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A STRUCTURAL WEIGHT ESTIMATION PRO-  
GRAM (SWEEP) FOR AIRCRAFT. VOLUME I -  
EXECUTIVE SUMMARY

L. Ascani

Rockwell International Corporation

Prepared for:

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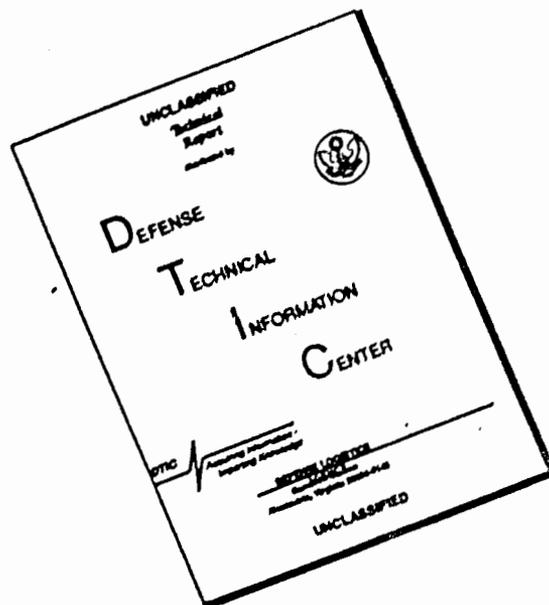
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Three computer programs were written with the objective of predicting the structural weight of aircraft through analytical methods. The first program, the structural weight estimation program (SWEEP), is a completely integrated program including routines for airloads, loads spectra, skin tem- peratures, material properties, flutter stiffness requirement, fatigue life, structural sizing, and for weight estimation of each of the major aircraft structural components. The program produces first-order weight estimates		

and indicates trends when parameters are varied. Fighters, bombers, and cargo aircraft can be analyzed by the program. The program operates within 100,000 octal units on the Control Data Corporation 6600 computer. Two stand-alone programs operating within 100,000 octal units were also developed to provide optional data sources for SWEEP. These include (1) the flexible airloads program to assess the effects of flexibility on lifting surface airloads, and (2) the flutter optimization program to optimize the stiffness distribution required for lifting surface flutter prevention.

This volume, Volume I, summarizes the program and its capabilities.

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Publication of this technical report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

*James H. Hall*  
JAMES H. HALL, Colonel, USAF  
Deputy for Development Planning

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## PREFACE

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Eugene L. Bahns, ASD/XRHD, was the Air Force program manager. Leonard Ascani was the program manager for Rockwell International. Other Rockwell personnel contributing to the project included:

G. Hayase	- Mass Properties
R. Hiyama	- Mass Properties
D. Chaloff	- Mass Properties
C. Martindale	- Mass Properties
H. Rockwell	- Mass Properties
R. Allen	- Mass Properties
P. Wildermuth	- Airloads
G. Rothamer	- Airloads
T. Byar	- Airloads
S. Siegel	- Structural Dynamics
S. Mellin	- Structure and Fatigue
H. Haroldson	- Thermodynamics
D. Konishi	- Advanced Composites
C. Hodson	- Structural Dynamics

The final report was published in 11 volumes; the complete list is as follows:

### Volume

I	"Executive Summary"
II	"Program Integration and Data Management Module"
III	"Airloads Estimation Module"
IV	"Material Properties, Structure Temperature, Flutter, and Fatigue"
V	"Air Induction System and Landing Gear Modules"
VI	"Wing and Empennage Module"
VII	"Fuselage Module"
VIII	"Programmer's Manual"
IX	"User's Manual"
X	"Flutter Optimization Stand-Alone Program"
XI	"Flexible Airloads Stand-Alone Program"

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## Section 1

### INTRODUCTION

The science of configuration synthesis and optimization of advanced aircraft characteristically involves broad-scope system trades requiring very rapid response to design perturbations. Successful advanced design operation requires the use of specialized techniques for subsystem and structures synthesis, sizing, and evaluation which differ from the usual analytical procedures used in detail design. This includes their flexibility of application, ability to function without large amounts of input data, and rapid mode of operation. Without a methodology possessing these features, structures and subsystems feedback becomes so cumbersome that basic aircraft configuration parametric exploration must be severely limited in the interests of time and funding. As the result of such limitation, the risk is high of adopting a less than optimum basic configuration at the very inception of a program, adversely affecting system effectiveness throughout the life of the design. Hundreds of interdependent variables must be evaluated in the concept formulation stage in order to provide the necessary information for intelligent evaluation of these variables enabling designers to identify critical areas of performance and sensitivity.

One of the strongest driving functions in aircraft configurations is structural weight. This is true both because of the sensitivity of nearly all aircraft performance factors to vehicle weight, and because of the relatively high fraction of gross weight which is attributable to airframe structural weight. In addition, structural weight is one of the most highly configuration-sensitive parameters in the aircraft, making it virtually impossible to separate configuration and structural synthesis during the conceptual phases of design. Unfortunately, in spite of its importance to the advanced design process, structural weight has traditionally been one of the most difficult of the design parameters to determine. This is true primarily because of the inherent complexity of the structural analysis task. The length and complexity of the analytical methods used in detail design and analysis render them unsuitable to the synthesis and optimization requirements of advanced conceptual work.

Previously, structural weight estimation programs used statistically derived equations which had severe limitations because of their inherent dependence on existing data. The accuracy of statistically derived equations decreases rapidly as one goes beyond the limits of the data base to which they were correlated. Secondly, they do not assess the merits of new materials or unique design features, nor do they reflect the actual environment (for example, gust loads, required life, dynamic inertia loads, temperatures, etc) in which the aircraft will operate. For these reasons, it became necessary to develop analytical structural weight estimation programs based upon problem dependent loading and design considerations.

Stand-alone weight estimation computer programs were developed for each major component of the airplane including fuselage, wing and empennage, landing gear, and air induction systems as well as secondary structures. These programs were expanded and new modules written which resulted in the completely integrated, continuously running system for aircraft structure, entitled "Structural Weight Estimation Program (SWEEP)." This program determines structural weight of aircraft by analytically evaluating the effects of loads, fatigue, stress, flutter, temperature, mass properties, manufacturing constraints, and materials in one computer run.

The effort covered the basic SWEEP program, which includes a rigid airloads module, a first-order flutter stiffness method, conventional metal structure synthesis, and advanced composite structural synthesis. Additionally, procedures were developed to evaluate the effects of flexible loads and flutter optimization for lifting surfaces. The flutter and flexible loads procedures were developed as stand-alone programs that may be used to generate data independent of the basic SWEEP program. These data can then be used in SWEEP, at the option of the user, to replace the requirements data generated by the built-in loads and flutter programs. The SWEEP program capabilities are described briefly in References 1 and 2. The rigid airloads module and the stand-alone flutter optimization program are presented in References 3 and 4, respectively.

