

SYNTHESIS OF AIRCRAFT STRUCTURES USING INTEGRATED DESIGN AND ANALYSIS METHODS - STATUS REPORT

Jaroslawn Sobieszczanski-Sobieski and Robert C. Goetz
NASA Langley Research Center

SUMMARY

This paper gives a status report and describes the future work directions of a systematic research effort to develop and validate methods for structural sizing of an airframe designed with the use of composite materials and active controls. This research program includes procedures for computing aeroelastic loads, static and dynamic aeroelasticity, analysis and synthesis of active controls, and optimization techniques. Development of the methods is concerned with the most effective ways of integrating and sequencing the procedures in order to generate structural sizing and the associated active control system, which is optimal with respect to a given merit function constrained by strength and aeroelasticity requirements.

INTRODUCTION

Aircraft design depends on the strong coupling of a multitude of technical disciplines. For example, wing structural sizing is strongly influenced by aerodynamic loads and load control devices which are in turn defined by the structure's static and dynamic aeroelastic characteristics. Conventionally, these interdependencies are included in the design process through a sequence of analyses and iterative reanalyses. An example of one such conventional iterative process used is illustrated in figure 1 (ref. 1). In this process the structure is first sized for strength and is then resized to add stiffness, if necessary, to satisfy flutter requirements. This process becomes more complex when the vehicle includes active control systems, such as flutter and loads control which must be designed concurrently with the structure itself.

A recognized deficiency of the conventional approach, which amounts to a series of suboptimizations, is the inability to optimize the final configuration (refs. 2-5). This inability is because the conventional approach does not maximize a single merit function (objective function) for the total system. That is, an assembly of coupled subsystems, even if each is optimized individually, does not constitute an optimum for the whole system. This deficiency is usually aggravated by economic and time constraints which in practice often preclude closure of all of the iteration loops.

A mathematically consistent alternative approach is needed which leads to an optimal system with all constraints satisfied and all couplings accounted

for. This approach would integrate all of the analyses into one iterative loop with a formalized optimization algorithm as illustrated in figure 2. This approach, although conceptionally simple, cannot be readily implemented today for complex aircraft configurations because of the prohibitive computational costs associated with the large number of repetitive analyses required by the very large number of design variables and constraints.

Langley Research Center has undertaken an activity to develop the analysis and synthesis techniques needed to implement the integrated optimization method shown in figure 2. This activity is a Program to Integrate Controls, Aerodynamics, Structures, Software and Optimization for Vehicle Analysis and Synthesis (PICASSO) (fig. 3). The long-term goal of PICASSO is to develop an integrated multidisciplinary analysis and synthesis methodology for a wide range of aerospace vehicles. Emphasis is focused on developing the methodology necessary to include composite structures, advanced technology aerodynamics, and active controls. The purpose of this paper is to describe the status and future plans of that part of the total effort which is associated with structural synthesis including active controls.

INTEGRATED APPROACH

Several computer codes have already been integrated into a versatile, modular system (ref. 6) to explore various structural synthesis and optimization methods. This system consists of a data base and executive software as depicted in figure 4. The data base includes computer codes to do specific calculations, e.g., a finite element code to do structural analysis (SPAR, ref. 7), numerical data describing mathematical models of specific vehicle configurations, and sets of executive commands in which each set is a procedure carrying out a typical engineering task, e.g., structural resizing for given loads.

Executive software is entirely provided by the Control Data Corporation (CDC) Network Operating System (NOS 1.2). This software consists of a command language and auxiliary utilities which permit storing and retrieving files containing codes, data, execution procedures, and file modification.

Codes currently available in the system are listed in figure 4. Information about these codes is provided in reference 8. In order to utilize existing codes and those which will be developed in the future, a guideline in the development of the integrated system is the ability to incorporate existing codes without internal code changes. This is accomplished by suitable pre- and post-processors. These processors are usually small, stand-alone FORTRAN codes, which perform data conversions to bridge differences between a given code input-output format and the system data storage format. The computer system enables several users to experiment simultaneously on a time-sharing basis with the computations sequenced in various ways within typical engineering tasks, as shown in the right-hand side portion of figure 4.

To develop new synthesis methodology, the integrated system is being used to study various aircraft configurations. Included are several configurations

of a supersonic transport and a subscale model of a fuel efficient subsonic transport. These configurations were selected to represent diverse types of subsonic and supersonic aircraft with both low and high aspect ratio wings. As an example of the complexity of the mathematical model available in the data base, a finite element model of one supersonic transport configuration is shown in figure 5 (ref. 9). One half of the symmetric model contains 750 grid points, 2140 elastic degrees of freedom, and 2400 elements representing construction details as shown in the inserts. The number of variables used to size the structure varies from 720 for the metal wing to over 1900 for the composite wing.

ANALYSIS AND SYNTHESIS METHODOLOGY

Through application studies, the system of integrated computer codes described in the preceding section provides a tool for investigating and developing analysis and synthesis methodology. It is also useful in defining missing technical capability and to identify operations which are now impractical and need further development.

