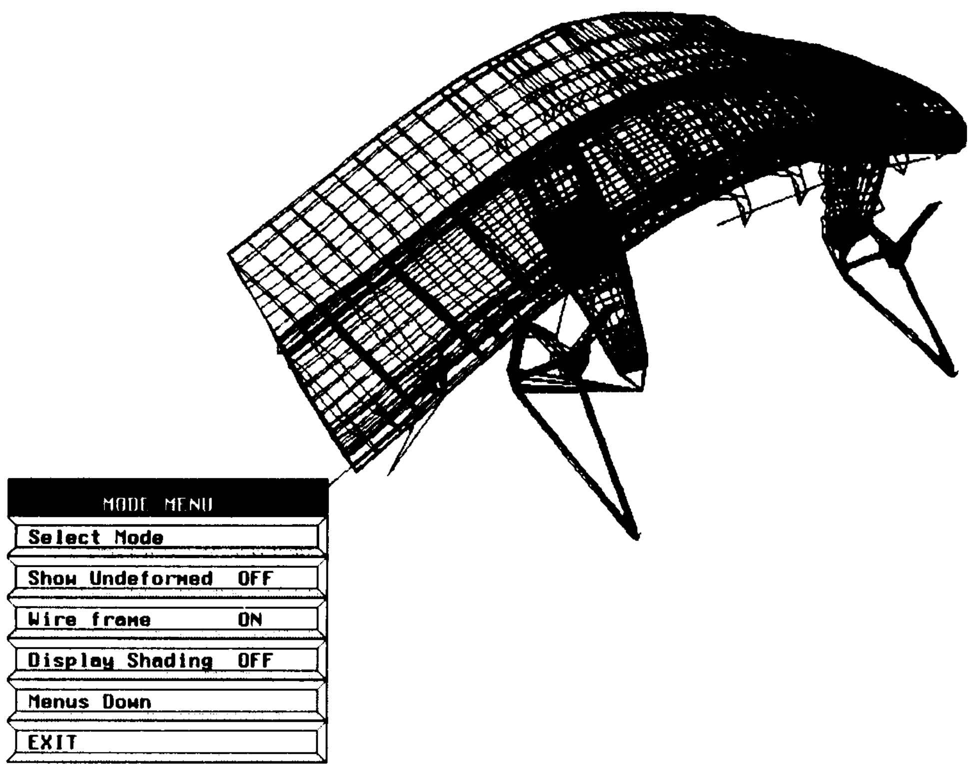

Figure 6

AERO-MESH MODELER FOR DOUBLET LATTICE AERODYNAMICS

In a recent development, work has been initiated to add an aero-mesh modeler to the IMAGES system for aeroelastic analysis and design. Neither PATRAN nor Douglas' Computer Graphics Structural Analysis (CGSA) program provides this kind of modeling capability. Currently, we are developing models from an existing data base of components of generic aircraft parts, as well as from three-view drawings. This new capability has been under development since July 15, 1988. Figure 7 shows the aero-mesh model being developed with this new Douglas graphics system.