In summary, the primary objective of the effort documented in this report and supporting volumes is to develop analytical computer programs capable of predicting the weight of aircraft structural components suitable for use during the conceptual phase of the aircraft design cycle.

## Section II

### SWEEP PROGRAM DESCRIPTION

SWEEP is a computer program with major engineering analysis modules structured around preliminary design procedures and integrated into a working program that can completely analyze structure weights and mass properties of major vehicle components.

The basis for the structural weight analysis in SWEEP is an approximation of the procedures and methods used in the actual structural analysis and design processes through the creation of an engineering description of the components in terms of physical geometries, design criteria, structural sizings, and mass properties. This is accomplished through mathematical modeling procedures and the adaptation of theoretical, empirical, and/or statistical methods to a logical, but flexible, interrelated computational procedure.

The engineering objective for the program is to provide rational weight estimates and trend prediction data early in the design cycle based on rational engineering principles, procedures, and practices, with a computing system that can respond to the demands of the configuration analyst by allowing for selection of various design options. Synthesis of design, sizing, and mass properties data are geared to provide analytical assessments to parameters not inherent in statistically based methods. The weight prediction modules of SWEEP are structured so that proper evaluation can be made of the effects of vehicle environment and design requirements on the aircraft structural characteristics through assessments of design loads, dynamic pressure, design temperatures, service life, and ground handling requirements, etc, and the merits of structural design concepts and materials.

Weight prediction of primary structural components are based on physical dimensions and structural size requirements. The structural sizes are synthesized from design requirements and criteria data developed from evaluation of configuration design criteria by special analysis routines. Predicted weights of structural components for which analytical procedures cannot be adapted are based on statistically derived weight estimation equations.

In a generalized program such as this, synthesis and weight analysis procedures cannot identify all the structural elements and/or provisions required for all major structural components, nor can all unique design requirements and criteria, novel design concepts, etc, be accounted for; however, assessments are made and weights are predicted for the majority of structural arrangements encountered. Accounting is made for program inaccuracies and for normal provisions and requirements, not considered by the analysis, through a weight indexing program correlation scheme using indexing constants. These indexing constants are part of each weight module data bank ordered

such that they can be revised in the input data set. The degree and direction of incremental changes to these indexing factors for the most part must be based on good technical engineering judgment and understanding of program capability.

#### PROGRAM CAPABILITY

SWEEP has the capability of analyzing several types of aircraft, their structural components, and features including:

1. Aircraft - cargo, attack, fighter, bomber
2. Structural components - wing, fuselage, horizontal tail or canard, vertical tail, landing gear, engine pylons, engine nacelles, and/or air induction system
3. Features - fixed and variable sweep wing, pylon-mounted or -buried engines, cargo doors, multiple weapons bays, straight or curved wing planforms, unique loading conditions, advanced composite lifting surfaces, design speeds up to mach 3, canard stabilizer, T-tail arrangement

SWEEP is programmed for flexibility as a weight estimating tool. Since the type of problem and the type of data required will vary, the program contains three significant operational features:

1. The capability of analyzing a complete air vehicle configuration, based on the initial set of assumptions.
2. The ability to select an arbitrary combination of components.
3. The capability of running any number of cases, including combinations of points 1 and 2, for each setup on the computer.

The structure weights predicted are results of analytical procedures in the various modules that make up the program. These routines interpret and convert problem description information into mathematical and engineering data, resulting in a logical description of the air vehicle configuration and design criteria, and a three-dimensional approximation of the physical geometry of the configuration.

From these data, design requirements, such as design loads, section geometrics, etc, can be evaluated, and logical selection made of critical design requirements. Also, structural concepts, structural design parameters, and materials can be defined for the structural synthesis routines.

## SWEEP STRUCTURE

The basic SWEEP program performs four categories of tasks: input, design data development, weight analysis, and output. It is comprised of a main overlay and 18 primary overlays, as shown in Figure 1.

The use of an overlay structure, coupled with other programming techniques (refer to Volume VIII, Programmer's Manual), permits the program to operate within a computer memory of 100,000 octal words on the Control Data CDC 6600 computer. When the advanced composite torque box design option, Overlay (18,0), is not required, this memory requirement reduces to less than 50,000 octal words.

The physical running of SWEEP requires:

1. A program tape or disk file
2. A permanent (default) data bank tape or disk file
3. A deck of input data cards (problem description)

The problem description data deck consists of job control cards, case title cards, and a set of variable data cards to describe the design problem. Analysis control data are indicator words used to communicate with the analysis control routines so that the internal logic can be controlled. In normal, second-iteration jobs, approximately 800 to 1,500 pieces of data may be required (160 to 300 cards). Initially, the maximum input data capacity is sized to 14,000 pieces of data (2,800 cards).

The total program operates in less than 50,000 octal core locations and one level of overlay and is written in FORTRAN IV extended programming language.

## INPUT DATA PROCESSING MODULE

The input data set consists of that required to describe the types of aircraft, components, design concepts, and features which SWEEP evaluates analytically. In addition, SWEEP is capable of accepting data in various stages of refinements including initial assumed data available in early stages of the design cycle through detail design data resulting from a more formal engineering design cycle. Those include discrete design loads, flutter requirements, etc.