Structural Sizing for Strength

Current capability.- Conventional iterative analyses of aerodynamic loads on a flexible aircraft and iterative resizing of structural components are illustrated in the left of figure 6, as a sequence of two iterative loops, nested in a third overall loop. The sequence of these operations when combined into a common iterative loop is shown in the right of figure 6. Detailed discussion of this new iteration approach is given in reference 10. Resizing of the structure is accomplished by using a nonlinear mathematical programming technique designed to minimize weight of each individual structural component separately. Each component is subject to constraints of strength and local buckling due to internal forces acting from the surrounding structure. These forces are held invariant in the optimization of each component and are updated by analysis of the complete structure. The update analysis is carried out after all components have been optimized. The resizing requires several repetitive iterations (usually 3 to 7). Figure 7 gives an example of a wing resized by this approach. Indicated in the figure is the level of detail of the approach where very localized component dimensions are included as design variables. A more detailed description of the approach is presented in references 9, 11, and 12.

Development direction.- As pointed out in reference 11, this approach does not guarantee a minimum weight design since there is no system level objective function to which all structural components would contribute. To remove this shortcoming, a method similar to that proposed in reference 4 (a systematic, multilevel optimization) is to be implemented and evaluated for metal and composite structures.

Experience to date suggests that improved structural analysis is a key element to future system synthesis. Improvements are necessary to trade,

in a controlled manner, analysis accuracy for computational cost and to generate, as part of the solution, sensitivity (gradient) information needed for optimization. Two concepts for trading analysis accuracy and computational cost (and producing gradient information) are proposed in references 13 and 14, while decomposition of a large structural analysis problem into smaller sub-problems by substructuring is discussed in reference 15. These concepts are broadly referred to as dimensionality reduction and extrapolation methods. Implementation of these concepts are enhanced by several techniques reported in the last decade, which originated from the need to correlate mathematical models with experimental data (refs. 16-18). Seven of these promising techniques are outlined on figure 8 and are currently being evaluated.

Another key need lies in the broad area of computational aerodynamics, because of its obvious impact on the accuracy of the structural analyses results. Improvements are critically needed for predicting loads at transonic speeds, high angle of attack, and for supercritical airfoils. These requirements are for complete wing-body-empennage configurations and include accuracy versus computational cost and data on sensitivity to changes in the configuration geometry and dynamic characteristics.

Structural Sizing for Flutter

Current capability.- Using conventional design methodology a strength resized airframe is analyzed for flutter and, if necessary, stiffened by adding layers of new material as shown for a representative metal wing in figure 9. The amount of new material added is minimized using a nonlinear programming method. The methodology is innovative in two ways: the new material is added to strength sizing as a new minimum gage (ref. 9); the flutter analysis is carried out on a simplified finite element model as compared to the one used in strength resizing (ref. 19).

Development direction.- The next step is to simultaneously combine flutter and strength optimization to realize the benefits of reduced weight as described in reference 2. These benefits are particularly large if the directional properties of composite material are to be exploited (aeroelastic tailoring) as reported in references 20-22.

Structural Sizing for Gust Load Response

Current capability.- Strength sized and flutter free flexible airframes are subjected to a comprehensive dynamic gust response analysis by methods described in reference 23. These methods are computationally expensive for structural synthesis procedures. Therefore, resizing is carried out by a well-known quasi-static gust method which reduces the gust to another steady state maneuver.

Development directions.- For highly gust sensitive aircraft configurations, it will be necessary to include gust as another constraint in the strength-flutter optimization. Therefore, the dynamic response methods will have to be modified for more efficient repetitive use in the optimization loop. A

mathematically rational way of combining statistically defined gust stresses with the deterministic stresses due to maneuvers is being developed. Two candidate approaches are under consideration. One is a combinatorial approach to define the worst possible combination of statistical stresses to be superimposed on the deterministic stresses, The second approach replaces the worst combination with the equal probability combinations.

Structural Sizing Including Active Controls

Current capabilities.- Analytical techniques for active flutter suppression analysis and synthesis are defined in references 24-26. Synthesis capability for flutter suppression exists using modern control theory (ref. 24), the "aerodynamic energy method" (ref. 25), and classical control theory (ref. 26). The results of modern control theory are being practicalized, without having to measure the states of each variable, through the use of nonlinear programming techniques.

An example of active flutter suppression for a strength sized supersonic transport is shown in figure 10. The figure shows the vehicle flutter boundaries with respect to the flight envelope. The dashed line boundary indicates a flutter deficiency of the airframe sized for strength. By using active flutter suppression the flutter boundary is shifted to a position indicated by the solid line, which is outside of the flight envelope. The weight of the active control system is estimated according to reference 27. This weight is about five times smaller than the weight requirement for a structural fix defined in the studies reported in reference 9.

Development directions.- In addition to flutter suppression, capability is being developed to synthesize control systems for gust load alleviation, maneuver load control, and relaxed static stability, using the methods mentioned above. Once these capabilities are developed, studies to determine the maximum benefits on structural sizing and weight by integrating active controls into the initial design stage will be undertaken. The use of formal optimization techniques is to be further expanded to include the active control surface size and location as design variables. Additionally, the optimum manner of controlling aeroelastic behavior will be explored. This will include combining the passive control benefits of composite aeroelastic tailoring and the benefits of active controls.

