Automated Procedures for Sizing Aerospace Vehicle Structures (SAVES)

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A system of computer programs which is being developed to automate the preliminary structural design of a complete aerospace vehicle is described The system, called SAVES, contains automated procedures for: 1) generation of aerodynamic and structures analytical models. 2) calculation of external loads. 3) finite-element structural analysis, 4) member resizing, 5) flutter analysis, and 6) graphic output of design information. The versatility of the model generation routines is demonstrated by structural models generated for a space shuttle orbiter an advanced technology transport, and a hydrogen-fueled Mach 3 transport. Results are presented from a preliminary design study of a Mach 3 transport wing structure. The structure was sized to meet strength requirements and a flutter analysis was made of the resulting design. Two different levels of structural modeling were used to assess the effect of numerical results and computational time.

Introduction

THE design process for aerospace vehicles ranges from early preliminary design to detailed analysis of a final configuration. Existing computerized vehicle-design systems generally fit into two categories: 1) highly automated preliminary design systems based on statistical and empirical relations[1,2] and 2) less automated (but considerably more detailed) analysis and design systems.[3,4] For advanced vehicles, it is often not reliable to use extrapolated data from existing aircraft to form the basis for design decisions. Hence, there is a need for design procedures based on sound analytical methods that are sufficiently automated for use in preliminary design.

The purpose of the present paper is to describe results from a continuing effort at the Langley Research Center to develop efficient automated methods for preliminary structural design. An exploratory study of the preliminary design process led to the DAWNS (Design of Aircraft Wing Structures) program[5] which completely automates the strength design of aircraft wing structures. Procedures intended to automate the preliminary structural design of a complete vehicle based on both strength and stiffness requirements are currently under development. In this paper, the status of one system of computer programs called Sizing of Aerospace Vehicle Structures (SAVES) is discussed. The emphasis in the development of the SAVES system is to provide a basic framework of analysis and design procedures having an adequate depth of analysis to perform meaningful research on automated design methods. Various automated design procedures will be evaluated by exercising the SAVES system on vehicles of current interest. Therefore, future developments of the system will be tailored to satisfy these particular requirements rather than to provide a comprehensive, highly efficient, integrated design system which would satisfy the needs of a broad spectrum of users.

The general philosophy employed in the development of DAWNS and SAVES is described along with each step in the automated structural design process: 1) generation of external shape and finite-element model, 2) determination of external loads, 3) finite-element structural analysis, 4) member resizing based on fully stressed design for strength and other techniques for stiffness (flutter), and 5) graphic presentation of output information.

The versatility of the automated routines used in SAVES for generating finite-element models is demonstrated by the structural models developed for three vehicles of current interest: a space shuttle orbiter, an advanced technology transport, and a hydrogen-fueled Mach 3 transport. In addition, some preliminary structural design information generated by SAVES during a study of the Mach 3 transport wing is presented to illustrate various features of the program and the type of information that can be generated.

Automated Design Procedures for Aerospace Vehicle Structures

The general philosophy leading to an automated structural design program is to assemble efficient, discipline-oriented programs (configuration, loads, structural analysis, etc.) into one system, provide for efficient data transfer between disciplines, and provide the logic that will evaluate a design, make systematic design changes, and loop through the analysis-evaluation-design change cycle in an iterative process until the desired design is established.

Ideally, a design program would be able to consider a complete vehicle modeled in great detail in a very small amount of computer time. However, these requirements are contradictory. Realistically, these requirements can be approached by developing design programs which are tailored to a particular phase of the design process: crude models and short-run times for early preliminary design progressing to refined models, more complete analyses, and correspondingly longer run times for later design phases. This procedure is greatly enhanced by the capability to transfer design data from the initial phase to progressively more refined phases.

The DAWNS program is an example of a program tailored for use during early preliminary design when many design alternatives must be considered. DAWNS is limited to the strength design of wing structures using a relatively crude structural model. However, the computational time and computer storage requirements are small, and the program is

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Index categories: Aircraft Structural Design (Including Loads); Optimal Structural Design.

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completely automated. By using programs such as DAWNS, the various design alternatives are reduced to a few which must be refined and studied in greater detail in the latter phase of preliminary design. The SAVES system of programs is intended for use in this phase of design and can consider a refined model of a complete vehicle. However, the analysis programs required for the more refined models tend to require relatively large amounts of computer storage and computational time and hence are not readily incorporated into a completely automated system.

The cyclic design process currently used in SAVES for a given fixed external shape is shown schematically in Fig. 1. The blocks on the lefthand side of the figure show the portions of the process based on structural strength wherein the mass of the structure is minimized, subject to the requirement of having sufficient strength to carry the external design loads. The blocks on the right side illustrate the additional consideration of flutter, which depends on the stiffness of the structure. Other factors such as structural reliability (strength) and static aeroelastic effects (stiffness) should be considered but, as yet, are not included in SAVES.