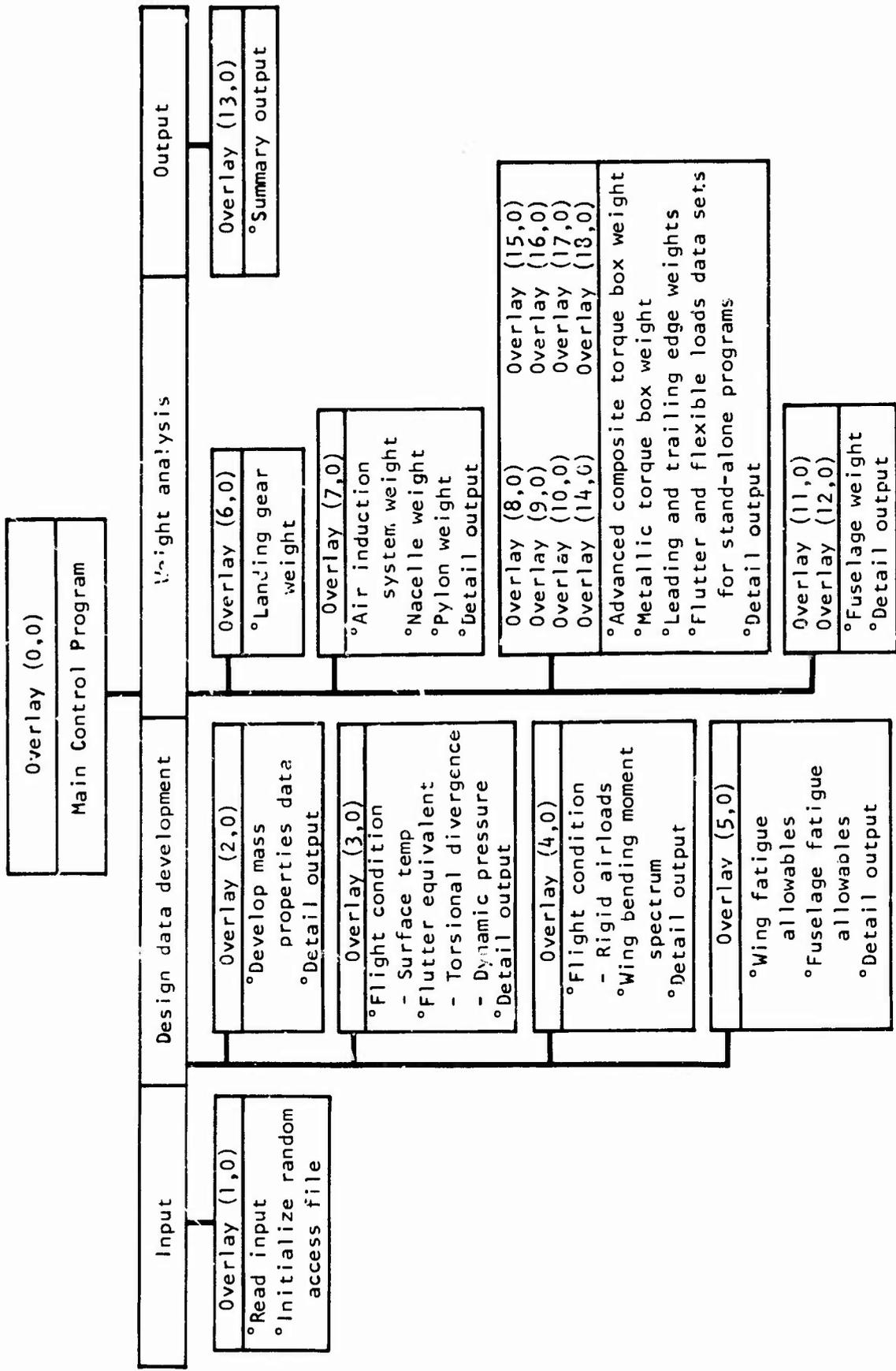


Figure 1. SWEEP structure.

The primary sources of data include:

1. A three-view drawing or other description of the configuration so that geometry and structure arrangement data can be derived and reduced for input.
2. A set of design assumptions to describe fully the performance, operating envelope, mission, and structure design concept of the configuration.

Initially, many of the structural design criteria are based on predetermined values of parameters in accordance with requirements specified in MIL 8860-8870 series specifications, MIL handbooks, etc. As the design progresses, more detailed design criteria definitions and design data can be used to override any data stored within the program.

#### DATA BANK

The SWEEP permanent data bank is a tape or disk file containing program constants, fixed tabulated data (such as required for estimating wing span load distributions), and default values for selected locations in the variable-data input decks.

Data bank information includes the following:

1. Aero data for loads
2. Spectrum data for fatigue
3. Weight constants and data for initial weight distribution
4. Flutter analysis constants
5. Material property description
6. Weight analysis constants and index factors

Each block of the input variable data region is initialized from this bank with program constants and default parameter values. Provisions and instructions for revision or extension of the various data subsets in this bank are inherent in the User's Manual input data descriptions and in the program internal data core maps provided in supporting volumes.

## VARIABLE DATA

This set of data must include information such as:

1. Geometry descriptions of each component so that the complete air vehicle can be described with a three-dimensional approximation.
2. Air vehicle mission and loading data.
3. Initial assumptions of weight distributions, particularly the fuselage dead weight distributions. These data must include estimates for items other than structure, such as propulsion systems, fixed equipment and subsystems, useful load, armament, and fuel.
4. Design criteria, structural arrangement/concept data for structural synthesis, and weight analysis.
5. Structural synthesis weight analysis data.

## DESIGN DATA DEVELOPMENT MODULES

### DATA MANAGEMENT MODULE

The primary purpose of the data management module, Overlay (2,0), is to develop mass properties data required for the execution of the airloads module, Overlay (4,0). It also provides inertia data to the other program modules.

This module determines vehicle weight, center-of-gravity position, inertia characteristics, design speeds, design limit maneuver load factors, and configuration geometry to be used by the airloads module. The airloads module uses these data to determine the design airloads on the structural components for use in the structural weight estimation process. The airloads module also uses these data to determine wing bending moment spectra for fatigue evaluation.

Since the structural weight estimation modules are multistation analysis programs, loads are calculated at discrete structural stations. Therefore, this module also processes and transmits data to the weight estimation modules, which insures compatibility between airloads, inertia definitions, and structural geometry.

## AIRLOADS MODULE

Two main branch functions are used in the airloads module to calculate the required data:

- The limit airload branch calculates critical gross airloads for all structural components of the airplane and centers of pressure for the wing, empennage, and fuselage and also computes the distributed shear, moments, and torsion on the wing and empennage.
- The load spectra branch calculates the fatigue spectra, for the required classes of airplanes, for use in the fatigue module. The output consists of wing bending moment spectra at two stations along the wingspan. In addition, a taxi spectrum is calculated for these same two wing stations.

A series of checkpoints are analyzed within the airloads module to find the most critical design conditions. These include both flaps-up and flaps-down cases, as well as critical maneuver and gust conditions along the speed profile of the aircraft (Figure 2). The conditions analyzed include:

1. Maximum positive and negative maneuver
2. Positive and negative vertical gust conditions
3. Lateral gust
4. Pitching and yawing accelerations
5. Flaps-down maneuver
6. Flaps-down 1.0 g trim

A selected matrix of conditions is checked which is a function of the airplane type and the probable critical flight condition. The points are pre-programmed within the airloads module and are used later in the weight modules for analysis.

## FATIGUE MODULE

Service life requirements are evaluated for wing tensile covers and fuselage panels. The load spectra for the given air vehicle and mission mix may be specified or calculated by the airloads module. These data, along with