Improvements are also needed for predicting distributed loads on oscillating control surfaces, especially on supercritical wings. These improvements are needed for the determination of control surface effectiveness and control system authority.

CONCLUDING REMARKS

The coupling between structures, aerodynamics and active controls points to a need for a mathematically rational unified optimization methodology to shape and size the airframe structure. This structural synthesis methodology

| ■■■■■■■■■■ |

should be based on a given merit function (e.g., weight) subject to realistic constraints (e.g., strength and stiffness).

A systematic research program has been established to achieve the development of such an optimization capability. Research on unified strength and flutter optimizations and resizing for gust response is in progress. A parallel effort to improve analysis and synthesis techniques for active controls is also underway. Structural and active control synthesis development is intended to provide the capability to predict the optimum control of static and dynamic aeroelastic behavior of airframes by passive and active means.

Missing elements which need further development for a totally integrated optimization method are

(1) Analytical formulations that give sensitivity results and permit trades between accuracy and computational speed for static and dynamic structural behavior, for definition of steady and unsteady aerodynamic loadings, and for description of active control systems.

(2) Multilevel optimization procedures which permit addressing of global constraints (e.g., flutter) and local constraints (e.g., buckling of a wing cover panel stiffened with stringers).

(3) Advanced computational aerodynamics for conventional and supercritical wings with controls in the transonic and high angle of attack regimes.

(4) Active control synthesis techniques for relaxed static stability and the control of loads.

REFERENCES

1. Sakata, I. F.; and Davis, G. W.; Advanced Structures Technology Applied to a Supersonic Cruise Arrow Wing Configuration. Proceedings of the SCAR Conference, NASA CP-001, Part 2, November 1976, pp. 603-636.
2. Stroud, W. J.; Dexter, C. B.; and Stein, M.; Automated Preliminary Design of Simplified Wing Structures to Satisfy Strength and Flutter Requirements. NASA TN D-6534, December 1971.
3. Sobieszczanski, J.: Sizing of Complex Structure by the Integration of Several Different Optimal Design Algorithms, AGARD-LS-70, Sept. 1974.
4. Schmit, L. A., Jr.; and Ramanathan, R. K.: Multilevel Approach to Minimum Weight Design Including Buckling Constraints. AIAA Journal, vol. 16, no. 2, Feb. 1978, pp. 97-104.
5. Lasdon, L. S.: Optimization Theory for Large Systems. McMillan Co., New York, 1970.
6. Sobieszczanski, J.: Building a Computer-Aided Design Capability Using a Standard Time Share Operating System. Integrated Design and Analysis of Structures, Proceedings of ASME Winter Annual Meeting, Houston, TX December 1975.
7. Whetstone, W. D.: SPAR Structural Analysis System Reference Manual. NASA CR-145098-1, February 1977.
8. Giles, G.: Computer-Aided Methods for Analysis and Synthesis of Supersonic Cruise Aircraft Structures. Proceedings of the SCAR Conference, NASA CP-001, Part 2, Nov. 1976, pp. 637-658.
9. Sobieszczanski, J.; McCullers, L. A.; Ricketts, R. H.; Santoro, N. J.; Beskenis, S. D.; and Kurtze, W. L.: Structural Design Studies of a Supersonic Cruise Arrow Wing Configuration. Proceedings of the SCAR Conference, NASA CP-001, Part 2, Nov. 1976, pp. 659-684.
10. Giles, G. L.; and McCullers, L. A.: Simultaneous Calculation of Aircraft Design Loads and Structural Member Sizes. AIAA 1975 Aircraft Systems and Technology Meeting, Los Angeles, CA, Aug. 1975. AIAA No. 75-965.
11. Sobieszczanski, J.; and Loendorf, D.: Automated Sizing of Large Structures by Mixed Optimization Methods. Second Symposium on Structural Optimization, Milan, Italy, April 1973. AGARD Conference Proceedings No. 123.
12. Sobieszczanski-Sobieski, J.: An Integrated Computer Procedure for Sizing of Composite Airframe Structures. NASA TP-1300, 1978.