Presently, the various analysis and design modules indicated by the boxes in Fig. 1 are not integrated into a single program, but are operated as a system of separate programs with data transferred between modules by punched cards or magnetic tapes. Analytical models are used to represent the actual vehicle during this design process: panels arranged on the external surface of the vehicle are used for aerodynamic calculations and the structure is represented by an assemblage of finite elements. The design data calculated by each portion of the system are referenced to these analytical models. Efficient methods of data transfer between models used for various disciplines (aerodynamics and structures), as well as between models with different levels of refinement within a given discipline, are an essential requirement of automated design systems. Static aeroelastic effects are not presently included in the strength design so aerodynamic pressure distributions are transformed to a set of statically equivalent forces at the structural grid points. For the flutter analysis, the behavior of the structure is represented by contributions of the natural vibration modes whose deflection shapes are transformed to the aerodynamic grid using a polynomial curve-fitting procedure. Furthermore, simple, yet versatile, input is necessary so that excessive time for input preparation does not negate the effectiveness of efficient design and analysis procedures. Thus, automated input data generation routines were developed for SAVES along with procedures to provide an interface between the aerodynamic and structural models.

Existing analysis and design programs of sufficient capacity to handle refined models of a complete vehicle have been assembled into the SAVES system and are operational. Certain modules shown in Fig. 1, such as EXTERNAL CONFIGURATION and GENERATE STRUCTURAL ARRANGEMENTS, are well defined, whereas others, such as MASS PROPERTIES and PARAMETRIC FLUTTER FIX (shown in the dashed blocks), have not yet been incorporated into SAVES. Future effort on SAVES will be directed at increasing the efficiency of existing modules, providing better integration of, and data transfer between, the various modules, and incorporating modules which currently are not included.

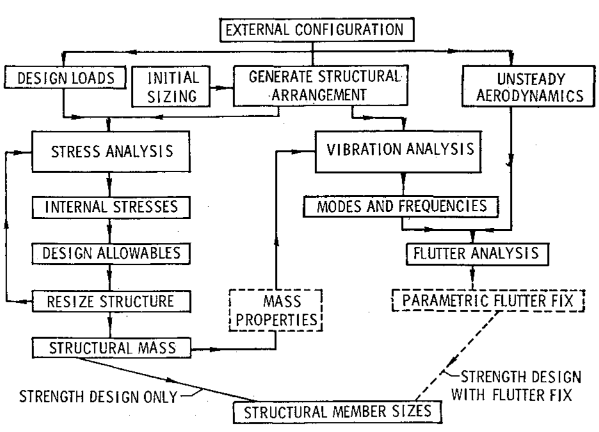

Fig. 1 Structural design process in SAVES.

Input Data Generation Routines

Input data generation routines were developed for SAVES for use in preliminary design studies. Although the routines have been exercised primarily on aerospace vehicle configurations, they are sufficiently general for application to a wide variety of stiffened shell structures.

Data generation routines substantially reduce the man-hours required for model generation since they require a minimum of input data which can be readily obtained from preliminary drawings. The routines also greatly reduce errors resulting from such factors as mispunched data cards and incorrectly transcribed data—problems that are frequently experienced by the analyst when generating models by hand. An external shape is defined using the methods described in Ref. 6. Data generation routines are used to generate a finite-element model of the structure within this external shape. However, the generation of the finite-element model is not completely automated, in that the major components of the structure (wing, fuselage, empennage, etc.) are generated separately, and alterations needed to connect these components are made by hand. Details of preliminary versions of these routines are given in Ref. 7.

The versatility of the routines is demonstrated by the structural models generated for three vehicles of current interest: a space shuttle orbiter, an advanced technology transport, and a hydrogen-fueled Mach 3 transport. The level of sophistication of the preliminary design stage of each vehicle is indicated by the complexity of its structural arrangement. Computer-generated drawings of models of these vehicles are shown in Figs. 2–4, and data pertaining to the model generation are given in Table 1. The models generated are for one-half of the vehicle since, by using symmetrical and antisymmetrical

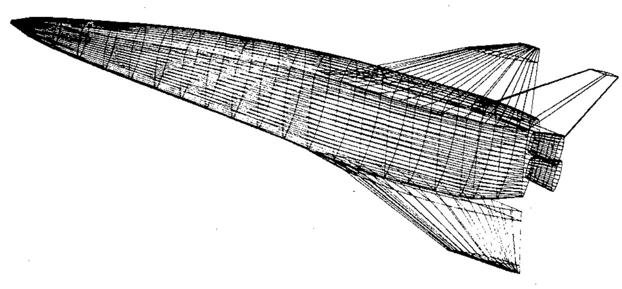

Fig. 2a Space shuttle orbiter concept, external shape.

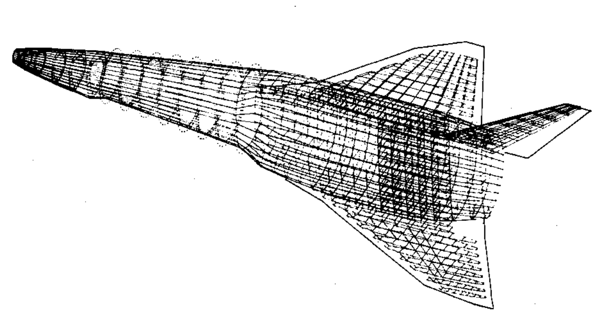

Fig. 2b Space shuttle orbiter concept, finite-element model.