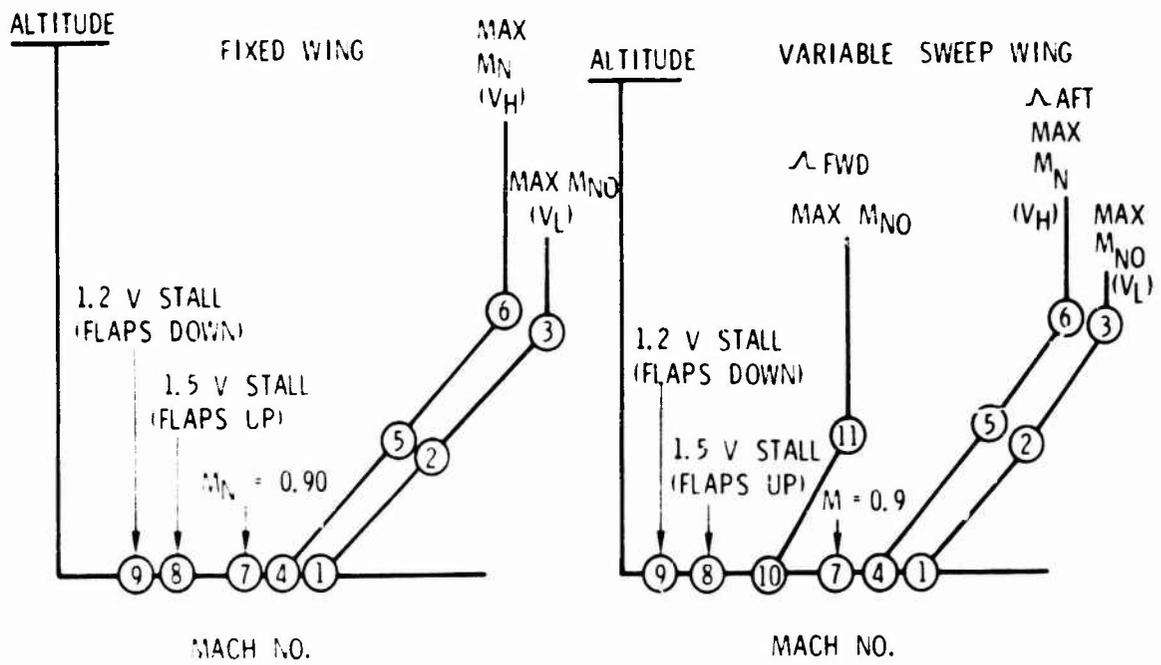


Figure 2. Airload checkpoints.

material tensile and strain behavior properties, are used by the fatigue module routines to evaluate cumulative fatigue damage on the tension cover of the wing bending box for the required life, scatter factors, and assumed stress concentration factor. The stress level for each of the spectra cyclic conditions are iterated until service life is satisfied.

The output of this analysis is a tension cutoff stress, resulting in an ultimate allowable stress less than or equal to the tension ultimate stress of the material.

Material behavior properties in the data bank include steels, titanium, and various aluminum alloys.

#### FLUTTER AND TEMPERATURE MODULE

The flutter and temperature module, Overlay (5,0), develops the flutter stiffness criteria used by the torque box stiffness requirement routines in the wing and empennage module, and sets up skin temperatures associated with the input set of design flight load conditions. The results are saved on disk file for later access by the loads, fuselage, and lifting surface modules.

Part of the torque box stiffness estimation method is applied in Overlay (5,0) and part in the wing module. Overlay (5,0) determines the maximum dynamic pressure at which each lifting surface is flutter-free in subsonic flight, based on empirical data. The actual spanwise stiffness requirements are computed within the wing module.

The development of the SWEEP flutter method is based on the observation of some degree of correlation between the flutter speed and the static aeroelastic torsional divergence speed of an equivalent straight wing. The correlation is expressed by means of a parameter,  $c_e$ , which is a function of aspect ratio, sweep angle, and taper ratio. The expression for the parameter was derived from an envelope curve around a large number of points corresponding to theoretical and experimental evaluations of flutter speeds of a large variety of lifting surface types. The use of this "torsional divergence criterion" greatly simplifies the problem. The aerodynamic forces are not frequency-dependent, and inertia forces are eliminated from the problem. The method determines the optimum stiffness distribution by calculating the stiffness distribution which will result in a constant shear stress over the span of the wing in the torsional divergence mode. Naturally, some accuracy is lost, but since the correlation parameter is determined from actual flutter data, it may be thought of as "taking an average" of inertia and other effects to which torsional divergence considerations alone cannot relate.

## WEIGHT ANALYSIS MODULES

Previously developed analytical weight estimation programs provide the basis for the SWEEP structure, approach, and programming procedures. The design data routines of these programs provided many of the routines of the design data modules of SWEEP. The structural synthesis and weight analysis routines, with some revisions and improvements, form the basis for the five major modules of the weight analysis section.

### STRUCTURAL SYNTHESIS - WING AND EMPENNAGE (METAL STRUCTURE OPTION)

Structural concepts that can be synthesized for torque box analysis of wing and tail surfaces include multispar and multirib constructions for covers, stringer-stiffened front and rear spars, and corrugated web intermediate ribs and spars. Cover configurations for multispar concepts include plate and honeycomb panels.

In multirib concepts, cover designs can include riveted Z-stringer-stiffened skins, milled plates with integral Z's, or I-stiffeners, as shown in Figure 3. Column general stability, local web, flange, and sheet crippling requirements are analyzed within specified constraints so that strength and stability conditions are satisfied with the best distribution of material between the skin and stringer elements.

A sophisticated search system has been developed for stringer analysis. Basically, the synthesis involves searches to optimize the number of stringers or stringer spacings, compression allowables, stringer-skin geometries, and optimum rib spacings.

### STRUCTURAL SYNTHESIS - WING AND EMPENNAGE (ADVANCED COMPOSITE OPTIONS)

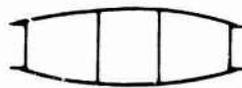
The wing and empennage module also includes the capability of synthesizing composite material structural components and predicts their weights to the same first-order level as the metal design analysis.

The program is capable of synthesizing three torque-box design concepts for advanced composite materials. The parameters considered include flexural moments, shear strength, local and general instability, torsional and flexural stiffness, and fabrication/manufacturing constraints. The three structural concepts included are:

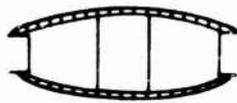
1. Multispar, unstiffened skin design concepts
2. Multispar, honeycomb panel design concepts
3. Multirib, stiffened skin design concepts

• MULTISPAR

- PLATES



- HONEYCOMB PANELS



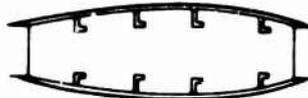
} SEARCH FOR NO. OF SPARS

• MULTIRIBS

- RIVETED Z



- INTEGRAL Z



- INTEGRAL I



} SEARCH FOR

• NO. OF STRINGERS

• ALLOWABLE STRESS

• OPTIMUM GEOMETRY

Figure 3. Structural synthesis - wings and empennage.

The cover synthesis procedures require descriptions of lamina (single-ply) properties for the composite material under consideration. These are similar to the metal physical and mechanical properties required for metal design; that is, modulus of elasticity, shear modulus, Poisson's ratio, and maximum compressive, tension, and shear allowable stresses. The lamina thickness and density must also be specified.

Composite cover panels consist of various layers of lamina (laminates) with fiber orientations dependent upon the critical loads the structure must resist and the stability and stiffness properties which must be met. Many possible combinations exist for the number of layers and orientations to meet strength, stiffness, and stability criteria. The synthesized panels are assumed to be symmetric in layup, each half panel containing three sets of lamina with predetermined orientations with the number of plies per set dependent upon the design criteria. The orientations for these sets is assumed to be 0, and 90 degrees. Theta,  $\theta$ , is preset at 45 degrees.