13. Sobieszczanski, J.; and Storaasli, O. O.: On the Accuracy of the Taylor Approximation for Structure Resizing. AIAA Journal, vol. 12, no. 2, Feb. 1974, pp. 231-233.
14. Noor, A. K.; and Lowder, H. E.: Approximate Techniques of Structural Reanalysis. Computers and Structures, vol. 4, 1974, pp. 801-812.
15. Noor, A. K.; Kamel, H. A.; and Fulton, R. E.: Substructuring Techniques-Status and Projections. Computers and Structures, vol. 9, no. 1, 1978.
16. Chen, J. C.; and Wada, B. K.: Matrix Perturbation for Structural Dynamic Analysis. AIAA Journal, vol. 15, no. 8, August 1977.
17. Berman, A.; and Flannelly, W., G.: Theory of Incomplete Models of Dynamic Structures. AIAA Journal, vol. 9., no. 8, August 1971, pp. 1481-1487.
18. Chen, J. C.; and Wada, B. K.: Criteria for Analysis - Test Correlation of Structural Dynamic Systems. Journal of Applied Mechanics, Transactions of ASME, vol. 42, no. 2, June 1975, pp. 471-477.
19. Ricketts, R. H.; and Sobieszczanski, J.: Simplified and Refined Structural Modeling for Economical Flutter Analysis and Design. AIAA 18th Structures, Structural Dynamics and Materials Conference, San Diego, Cal., March 1977. AIAA Paper No. 77-421.
20. Aeroelastic Tailoring of Advanced Composite Structures for Military Aircraft. Vol. 3, User's Guide for Procedure TSD, AFFDL-TR-76-100, Feb. 1978.
21. McCullers, L. A.: Automated Design of Advanced Composite Structures. ASME Winter Annual Meeting, Structural Optimization Symposium, N. Y., Nov. 1974, pp. 119-134.
22. Starnes, J. H.; and Haftka, R. T.: Preliminary Design of Composite Wings for Buckling Strength and Displacement Constraints. Proceedings of AIAA/ASME 19th Structures, Structural Dynamics and Materials Conference, Apr. 1978. AIAA Paper No. 78-466.
23. Miller, R. D.; Kroll, R. I.; and Clemmons, R. E.: Dynamic Loads Analysis System (DYLOFLEX) Summary. NASA CR-2846, May 1978.
24. Newsom, J. R.: Synthesis of Active Flutter Suppression Systems Using Optimal Control Theory. AIAA Guidance and Control Conference, Palo Alto, Cal., Aug. 1978. AIAA Paper No. 78-1270.
25. Nissim, E.; and Abel, I.: Development and Application of an Optimization Procedure for Flutter Suppression Using the Aerodynamic Energy Concept. NASA TP 1137, Feb. 1978.
26. Visor, O. E.; and Sevart, F. D.: Preliminary Design Study of a Flutter Suppression Control System for the BQM-34E/F Drone Aircraft with a Super-critical Wing-Final Report. NASA CR-145208, 1976.

27. Anderson, R. D.; Flora, C. C.; Nelson, R. H.; Raymond, E. T.; and Vincent, J. H.: Development of Weight and Cost Estimates for Lifting Surfaces With Active Controls. NASA CR-144937, 1976.

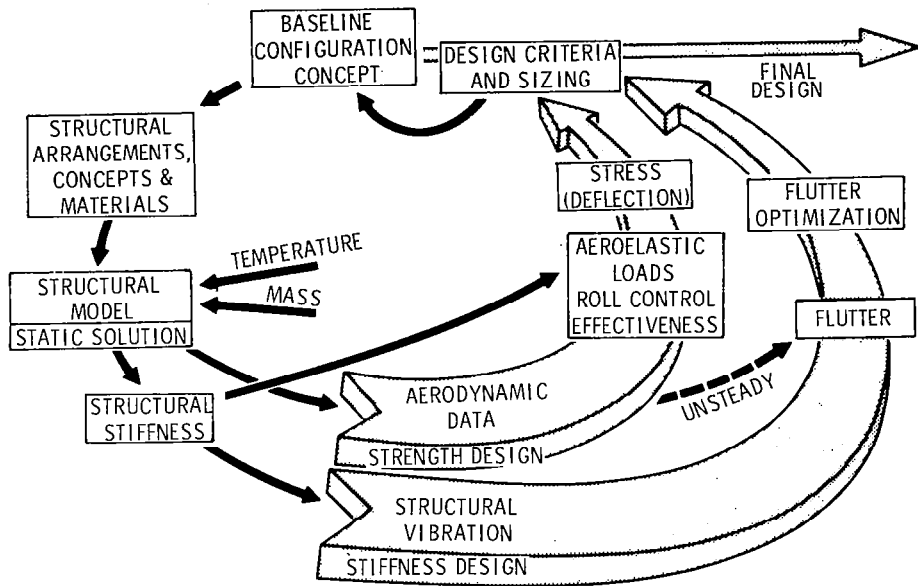


Figure 1 Strength and flutter resizing - typical application (ref. 1).

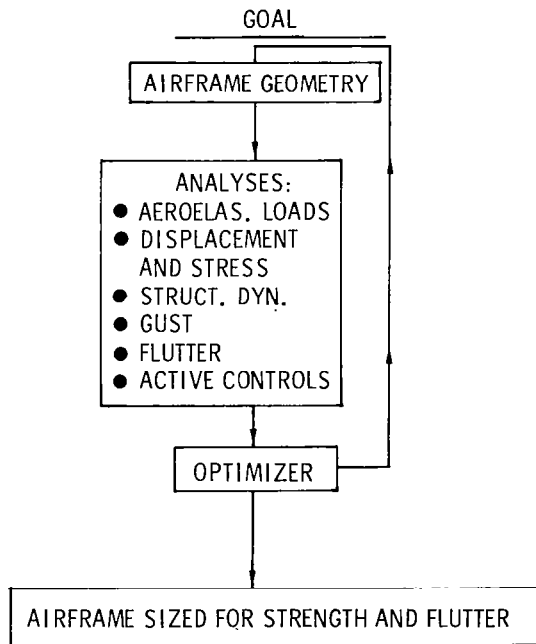


Figure 2 Integrated optimization method.