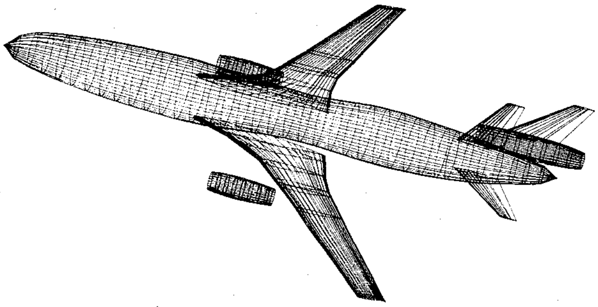

Fig. 3a Tri-jet advanced technology transport concept, external shape.

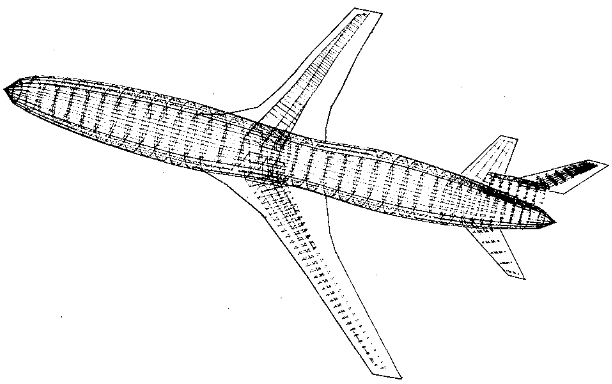

Fig. 3b Tri-jet advanced technology transport concept, finite-element model.

analyses, the behavior of the total vehicle can be considered. Graphical symmetry was used to make the drawings of the complete models, but information given in Table 1 is for half-models.

The most complex structure considered is for one concept of the shuttle orbiter developed during the phase B studies. The numerically defined external shape and corresponding finite-element model generated within this shape are shown in Figs. 2a and 2b, respectively. Structures for the aerodynamic surfaces (wings and empennage) are composed of membrane plate elements for the skin panels and shear elements for the rib and spar webs. Frames, longerons, and skin panels are represented in the fuselage model.

The fuselage frames are modeled as deep beams; however, models could also be generated using bar elements for the frames. A portion of the load-carrying structure is a double-bubble fuel tank with external frames. This structural detail and the incorporation of external frames on the tank portion of the structure and internal frames on the remainder of the structure were readily modeled using the automated routines.

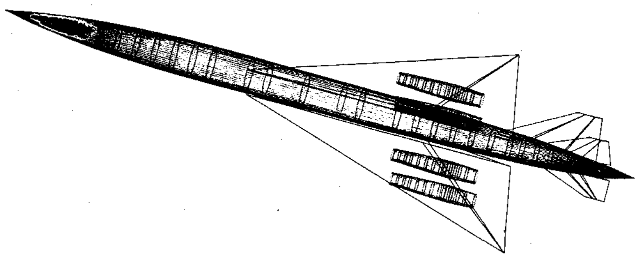

Fig. 4a Hydrogen-fueled Mach 3 transport concept, external shape.

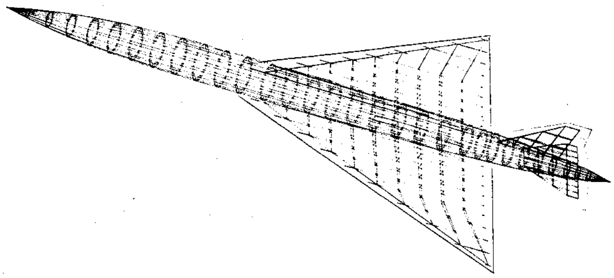

Fig. 4b Hydrogen-fueled Mach 3 transport concept, finite element model.

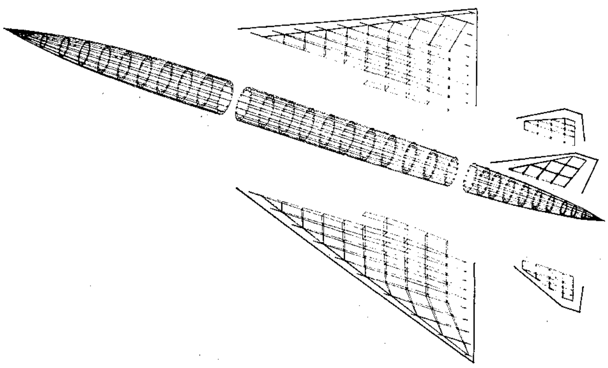

Fig. 4c Hydrogen-fueled Mach 3 transport concept, exploded view of finite element model.

A typical advanced technology transport (ATT) such as the one shown in Fig. 3 is characterized by its area-ruled fuselage and highly cambered supercritical wing. Wing structures and horizontal or vertical tail structures are generated by the same routine. The nacelle structure located between the fuselage and vertical tail was generated using the same procedures as were used to generate the segments of the fuselage structure.