The number of 0-degree plies is initially selected to resist the cover spanwise axial loads. Then, the number of 45-degree plies, in the multispar unstiffened skin case, is determined by assuming that  $[0_1/\pm 45_M]_S$  will not fail in general instability for combined loadings of compression and shear. The 45-degree laminates are checked for stiffness requirements and increased if necessary.

The required number of 90-degree plies are assumed to be a nominal percentage of the total 0- and 45-degree plies, a "rule of thumb" solution, since the 90-degree orientation requirements cannot be determined with the available design loads and criteria.

Honeycomb panel and stiffened-skin synthesis procedures are treated in a similar manner, except the stability analysis for these types of cover designs is somewhat more complex. The honeycomb analysis requires evaluation of the core properties and their effects on the stability of the structure, while the stiffened skin analysis must treat the compatibility and interactions of the skin and stringer at the design point. Local instability requirements such as wrinkling and crippling are also considered.

Correlation factors, basically weight indexing factors, are provided for the estimated component structures of the torque box. These factors are initially the same as those used for metal structures, unless the user indicates otherwise. A schedule for minimum number of plies, minimum gages, and other design constraints are provided in the data bank, along with composite material properties.

## FLUTTER AND LOADS SUPPORT DATA GENERATION PROGRAM OPTION

Because of the common input data required for both the flutter optimization and the flexible loads stand-alone programs previously mentioned, this option is available as a computerized method of generating the required data for these programs. Since the basic SWEEP program inherently develops most of the data required in the form of stiffness, geometry, speed altitude envelopes, etc, required for the flutter and airloads stand-alone program, this data generation option is available to generate input/output data that are used directly with the flutter and flexible loads programs. Additional data, particularly mass properties data, are also developed to supply information for these programs. The final output of the program produces all data required for both the flutter and the loads module in the form of punched cards, requiring a minimum of additional effort in setting up the flutter and loads program decks.

The data generation program, combined with the flutter optimization and flexible loads programs, is part of an iterative design cycle in which the effects of wing flutter stiffness requirements and wing flexibility are optimized for optimum spanwise distributions of wing torque-box material. This iteration cycle operates with SWEEP in a manual mode with the stand-alone flutter and loads programs generating data in tandem, each producing, as output, a deck of punched data cards which are used as input data for SWEEP.

Data punched for the flutter program include air vehicle speed profile data, wing geometry data including spanwise torque-box section geometry data, structural EI (bending) and GJ (torsional) data at each wing station, spanwise panel weights, centers of gravity, and moments of inertia. Each card is addressed to data locations required by the flutter program. Flexible loads analysis program data include all the required configuration and component data which are used by the vehicle loads analysis module of the basic SWEEP program. Additional data, including wing spanwise EI, GJ, and weight distribution data, are also part of the output data set.

The output from the data generation program includes not only the final weight summary data for the default output, but also final wing torque-box structural sizing and weight analysis data, component airloads data, and listings of the punched data for each program.

## STRUCTURAL SYNTHESIS - FUSILLAGE

The fuselage weight analysis module includes structural synthesis methods and classical mathematical stress analyses routines to determine the weight of fuselage shell structure.

The major synthesis routines, as shown in Figure 4, include:

1. Net design loads analysis. Much of the fuselage design loads analysis is performed within the fuselage module, since loads for the various design conditions are dependent on fuselage content weight distribution and structural arrangements.
2. Major bulkhead and shell analysis. The shell analysis considers longeron-shear panel arrangements or skin-stringer-frame arrangements. Search routines are included which optimize stringer spacing for skin-stringer fuselages. Constraint on stringer geometry can also be included, at the option of the user, to determine the effect of stringer spacing.
3. Local effects analysis. Local effects of cutouts, fuel pressure, panel flutter, acoustics, and concentrated loads are also considered in the analysis.

#### AIR INDUCTION SYSTEM MODULE

A variable-geometry ramp weight estimating program, as shown in Figure 5, for two-dimensional inlets is used for this module. The program is an analytical approach to weights of two-, three-, and four-ramp variable geometry systems. The analysis uses as variables ramp pressure differential, geometry, and material properties.

Pressures are programmed as either/or, that is, the individual ramp pressures can be specified, if available, or the maximum duct pressure is inserted and the program calculates ramp pressures as a function of the duct pressure. The maximum duct pressure condition is a transient overpressure referred to as hammershock. For this routine, the hammershock pressure is programmed as a function of the duct operating total pressure. The duct total pressure is programmed as functions of the vehicle speed altitude profile and pressure recovery versus mach number. Total pressure is computed with the isentropic compressible flow equation and MIL-5008B specification pressure recovery curve.

The individual ramp length, width, and angles are input data; however, the program includes assumed ramp angles if they are not available. The program presently includes either/or capability for the locations of the ramp reaction (actuator) points.

