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DEVELOPMENT OF METHODS FOR THE ANALYSIS AND EVALUATION OF CCV AIRCRAFT

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ABSTRACT

The development of an advanced, computerized method for the analysis and evaluation of the aeroelastic stability and control parameters of controls-fixed and controls-free flight vehicles is presented. Specifically, the contractually developed Level 2.01 FLEXSTAB Computer Program System is described. Technical areas in aerodynamics, dynamics, and control system synthesis are defined in which further research and development are planned to extend the analysis capability of the System for future CCV applications.

INTRODUCTION

The development of computer programs to analyze and evaluate the aeroelastic characteristics of controls-fixed aircraft has intensified in past years. This increase in interest has been due to the design and construction of large transport aircraft, such as the Boeing 747, McDonnell Douglas DC-10, and Lockheed L-1011, and of the high performance aircraft, such as the SST and the B-1. Recent articles by Stauffer, Lewalt, and Hoblit (Reference 1) and Rowan and Burns (Reference 2) describe methods and capabilities currently available within the industry. This paper describes the Level 2.01 FLEXSTAB Computer Program System (Reference 3) that has been developed by the Control Criteria Branch for the aeroelastic stability and control analyses of both controls-fixed and controls-free military aircraft. This development included careful consideration of the applicability of the method to military mission objectives, the variety of potential military users of the method, the manpower and computer costs involved in using the method, and the criteria that govern the application of the method. This development has taken particular care to solve some of the problems that are unique to the analysis and evaluation of Control Configured Vehicle (CCV) aircraft operating at reduced frequencies that are small.

As noted, there are mission and user requirements placed upon any CCV-type aircraft analysis and evaluation method developed for the USAF. The mission objectives of these aircraft impose severe and complex requirements, requiring that the method analyze:

- The subsonic, transonic, supersonic, and hypersonic speed regimes.

- The complex, three-dimensional, aerodynamic interference flow fields of transport, bomber, and fighter aircraft.

- The structural dynamics of both low and the high structural aspect ratio lifting surfaces of aircraft.

- The static and dynamic stability of aircraft with both unusual inertial distributions and large translational and rotational rates of motion.

An examination of the major research and development organizations within the Air Force Flight Dynamics Laboratory (AFFDL) and the Aeronautical Systems Division at Wright-Patterson AFB indicates that there are three types of users who impose additional requirements:

- Those concerned with conceptual design and development only. These users desire a fast, inexpensive, and proven method that performs reliable design and evaluation of new and innovative aircraft.

- Those concerned with the responsibilities of following and monitoring the development of a new aircraft by the contractors, from the conceptual design to the flight test phases. Again versatility and cost/effectiveness are imperative due to the limited manpower that is available.

- Those concerned with developing new and advanced technologies for future applications. These users desire a well documented and versatile method that can be easily modified to prove their ideas before major computer program development is initiated.

As noted, each of these users has a unique problem that the method must address. Fortunately, these user requirements for high speed, low cost, and versatility are compatible and can be met using the large digital computer and aerodynamic and structural finite element theory.

The development of an analysis method to meet these requirements was begun in 1971 by the Control Criteria Branch of AFFDL. A 1973-1974 target date was set for the completion of the analysis method to ensure support for the development of the Ride Control System of the B-1 aircraft and the Reduced Static Stability systems proposed for several Lightweight Fighter aircraft configurations. At that time, descriptions of the existing analysis methods within the industry were meager and only a limited amount of financial resources were available for the planned contractual work.

An obvious technique for acquiring a CCV analysis and evaluation method would have been to purchase the most accurate and versatile, contractor-developed, design method available. Discussions with the aerospace contractors indicated that their existing design methods in flight controls, aerodynamics, structural analysis, and dynamics could suffice in the short term. However, due to the loose and often undocumented federation of computer programs used by each contractor, the AFFDL Control Criteria Branch would have had to purchase the "expert" who developed each program to implement this technique. Thus, it was impossible to make a direct purchase to satisfy the identified needs.

The search was then diverted to the newly developing controls-fixed aircraft analysis and evaluation methods that contained the necessary mathematical sophistication. The prime candidate in the 1971-1972 time period was the Level 1.01 FLEXSTAB Computer Program System being developed by the Boeing Company, Seattle, Washington, under contract to the NASA Ames Research Center (Reference 4). This program could not meet the USAF requirements in the transonic and hypersonic speed regimes, had a limited unsteady aerodynamics computational capability, had no turbulence analysis capability, and had a restricted mathematical representation of high aspect ratio structures via elastic axes and lumped masses. However, the programs were well documented, were somewhat modularized, and with some modifications could meet the majority of the requirements of the USAF. Of considerable benefit was the fact that NASA had already spent approximately $500,000 developing the aerodynamic and structural modules of FLEXSTAB. Thus, with limited expenditures by the Control Criteria Branch, the modules for flight control systems analysis could be added to meet both the time schedule and budget objectives.