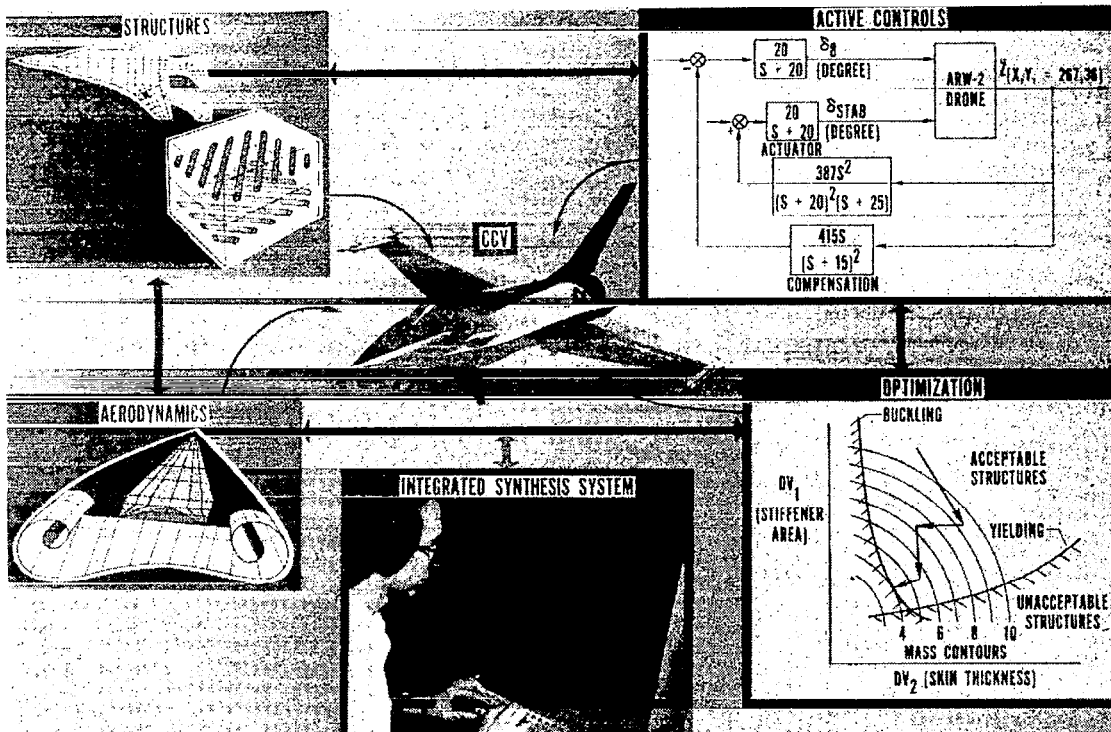
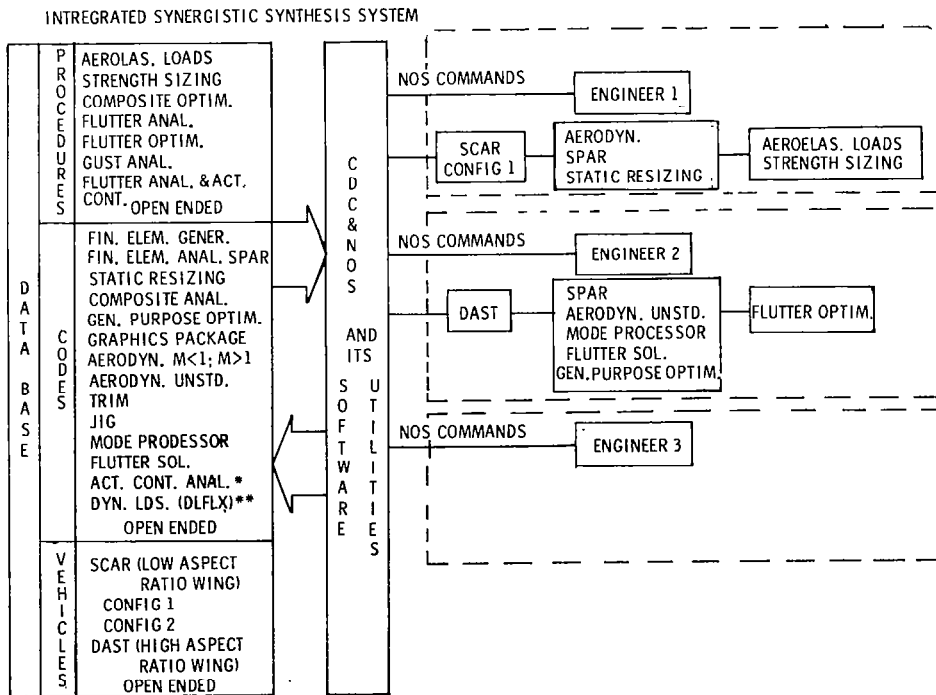


Figure 3 Program to Integrate Controls, Aerodynamics, Structures, Software, and Optimization (PICASSO):



* EXTERNALLY LINKED
 ** IN THE INSTALLATION PROCESS

Figure 4 Present integrated system of programs and data.