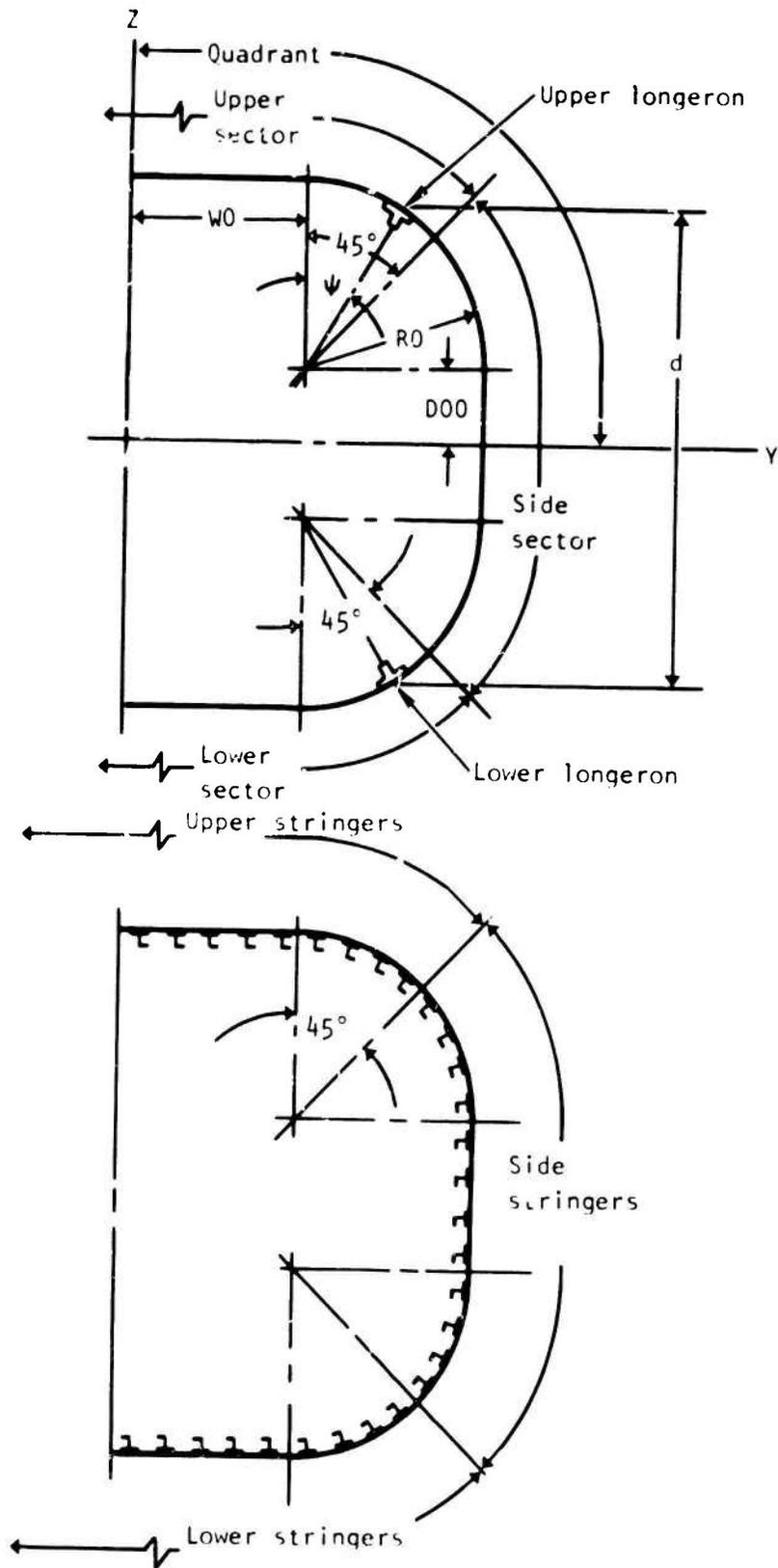


Figure 4. Structural synthesis - fuselage.

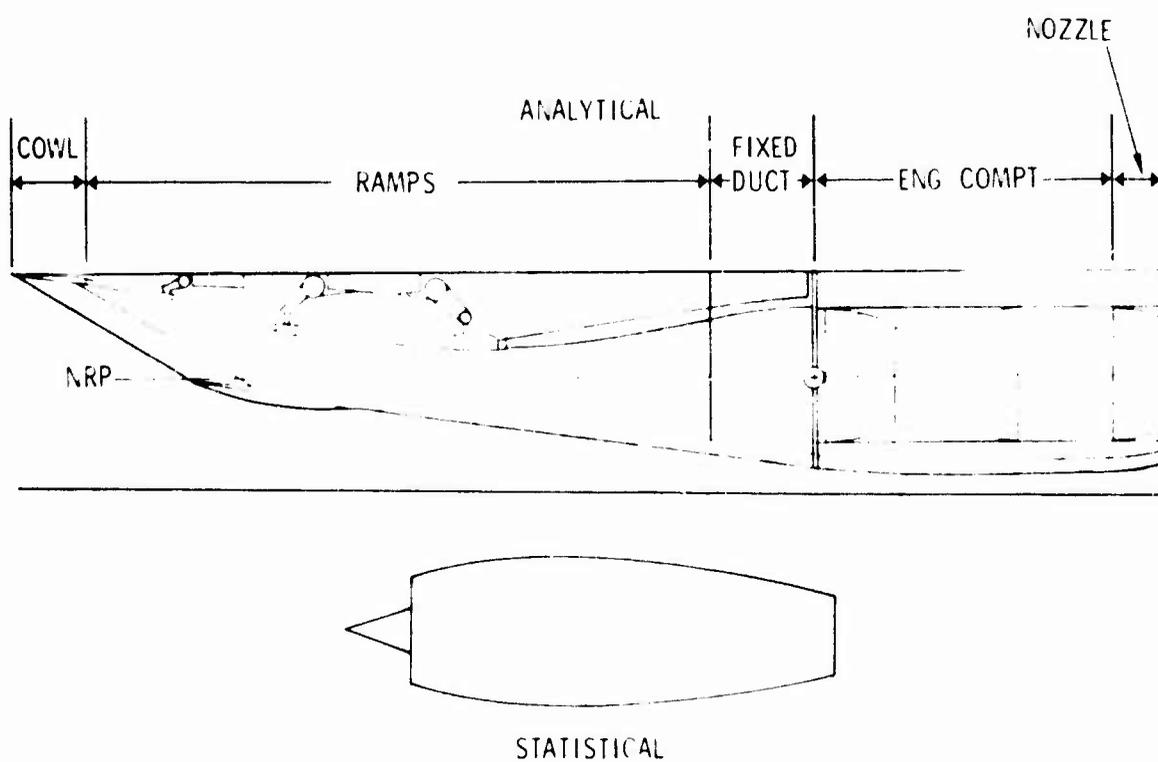


Figure 5. Two-dimensional air induction system.

A three-dimensional inlet spike weight, either expanding or fixed, is also available in this program. Three-dimensional inlet weights are obtained by a statistical approach for first-order weight approximations and are dependent on the speed profile of the air vehicle under analysis.

#### LANDING GEAR MODULE

An analytical approach to strut weight estimation which is applicable to both main and nose gear is used in order to add weight sensitivity to flotation requirements, vehicle landing speed, and sink speeds. The approach taken in this program is to accept one simplified design, shown in Figure 6, and provide sensitivity by creating subprograms involving geometry, running gear, ground loads, stress analysis, deflection, and weight calculations. Indexing coefficients are provided to improve the absolute value of the landing gear weight.

Ground loads are based on procurement agency specifications and are programmed as a basic part of the estimating process. The loading conditions which are checked include:

1. Two-point level:
  - a. Maximum vertical load
  - b. Spin-up
  - c. Springback
2. Drift landing
3. Braked roll
4. Unsymmetrical braking
5. Towing
6. Ground turning

The applicable conditions are checked for gear loads at the maximum take-off weight, maximum landing weight, and normal landing weight.