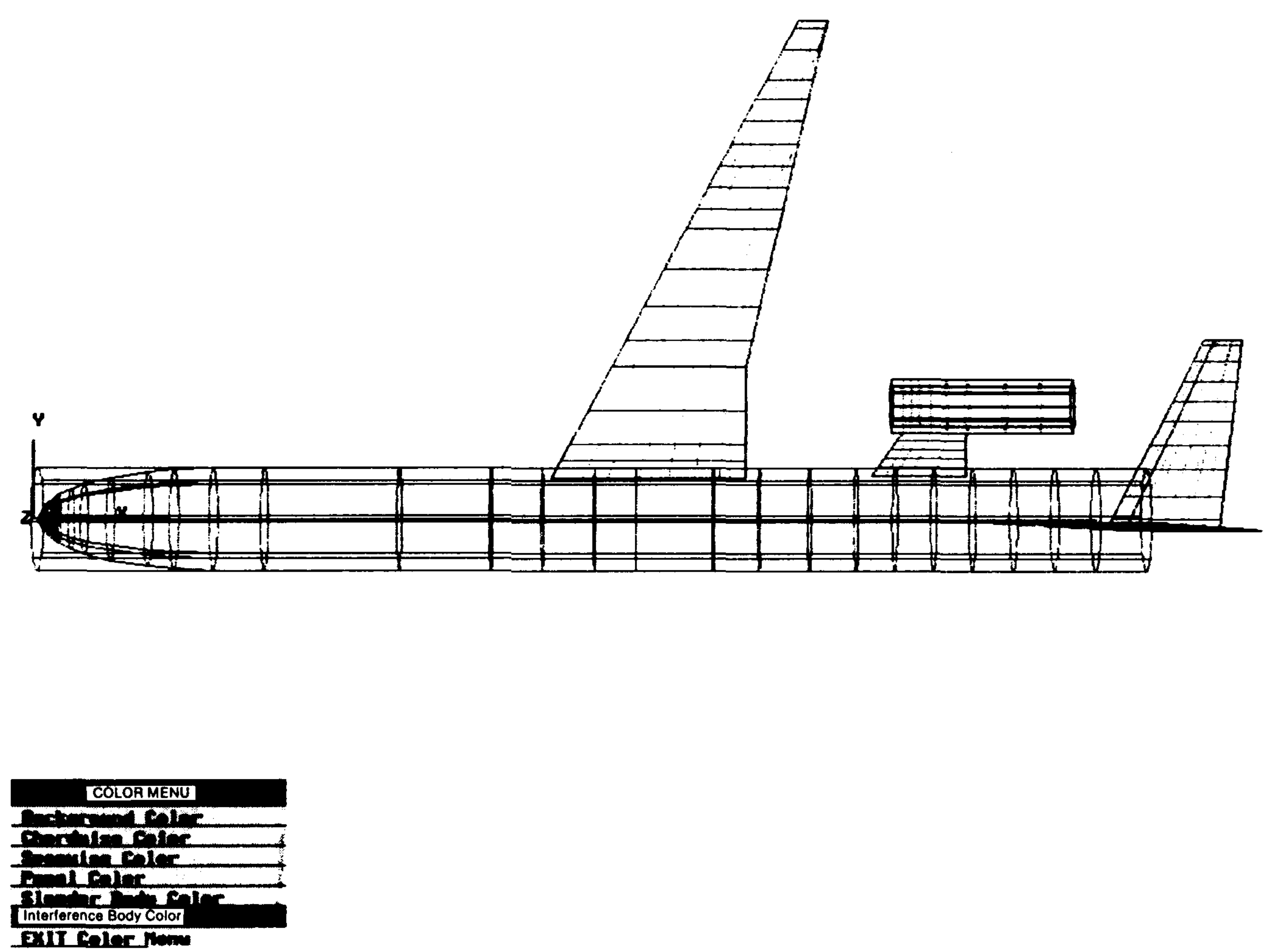

Figure 7

LOOKING BACK

Figure 8 shows the work completed and the work just initiated on the ADOP system. We have completed a large-order static and modal analysis system. We have demonstrated a fully stressed design capability for static strength. We have demonstrated a flutter analysis capability and computed design sensitivities for flutter and static strength. We have in place a time-domain integration system for modal models and work has been initiated on a direct integration package for large structural models. Work has been initiated on a new composite finite element library for analysis and design. We have in place a very powerful direct matrix abstraction language (ACL-DMAP), which in some respects is more powerful than the ASTROS-MAPOL or NASTRAN-DMAP languages. We have initiated work on the new static aeroelastic package, which will be coded largely in ACL-DMAP.

WORK COMPLETED

- LARGE ORDER STATIC ANALYSIS AND FSD DESIGN
- INTERFACE WITH SEMI-EMPIRICAL WEIGHTS PROGRAM
- LARGE-ORDER MODAL ANALYSIS
- FLUTTER ANALYSIS
- DIRECT MATRIX ABSTRACTION LANGUAGE (ACL-DMAP)
- TIME DOMAIN INTEGRATORS FOR MODAL MODELS

WORK JUST INITIATED

- INTERACTIVE GRAPHIC MODELER FOR AERO-MESH
- STATIC AEROELASTIC PACKAGE
- FLUTTER OPTIMIZER
- COMPOSITE FINITE ELEMENTS
- DIRECT INTEGRATORS FOR LARGE FINITE-ELEMENT MODELS

Figure 8

THE ROAD AHEAD

While much has been done, much remains to be done. We must complete work on our flutter optimization system. We must complete the static aeroelastic analysis and design package. We must develop a substructure capability for even larger finite-element models than we have currently analyzed. We must develop new procedures for global-local stress analysis to be used in analysis and design. We must initiate new work on aircraft structural loads. We must coordinate with new work being done in our Dynamics and Loads Research group on transonic flutter and aeroelastics. We must develop new procedures for fatigue life prediction, analysis, and design (Figure 9).

COMPLETE WORK JUST INITIATED

- INTERACTIVE GRAPHIC MODELER FOR AERO-MESH
- STATIC AEROELASTIC PACKAGE
- FLUTTER OPTIMIZER
- COMPOSITE FINITE ELEMENTS
- DIRECT INTEGRATORS FOR LARGE FINITE-ELEMENT MODELS

AREAS OF NEW WORK

- SUBSTRUCTURES, SUPERELEMENTS AND COMPONENT MODE SYNTHESIS
- GLOBAL/LOCAL STRESS ANALYSIS
- AIRCRAFT STRUCTURAL LOADS
- GEOMETRIC NONLINEARITY AND BUCKLING OPTIMIZATION
- TRANSONIC/SUPERSONIC FLUTTER AND AEROELASTIC ANALYSIS AND DESIGN
- FATIGUE LIFE, PREDICTION, ANALYSIS AND DESIGN

Figure 9