Table 1 Model generation data

Model	User prepared input cards		Cards in automatically generated structural model deck	Time for input preparation (man-hr)	Unconstrained degrees of freedom
	Aerodynamic	Structures			
Space shuttle orbiter (Fig. 2)	106	65	6500	<8	4845
Advanced technology transport (Fig. 3)	92	138	6200	<10	4821
Hydrogen-fueled Mach 3 transport (Fig. 4)	32	143	4000	<8	2547

The hydrogen-fueled Mach 3 transport shown in Fig. 4a was one of several used in recent mission analysis studies of hypersonic transports.[8] The finite-element model generated for this configuration is shown in Fig. 4b. The complete models consist of several individual components which are generated separately and must be joined together manually. Figure 4c presents an exploded view of the Mach 3 transport finite-element model. Such views allow evaluation of all the model components without the structural complexities occurring at the intersections. This view required a single translation of the unique coordinate system assigned to each component.

Sizing of Structural Members

The process used to size the structural members is outlined in Fig. 1. Prior to analyzing the structure, it is necessary to define the topology of the model, define initial member sizes (usually uniform over the entire structure unless a variable thickness distribution obtained from another preliminary design program is available), and determine the external loading. Currently, the aerodynamic pressures on the lifting surfaces are obtained from a supersonic Mach box program.[9] These pressures are converted to forces at the structural nodes with the same interface procedure used in DAWNS. It is anticipated that a version of the Woodward program[10] will be incorporated in SAVES which will provide both subsonic and supersonic analysis capability for wing-body combinations. Other loading conditions, such as landing or taxi loads, must be defined external to the SAVES system.

With the models and external loads defined, a static stress analysis can be made. The finite-element analysis program currently used in SAVES is NASTRAN (NASA Structural Analysis).[11,12] This analysis program is capable of analyzing finite-element models containing several thousand elements; models of this size are often necessary to represent a vehicle in the latter stages of preliminary design.[13] Although the current version of NASTRAN (Level 12) is relatively inefficient compared to state-of-the-art programs,[13,14] anticipated improvements will decrease average run times for the next public release of NASTRAN (Level 15) by approximately a factor of 3,[15] and planned future improvements are expected to produce a similar decrease between Levels 15 and 16.

The fully stressed design technique, which is used extensively in aircraft design,[16,17] is currently used in SAVES. During each iteration of the design process, the program resizes the cross-sectional dimensions of every member to move toward a fully stressed design based on minimum material gage restraints, buckling allowable stress, and material yield strength.

Buckling allowables are usually included in a fully stressed design program by specifying reduced material strength allowables for each member. In DAWNS and SAVES, buckling is included using mass-strength analyses[18,19] for flat plate and circular arc corrugated shear webs and flat plate, honeycomb and truss core sandwich cover panels. Buckling can also be incorporated into a design system by subroutines containing techniques for interpolating from previously generated design curves. A characteristic dimension for each member, such as width for plates, length for wide columns, or depth for shear webs, must be specified when using such mass-strength analyses. Often, in preliminary design, several actual members are represented by a single finite element in the structural model. Procedures which determine the number of actual members lumped into each finite element must be included so that the characteristic dimension based on the actual structure can be calculated.

An alternative to the fully stressed design procedure for fuselage structures is the mixed optimization method suggested in Ref. 20. In this method, the frame stiffness is specified, frame dimensions are determined using mathematical programing techniques, and the longerons and skin panels are sized using fully stressed design techniques. This procedure is repeated for different frame stiffnesses until the minimum mass design is determined. Such a procedure could be incorporated into the SAVES system.

The design process shown in Fig. 1 follows the conventional approach of designing for strength and "fixing" for flutter. Although considering strength and flutter design requirements concurrently might lead to lighter designs in some cases,[21] the present process may be sufficient for preliminary design for conventional metal construction. However, when designing advanced vehicles having filamentary composite primary structures, simultaneous optimization for both strength and flutter will certainly be desirable, since the properties of such materials permit a high degree of precision in tailoring and modifying stiffness and strength properties in a structure. Currently, the "flutter fix" in SAVES consists of parametric changes such as increasing the thickness of user-selected wing-box cover panels. However, it is anticipated that more sophisticated techniques such as mathematical programming,[21-23] or fully energized structures[24] will eventually be incorporated into SAVES. Such techniques would permit consideration of strength and flutter requirements concurrently.

Design Data and Display Techniques

Structural design programs can be used to provide the detailed information needed by the structural designer and to provide structural mass sensitivities for use in complete vehicle design synthesis studies. The detailed design information is needed to check the validity of results obtained from each step in the design process and to indicate possible design changes if a resulting design does not meet all specifications. Since these design data are so voluminous, an important part of a design system is the graphical output of these data.

The DAWNS program is implemented on an interactive cathode ray tube console which gives immediate graphical displays of design data. The designer can assess this information and make changes based on engineering judgment directly in the design process. Because of the larger computational times associated with SAVES, it does not appear feasible to implement the entire system of programs on an interactive console. However, the ability to retrieve detailed information from storage in a data base and examine it in graphical format on a CRT (cathode ray tube) is an addition to SAVES which would greatly facilitate the assessment of these data.