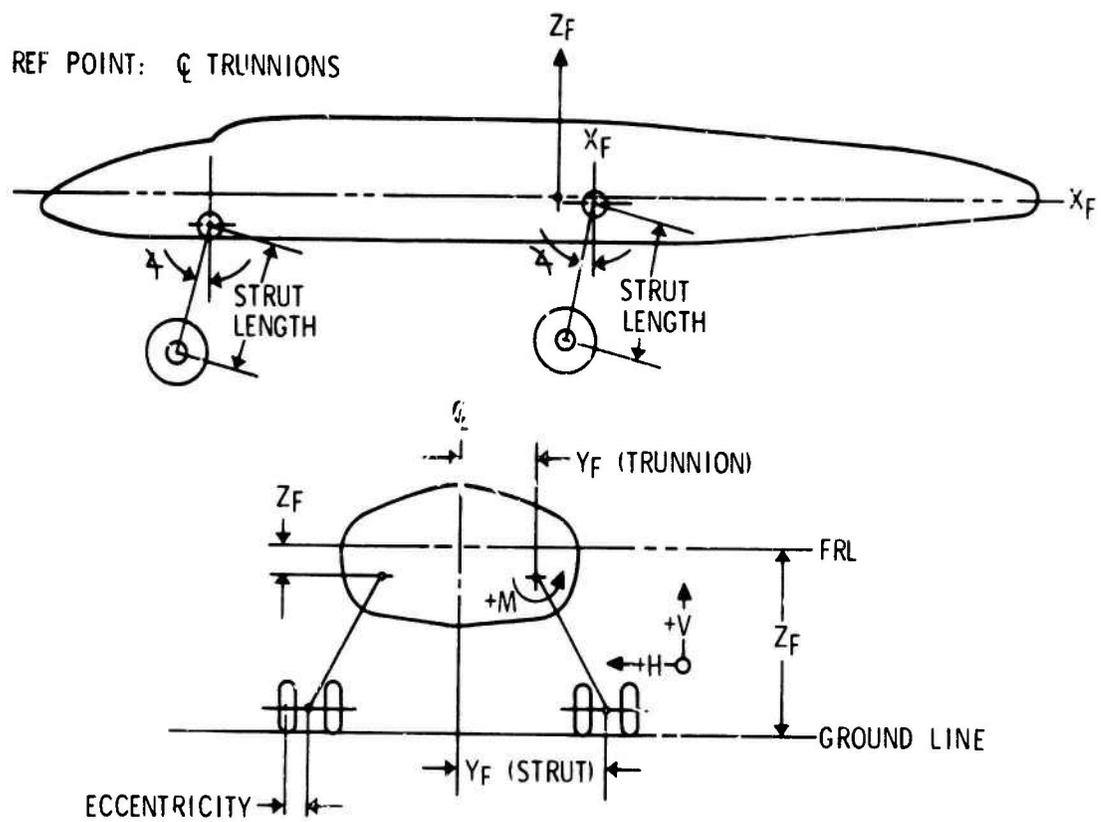


Figure 6. Landing gear arrangement.

Sink speeds, landing speeds, wing lift, and tire diameter are data specified for the load analysis. If the landing gear load factor is known, it can be entered and the program will bypass load factor calculations. Any available loads can be included as input data, while unavailable loads are calculated within the program. Vertical, side, and drag loads are converted to axial loads, bending moments, and torsion at two sections on the inner cylinder.

The weights of the landing gear struts are computed from the  $D/t$  established in the stress analysis portion. To provide a weight allowance for lugs, axles, bearings, retract mechanisms, etc, a statistical equation is used. This allowance, plus the weight of the wheels, brakes, and tires, provides the weight of the complete landing gear system.

#### OUTPUT DATA PROCESSING

For any problem run on SWEEP, the output data are controllable. The basic output is a weight summary of the analysis, as shown in Table 1, which summarizes the calculated structure weight and balance data combined with the assumed weight and balance data for propulsion, fixed equipment, useful load, and armament. A second tabulation of the initial assumption is printed for evaluation of the results.

Optional output that can be printed through control card indicators include three major types:

1. Details of weight analysis results
2. Details of structural synthesis results
3. Details of design data and requirements

TABLE 1. GROUP WEIGHT STATEMENT WEIGHT EMPTY BALANCE DATA

Parameter	Weight	Horizontal Arm
Weight Empty	126,122.50	943.11
Wing	35,793.93	972.28
Horizontal	3,329.01	1,842.00
Vertical	3,240.07	1,741.13
Body	27,579.29	971.30
Main gear	8,366.27	991.77
Nose gear	674.64	354.75
Surface controls	3,714.00	1,121.80
Engine section	3,847.98	806.92
Other structure	0.0	0.0
Engine	18,759.00	774.10
Accessory gearboxes	0.0	0.0
Air induction system	611.50	679.91
AIS actuation and controls	0.0	0.0
Exhaust system	3,577.00	845.67
Cooling and drains	144.00	803.90
Lubricating system	212.00	840.80
Fuel system	1,380.00	953.40
Engine controls	236.00	666.20
Starting system	320.00	768.30
Auxiliary power unit	554.00	844.70
Instruments	1,122.00	545.00
Hydraulic	1,489.00	881.90
Electrical	2,650.00	657.50
Electronics	2,347.00	592.40
Armament	0.0	0.0
Furnishings	3,320.00	596.80
Air conditioning	2,648.00	809.90
Photographic	0.0	0.0
Auxiliary gear	95.00	1,228.00
Other equipment	113.00	300.00

## Section III

### FLUTTER OPTIMIZATION STAND-ALONE PROGRAM

The stiffness of modern aircraft structures is determined to a great extent by the phenomenon of flutter. If stiffness distributions are not properly optimized for flutter, aircraft structures can become significantly heavier than necessary. As stated previously, the preprogrammed flutter program used with the basic SWEEP program is a simplified approach to the determination of flutter stiffness requirements. This is because of SWEEP program computer limitations and the program objectives of first-order weight approximations of the original contract. To enhance SWEEP weight estimations, an existing flutter program was modified as a separate stand-alone program. This program will optimize the distribution of strength and stiffness requirements throughout the span of a lifting surface, thereby providing the lightest possible structure consistent with strength and stiffness requirements.

The optimization method has been programmed to provide classical flutter stability of an aerodynamic surface up to a given required speed in one pass through the digital computer. This flutter stability is achieved through an iterative process that performs in each iteration the complete flutter analysis and the necessary incremental structural changes to raise the flutter speed. These changes are based on the concept that the most efficient distribution of structural material for a given loading is one that provides uniform stress, or its equivalent of constant strain energy per structural volume, throughout the deformed structure. The flow diagram of Figure 7 indicates the general sequence of the method.

The analysis starts with the strength-required structure. A sufficient number of modes are calculated in the vibration analysis for incorporation into the flutter analysis. The modal flutter equations, which are currently programmed to calculate automatically strip theory generalized aerodynamic forces for a spectrum of reduced frequency values based on the frequency range of the vibration modes, are solved for the classical velocity-damping-frequency solutions. The strain energy per structural volume is then calculated for the mode that goes unstable at the lowest speed. The structural stiffness is adjusted to increase the flutter speed, and the new structure, both stiffness and inertia, is incorporated in the mathematical model. The entire process is repeated until a structure is obtained for which the lowest unstable speed exceeds the required speed.