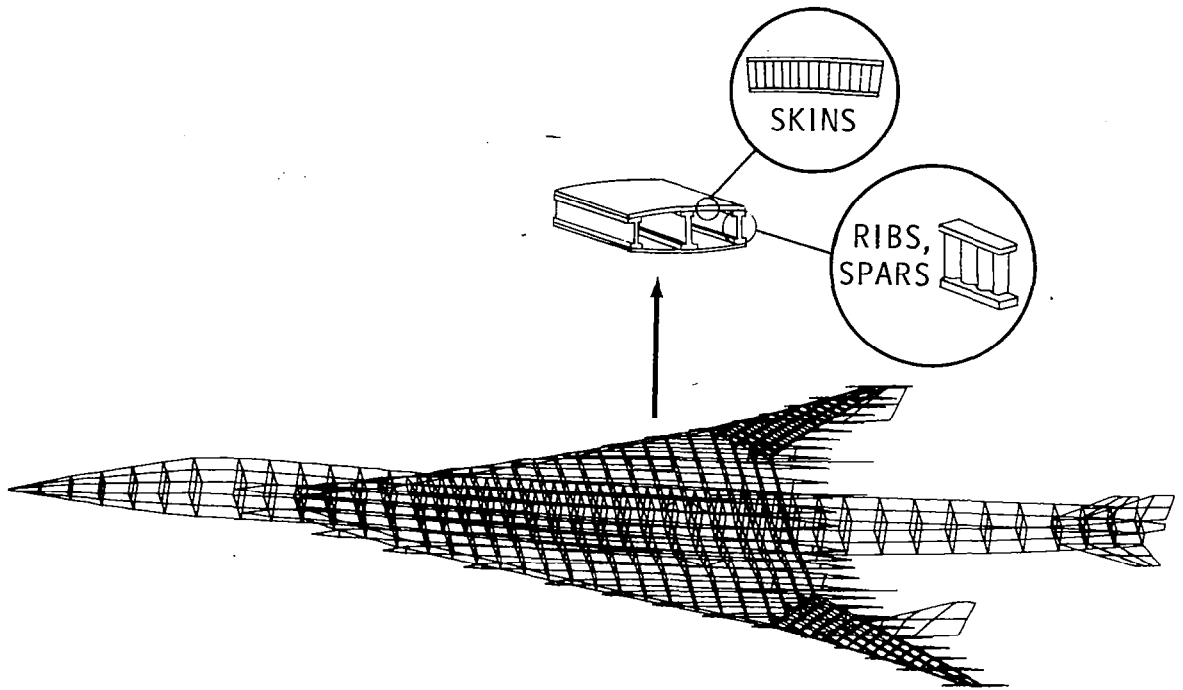


Figure 5 Finite element model of a supersonic transport aircraft (ref. 9).