Contour plots also provide a convenient means of displaying various types of design data. Contour plotting capability has been developed for the SAVES program, and a preliminary version of this procedure is discussed in Ref. 7. A contour plot of the Von Mises effective stress in the cover panels of the Mach 3 transport wing (Fig. 4b) is shown in Fig. 5. The magnitudes of the contour labels have been scaled for ease of presentation and hence show only relative magnitudes. In addition to stress distributions, other quantities such as static displacements, vibration mode shapes, and panel thickness distributions can also be presented in this form.

Preliminary Design Study

To illustrate typical results and computational times from both DAWNS and SAVES, some preliminary design results will be presented for the wing structure of the Mach 3 transport shown in Fig. 4. The base line or reference wing configuration used in this study is shown in Fig. 6. Basic geometric parameters of the delta wing are total planform area $S = 646$ m^2, leading-edge sweep angle $\Lambda = 65°$, and maximum airfoil thickness ratio $t/c = 0.05$ at the two-thirds chord location.

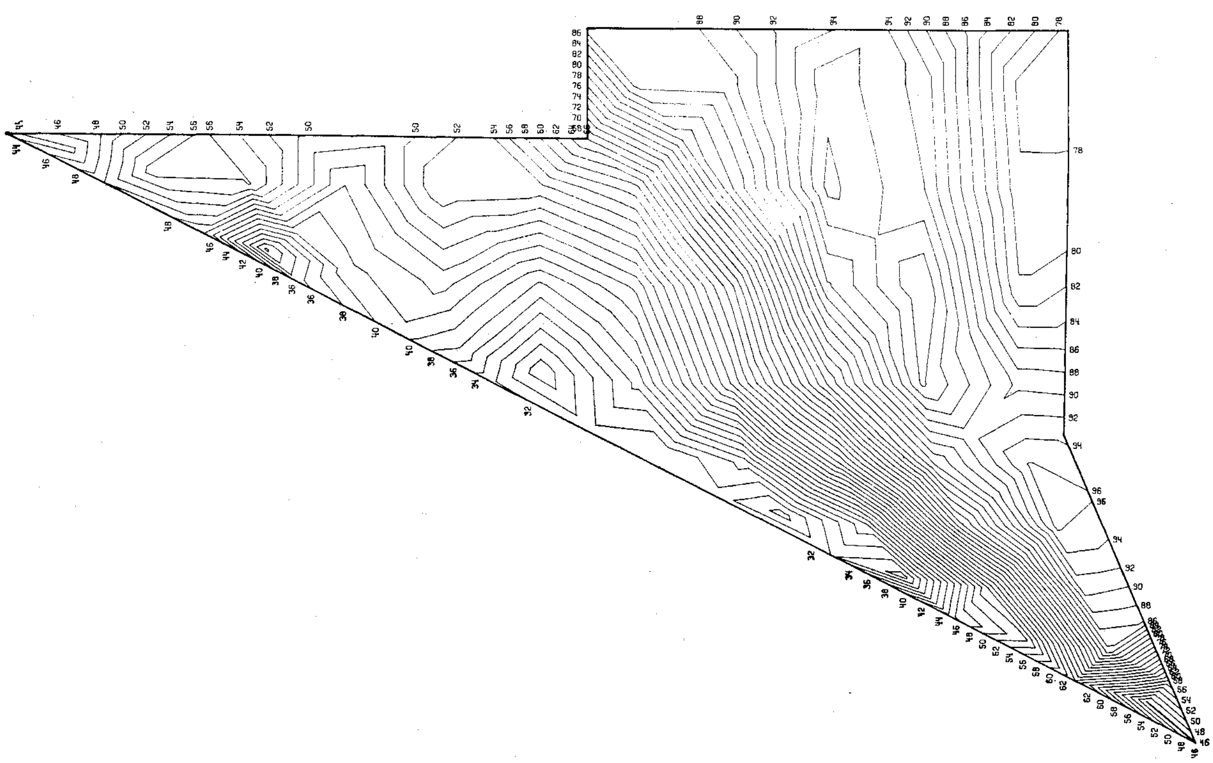

Fig. 5 Von Mises effective stress distribution.

In the study of Ref. 8, the airfoil was asymmetric with a flat lower surface, as shown in Fig. 6. However, DAWNS is restricted to symmetric airfoils, and a diamond airfoil was used for the present study.

The structural layout, typical of a delta wing, has a carry-through structure near the trailing edge of the wing, and the remaining spars are assumed to be attached to fuselage frames. The wing structure was assumed to be constructed of titanium. Cover panels of the wing were taken to be honeycomb core sandwich of 0.02 core density with a fixed depth of 2.54 cm. The rib and spar webs were taken to be circular arc corrugation. The design condition used in the study was a 2.0-g symmetric pull-up maneuver at $M = 3.0$ for a total aircraft mass of 236,000 kg. The effects of the inertial loads of the engine and control surface masses and the engine thrust loads were neglected.