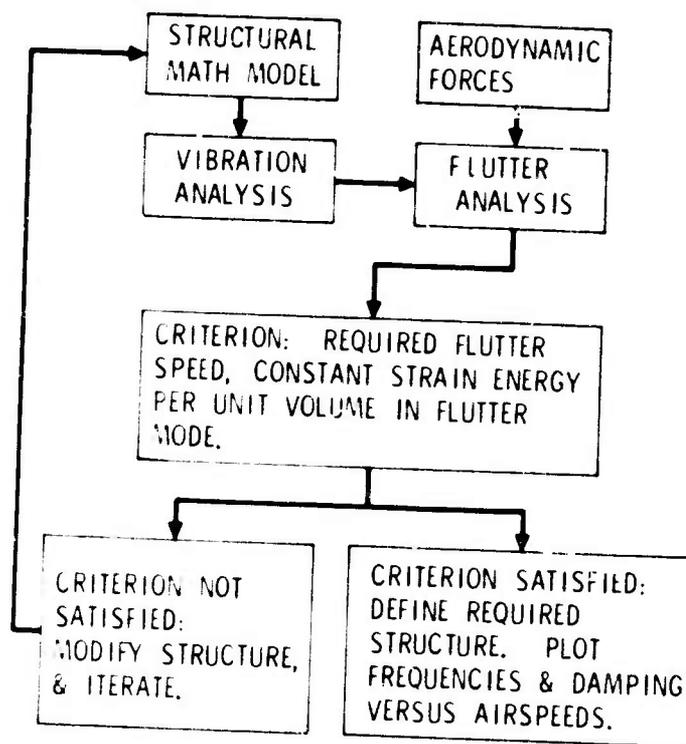


Figure 7. Flow diagram for flutter optimization program.

The structural mathematical model of the method assumes a spanwise box beam lying along the elastic axis of an aerodynamic surface. The beam is divided into a finite number of sections, each of which is allowed to bend and twist. The stiffness properties are described in terms of spanwise distributions of bending (EI) and torsional (GJ) stiffness. The inertial properties are described in terms of structural and nonstructural weight, center of gravity, and chordwise and spanwise moments of inertia for each beam section. The program is capable of including root and outboard break flexibilities, as well as the addition of external stores.

The aerodynamic forces used in the program are derived from subsonic strip theory, with the user's option of modifying the spanwise local lift curve slope and chordwise aerodynamic center to account for compressibility and aspect ratio effects.

Output data are in the form of spanwise stiffness requirements for one lifting surface and are in a format compatible as an optional external input to SWEEP in the form of punched cards so that data can be read directly from one program to the other with no intermediate steps.

This flutter program will optimize medium-to-high aspect ratios and medium-to-low sweeps for one lifting surface, and represents a significant step in the optimization of lifting surface structure.

## Section IV

### FLEXIBLE AIRLOADS STAND-ALONE PROGRAM

As a means of providing an alternate source of loads data for use with the SWEEP program, a flexible loads program was also developed. This program uses as a base an existing preliminary design aeroelastic method which is formulated to compute the effect of wing flexibility on the air vehicle component loads. The basic SWEEP program calculates load on a rigid airframe basis, while this program redistributes airloads along the span taking into account the aeroelastic effects on lift due to angle of attack and lift due to vertical acceleration. It requires GJ and EI stiffness distributions as input data as well as mass properties data. Its output is in the form of airload shears, bending moments, and torsion on the lifting surfaces of the air vehicle.

The methods used to calculate the redistributed wing loads are based on strip theory. The wing is divided into a number of equally spaced chordwise strips, as shown in Figure 3. Two structural influence coefficient points are used on the centerline of each strip, with values of the structural influence coefficients computed from input EI and GJ data.

The program requires external input data consisting of airplane geometry data identical to that used by the airloads module in SWEEP, the wing EI and GJ distribution and elastic axis location, and the specific flight condition (balance maneuver, vertical or lateral gust, and pitching or yawing acceleration), mach number and altitude combinations, limit maneuver load factors, pitching and yawing accelerations, airplane weight and center of gravity location, and estimated wing weight distribution. The program calculates the airload and center-of-pressure location of each airplane component and the airload shear, bending moment, and torsion distribution on the wing and empennage surfaces, all for each of the specified flight conditions. The output data consist of these calculated airloads and are also in the form of punched cards compatible as an optional external input to SWEEP.

- INCLUDES EFFECTS OF FLEXIBILITY
- REQUIRES BENDING & TORSION (EI, GJ) STIFFNESS
- OUTPUTS - SHEAR, BENDING, & TORSIONAL LOADS

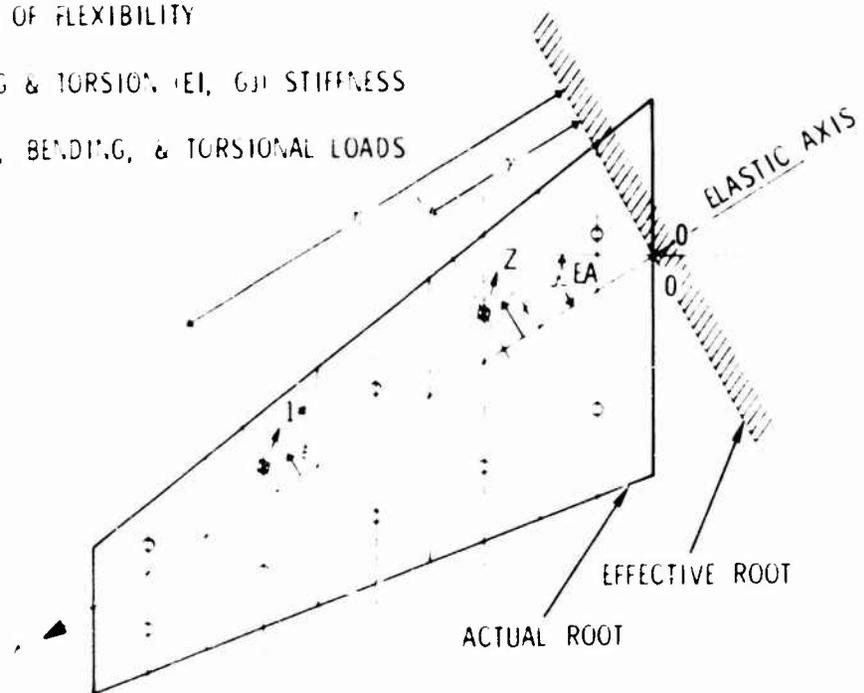


Figure 8. Wing diagram for aeroelastic loads analysis.

## Section V

### CONCLUSIONS

Use of automated analytical systems for advanced design has been demonstrated and has shown substantial reduction in turnaround time. The analytical methods used in SWEEP have been correlated through years of operation and have been successfully demonstrated using existing aircraft as baselines. The sensitivity of analytical methodology to changing criteria, materials, and construction methods is a must in today's, and the future's rapidly changing technology. Accurate assessment of these technologies, not possible without analytical approaches to the problem, must be encouraged to provide trade data for intelligent assessment of technological impacts. Future development will bring more computer automation techniques and more extensive use of interactive graphics. The programs available today are beginning to show the potential for weight and cost savings associated with the development of future aerospace vehicles.

## Section VI

### REFERENCES

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