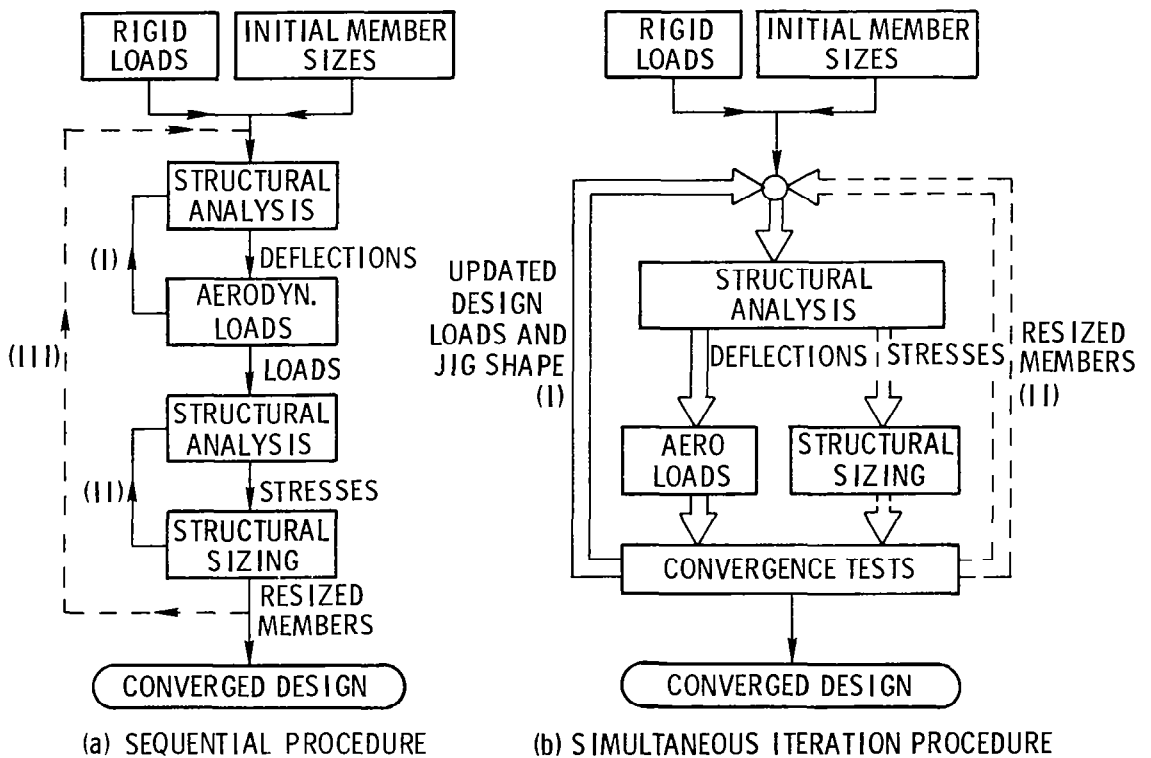


Figure 6 Conventional and improved procedures for aeroelastic load and structural resizing (ref. 10).

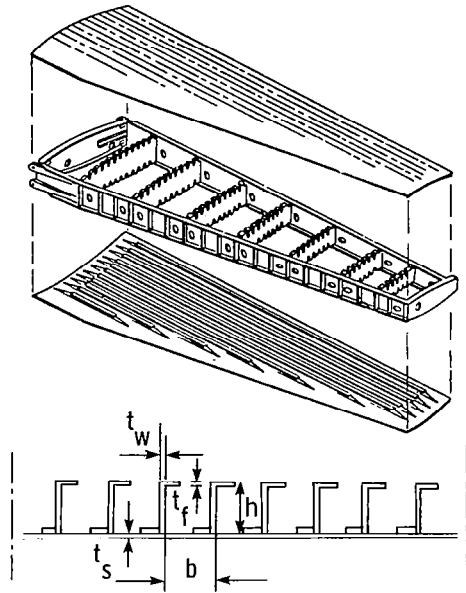


Figure 7 Example of the optimization of the wing structural components.

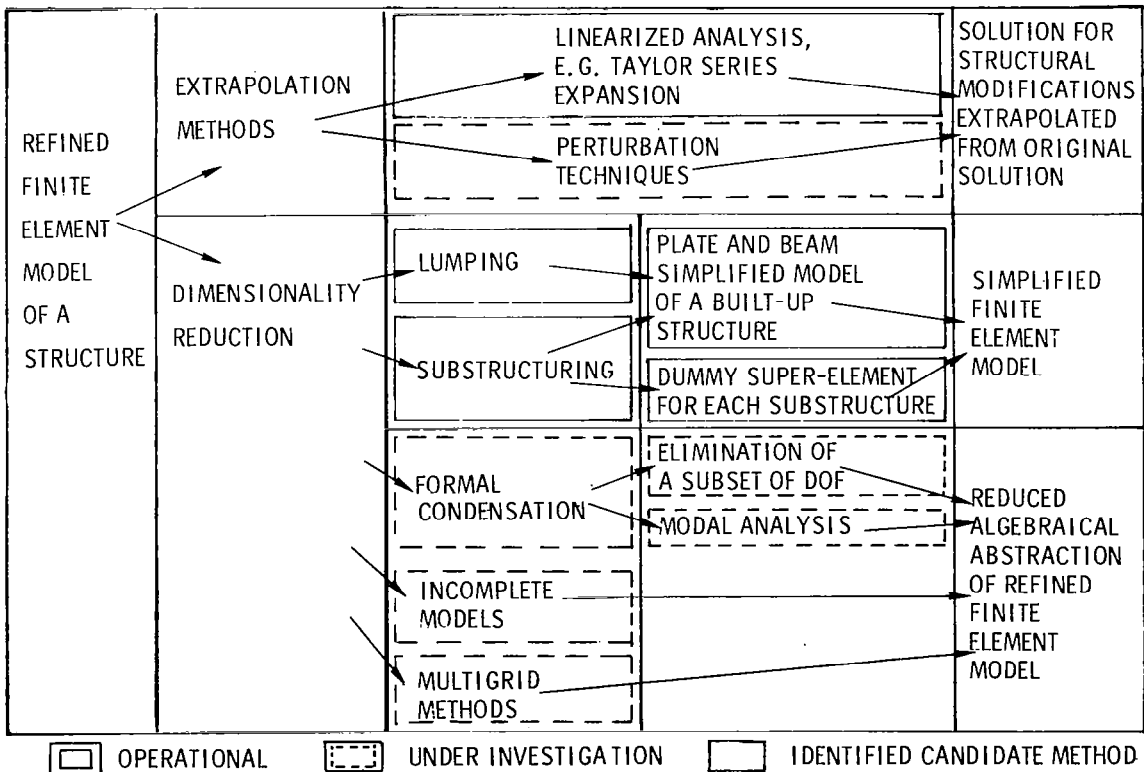


Figure 8 Candidate methods to accelerate structural analysis.