The two finite-element models used in the study are shown in Fig. 7. The wing cover panels were modeled using membrane plate elements, and the ribs and spars were modeled by shear webs. Every actual structural member is represented by a finite element in the model shown in Fig. 7a, which will be referred to herein as the refined model. In the less refined (or lumped) model, several actual structural members are represented by each finite element (Fig. 7b). The number of nodes and elements are given on the figure for each model. The boundary conditions used in the strength design consisted of constrained normal or in-plane displacements at the specified node points shown in Fig. 7.

DAWNS Results

The mass of the idealized structure normalized with respect to the mass of the base line configuration is shown in Fig. 8 for combinations of 55°, 65°, and 75° sweep angles and 3, 4, and 5% thickness ratios. The entire strength design process was carried out using the lumped model for each of these design points.

The study was initiated to determine the change in structural mass with change in sweep angle for a fixed wing area equal to the base line wing area and for the base line thickness ratio of 5%. This procedure resulted in corresponding changes in aspect ratio, as shown by the planform sketches in Fig. 8.

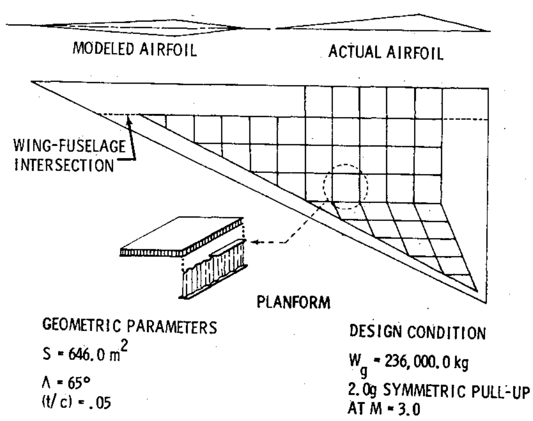

Fig. 6 Baseline wing configuration.

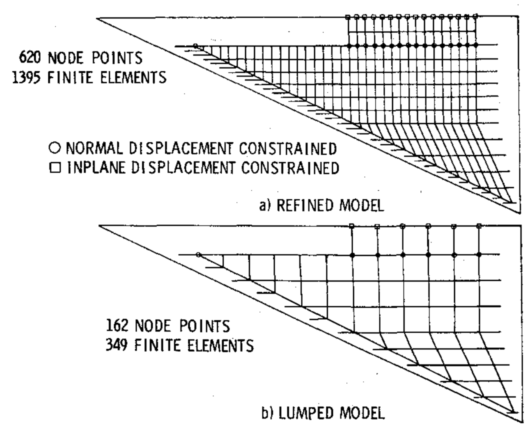

Fig. 7 Finite-element models of base-line wing structure.

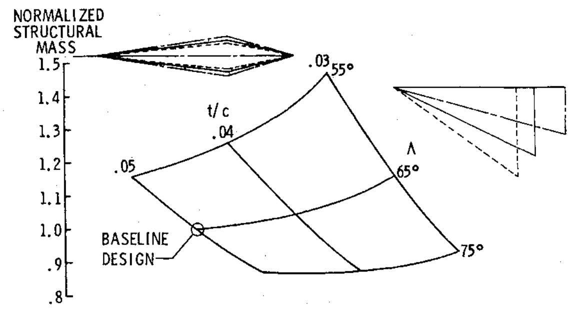

Fig. 8 DAWNS results for Mach 3 transport wing structure.

The initial study revealed that large areas of the wing cover panels were minimum gage material, and that the proportion of the wing mass designed by minimum gage considerations increased as the sweep angle increased. These results suggested that reducing the thickness ratio of the wing might yield an improved design (particularly for larger sweep angles), since the reduction of thickness would reduce the aerodynamic drag and might not significantly increase the structural mass.

Subsequent calculations confirmed that the reductions in thickness ratio did not significantly increase the wing mass, with the exception of the 55° wing at the lowest thickness ratio, as shown in Fig. 8. However, selection of an optimum design based on some performance characteristic such as range would require a trade study to determine the thickness ratio at which the reduction in drag would be negated by the increase in structural mass. It should be noted that the important consideration of flutter would have to be included in such a trade study because the thinner wings are more likely to violate the specified flutter requirements.

The DAWNS results were obtained using a CRT interactive console. Spar spacing was varied by the program user until the minimum total wing mass was determined. The number of spars of minimum mass was found to vary slightly with sweep angle. Each complete, fully stressed design to five iterations required approximately 4 min of central processing time on a CDC (Control Data Corporation) 6600 computer. About 3 hr were spent at the CRT console in generating the results shown in Fig. 8. This time included determination of proper spar spacing and assessment of the graphical displays of data as it was being generated.

SAVES Results

Only the baseline configuration was studied using the SAVES system of programs. The sequence of design procedures was exercised on both the lumped and refined models, and three design cycles were required to achieve converged results. Relative computational times required for each strength design are shown in Fig. 9. For the lumped model, the SAVES design system required considerably more time than that required by DAWNS. This is to be expected, because DAWNS was tailored to be computationally efficient. The SAVES system, on the other hand, has a much larger model capacity and a broader analytical capability with the associated penalty of larger computation time.