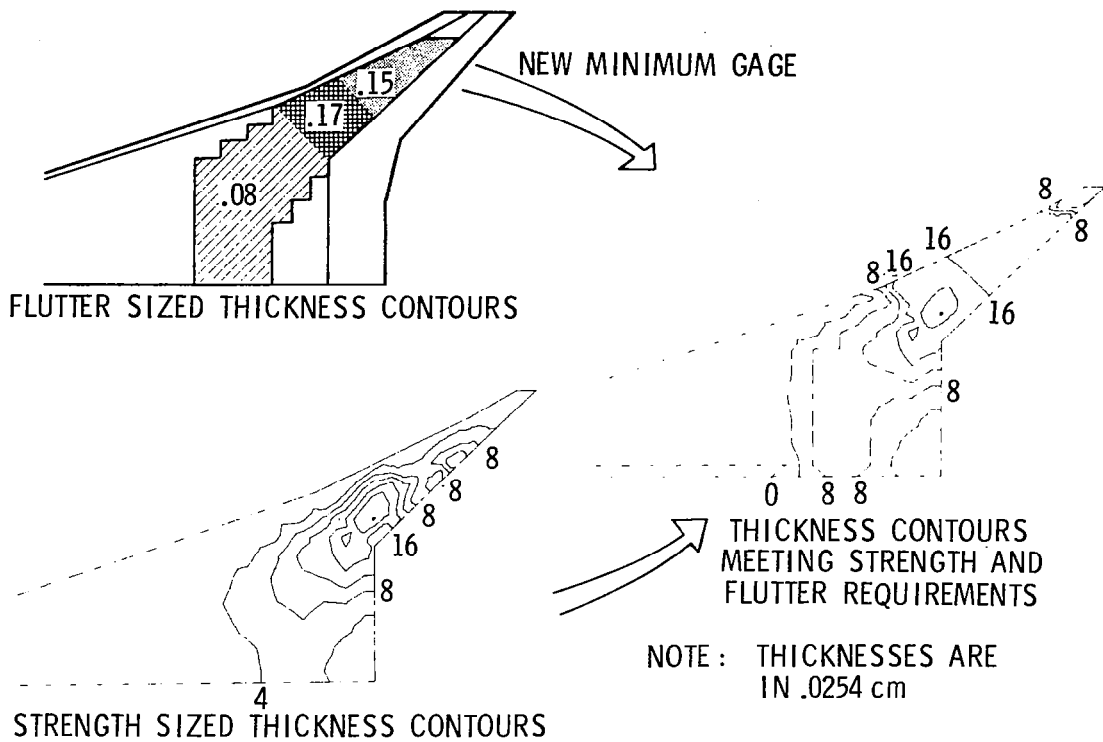


Figure 9 Example of flutter stiffening by imposing a new minimum gage on the strength design (ref. 9).

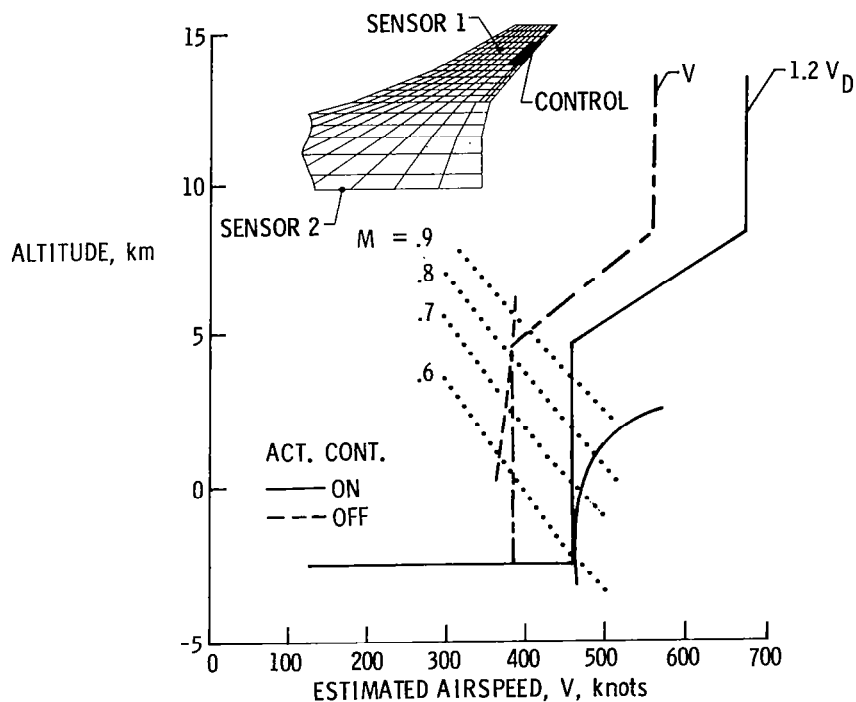


Figure 10 Flutter suppression by means of active controls. M is Mach number and V_D is diving velocity.