The mass of the lumped model was in close agreement with the mass of the refined model; thus, use of the lumped model was adequate to calculate the total structural mass. However, the agreement is not as good for the detailed information needed by the structural designer, as illustrated by the chordwise stress distribution in the cover panels near the wing-fuselage intersection shown in Fig. 10 for both the lumped and refined models. The lumped model gives the gross distribution of stresses, while SAVES gives the stress in each individual panel.

In this study, the lumped and refined models represent the same structural arrangement. However, in the actual design

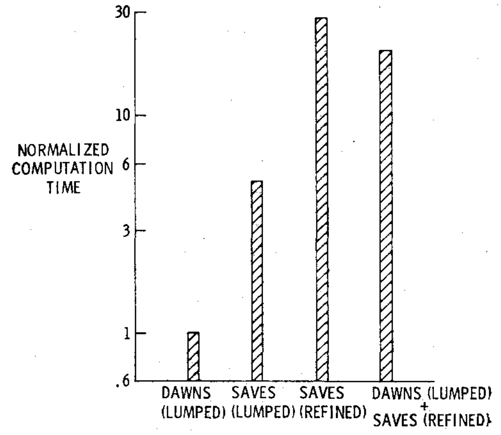

Fig. 9 Relative computation time for design of wings in Fig. 8 (normalization factor ≈ 100 sec of CPU time.)

process, the need for the refined model would be dictated by the structural details which could not be adequately represented by the lumped model. Structural details such as cutouts, wheel wells, and engine and control surface attachments would produce stress gradients of such magnitude that a refined grid would be required.

The results from the lumped and refined models shown in Fig. 9 suggest that if member sizes obtained from DAWNS were used as input to SAVES rather than uniform initial sizes, a significant reduction in computational time would result for the refined model (essentially the time for one analysis cycle in the present study). This procedure was used for the final case shown in Fig. 9 in which the thicknesses of the wing skin panels from a DAWNS design of the lumped wing model were used as initial member sizes for a single cycle (analysis-resize-analysis) through the SAVES system using the refined model. The mass agreed very well with the mass from the previous refined model analysis, and the computation times were much less. This procedure of using more specialized design programs to generate initial sizes for components of a complete vehicle and then refining the design using the large capability of SAVES will greatly enhance the usefulness of SAVES and specialized programs such as DAWNS, FADES, (Fuselage Analysis and Design Synthesis)[20] and SWIFT.[21]

Flutter Results

The flutter analysis portion of the SAVES system (Fig. 1) was applied to the wing structure which had been sized for strength requirements only. The structural mass of the leading and trailing edges was determined using empirical equations and was lumped on beams extending from the main

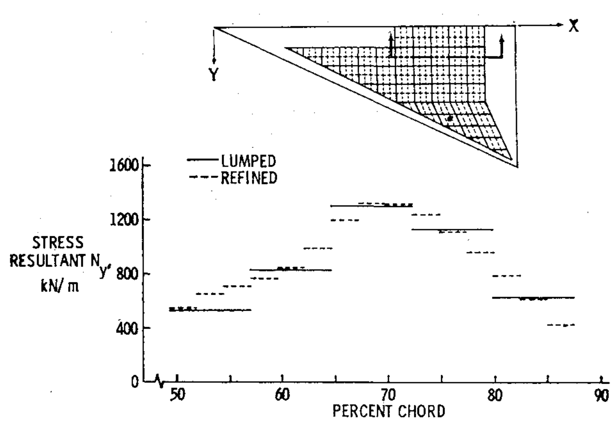

Fig. 10 Stress distribution near wing-fuselage intersection.

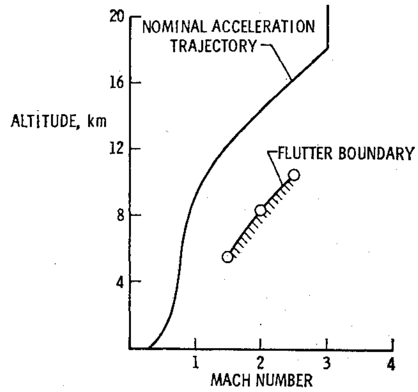

Fig. 11 Flutter boundary of baseline wing for hydrogen-fueled Mach 3 transport.

structural box (see Fig. 4b). In addition, two 6800-kg engines were assumed to be attached to the semispan model of the wing structure. For simplicity, the wing was assumed to be clamped along the wing-fuselage intersection for the flutter calculations; in later stages of design, the effects of fuselage flexibility would be considered in these calculations.

Natural vibration modes and frequencies of the wing were calculated using NASTRAN. Unsteady aerodynamic loadings at Mach numbers of 1.5, 2.0, and 2.5 were calculated using a Mach box aerodynamic program.[25] Flutter calculations were made for both the lumped and the refined models. For the refined model, 20 chordwise Mach boxes were used in the aerodynamic calculations, whereas 15 were used for the lumped model. The flutter boundary obtained for the refined model using six modes is shown in Fig. 11. These preliminary results indicate that, for the Mach number range considered, the baseline wing does not appear to be flutter critical, although the effects of fuselage flexibility could alter this result. In addition, the baseline wing had a thickness ratio of 0.05, and the wings with lower thickness ratios considered in the strength designs of Fig. 8 would be more susceptible to flutter. An increase in structural mass above that required for strength could be required to provide an adequate flutter margin for the thinner wings. However, such a design study was considered beyond the scope of the present paper.

Calculations were made for the base-line design to assess the accuracy of results for different levels of modeling and number of modes used in the flutter analysis. These results are shown in Table 2. Results for the refined model indicate that at least five modes are required for the flutter calculations. Use of six modes gives results which appear to be essentially converged. There is considerable discrepancy between the results for the lumped model using six modes and the corresponding refined model for a Mach number of 1.5. However, the agreement becomes better with increasing Mach number, and is quite good at $M = 2.5$.

The results for the refined and lumped models were calculated using the mass of the idealized primary structure. Idealized structural masses calculated from finite-element models must typically be increased by a factor of 1.5–2.0 in order to correspond to the mass of actual structures. In an attempt to represent more accurately the actual structural mass, a factor of 1.8 was selected, and this additional mass was incorporated into the model by increasing the density of the rib and spar elements. The six-mode flutter results obtained for this modified lumped model indicate a slight decrease in the critical flutter altitude.

Table 2 Summary of flutter results

Configuration	Number of modes	$M = 1.5$ alt, km	$M = 2.0$ alt, km	$M = 2.5$ alt, km
Refined	6	5.49	8.38	10.44
	5	5.33	8.08	10.36
	4	<0	4.57	7.24
Lumped	6	7.16	7.48	10.21
	5	3.81	6.55	8.84
Modified lumped	6	7.15	7.47	9.92

Computation Times

The computational times for each step in the design process currently used in SAVES were examined to determine where additional computational efficiency would be most beneficial. Computer times are shown in Table 3 for both the lumped and refined models. As was expected, the structural analysis portion of the process (static and dynamic) consumed a large portion of the total time. This emphasizes the need for computationally efficient structural analysis programs if automated design procedures are to be effective. The time required for calculating the modes and frequencies of the refined model could be substantially reduced by lumping structural masses, a technique which reduces the dynamic

Table 3 Computation times for SAVES design process

Steps in design process	Number of analysis	Computation time for single analysis: Lumped model CPU sec	Lumped model PPU[a] sec	Lumped model Core 1000^{8}	Refined model CPU sec	Refined model PPU sec	Refined model Core 1000^{8}
Generate finite-element model	1	9.6[b]	35.9	70	18.9[b]	31.6	70
Calculate forces on model (aerodynamics and lumping)	1	42.1[a]	121.6	70	45.9[a]	96.8	140
NASTRAN static structural analysis	3	134.4	686.2	140	894.4	1592.6	140
Member resizing	2	24.4	84.3	40	37.3	120.8	60
NASTRAN dynamic analysis (frequencies and mode shapes)	1	283.4[c]	1093.9	140	6025.8[d]	5716.5	300
		(61 dynamic deg of freedom)			(258 dynamic deg of freedom)		
Generate generalized aerodynamic forces (6 modes)	1	446.2	197.7	110	1629.3	291.7	110
Flutter analysis (6 modes, 3 Mach numbers, 4 densities, and 305 reduced frequencies)	e	Same as refined model			366.2	1847.6	70

[a] PPU times are dependent on operating system and gives only a rough approximation of peripheral time requirements.
[b] Runs on CDC 6400 converted to 6600 run times by dividing by a factor of 2.0.
[c] Givens' method used to obtain eigenvalues.
[d] Inverse power method used to obtain eigenvalues (6 modes).
[e] Depends on the number of conditions examined during study.

degrees of freedom. Such a procedure does not alter the structural stiffness representation and generally leads to satisfactory results. However, automated procedures to define the lumped mass properties have not yet been incorporated into SAVES.

Table 3 also reveals that the computation times required for flutter analyses of low-aspect-ratio wings are large, because lifting surface unsteady aerodynamics and a finite-element representation of the structure are required to obtain realistic analytical predictions. The programs used in the flutter calculations were developed for analysis applications and use procedures that are inefficient when applied to the iterative design process. If the design process is to be extended to size structural members to meet strength and flutter requirements simultaneously, methods of increasing the efficiency of the flutter calculations will have to be developed for use with automated design procedures.

Concluding Remarks

Results from a continuing effort to develop automated methods for preliminary structural design have been described. The general philosopy employed in the development of the DAWNS program for the design of wing structures and the SAVES system of programs for the design of the primary structure of the complete vehicle was discussed. The status of the SAVES system, which is under development, was given with emphasis placed on automated routines for generation of finite-element models. Illustrative numerical results were presented for one concept of a hydrogen-fueled Mach 3 transport wing. These results indicated that crude or lumped models can be used to calculate total wing mass, but more refined models are required to provide the detailed information required by the structural designer. If the design process is to be extended to size structural members to meet strength and flutter requirements simultaneously, methods of increasing the efficiency of the flutter calculations will have to be developed for use with automated design procedures.

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