The development plan to construct the control system analysis modules was formulated and coordinated with NASA Ames Research Center (ARC). It was decided that NASA/ARC would concentrate their immediate resources in further checking the accuracy of the aerodynamics and structures modules of Level 1.01 FLEXSTAB. Meanwhile, the Control Criteria Branch would implement Level 1.01 at Wright-Patterson Air Force Base (WPAFB) to measure the accuracy and efficiency of the programs using current military bomber, transport, and fighter aircraft as test cases. In addition, the AFFDL would begin a contractual effort to develop the control system analysis modules. The combination of these aerodynamic, structural, and control system analysis modules would then form the basis for Level 2.01 FLEXSTAB to be used by NASA and USAF in the stability and control analysis of conventional and CCV-type aircraft.

The Level 2.01 FLEXSTAB Computer Program System is in the final check-out phase. The contracted work is scheduled for completion in November, 1974. The Control Criteria Branch has been evaluating a pre-release version of Level 2.01 since February, 1974 with the primary applications being made to the C-5A, B-52E, B-1, and F-111 TACT aircraft. An oral technical presentation is scheduled for October, 1974 at the AFFDL. Several papers will be presented by the contractor in coming technical meetings to more fully describe Level 2.01 and to illustrate its application to the B-52E and other aircraft.

DESCRIPTION OF LEVEL 2.01 FLEXSTAB

The development of the control system analysis modules and the interfacing of them to the Level 1.01 aerodynamic and strutures modules has been done under an AFFDL research and development contract with the Boeing Company, Seattle, Washington. As a first step in the contract, the principal investigators established firm guidelines to meet the Statement of Work from the Control Criteria Branch. Their initial report (Reference 5) on the contract summarized these guidelines:

No predetermination of "important motion parameters" per previous short cuts in analysis. The equations of motion should not be "tailored" for conventional aircraft, e.g., the method would not neglect the forward speed degree of freedom of the "body-fixed" axis system as currently practiced by most structural dynamacists.

The initial conditions of motion to be as general as possible. Only the initial conditions of linear and angular accelerations were eliminated because of theoretical aerodynamic problems.

Reasonable restriction of the number of feedback and pilot inputs and of the order of the control system filters.

Hinge moment aerodynamic effects represented as an option.

Compatibility with the Level 1.01 FLEXSTAB program to take advantage of NASA sponsored improvements. In fact, the NASA coding requirements for the Level 1.01 FLEXSTAB were specified by the Control Criteria Branch.

No higher user skill level than the capability to create simple Fortran statements as taught to Freshmen engineering students.

Independence from the specialized math models of actuators, of control surface/actuator coupling, and of turbulence Power Spectral Density shapes.

Capability for the analysis of both the open and closed loop system responses due to deterministic gusts and due to random turbulence.

Input data formats that minimize the preparatory work required by the user.

Minimization of the complexity of modules within each program to permit the user to understand the basic calculations by the program.

A program structure that provides for a maximum number of accurately determined complex number roots.

Computer overlay structure that minimize the computer cycle time in production runs.

Above all else, it was established that program risks must be identified and reported before the initiation of any detailed engineering and coding. These high risk areas were to be avoided until a program existed that could numerically demonstrate the analysis and the evaluation problems in these areas and, at that point, USAF or NASA funding on specific high risk/high payoff areas could be initiated. The test case specified to check Level 2.01 FLEXSTAB is the B-52 LAMS (Reference 6) at Flight Condition 1: $M = 0.569$, Altitude = 4,000 ft, Weight = 350,000 lbs., and Center of Mass = $0.298\bar{c}$.

Physical Structure of Level 2.01 FLEXSTAB

As mentioned, the Level 1.01 FLEXSTAB programs were intended for the stability and control analysis of controls-fixed aircraft. In order to improve the efficiency and suitability of the Level 2.01 Systems for both controls-fixed and controls-free aircraft analysis and in order to meet the stated guidelines, the 16 computer programs of Level 1.01 (Figure 1) were overlayed and restructured. This meant modification of all four sections of FLEXSTAB: Airplane Definition, Airplane Stability Evaluation, Graphical Display, and Auxiliary Program sections. The net result in Level 2.01 FLEXSTAB is 13 computer programs (Figure 2) that are interconnected by cards and magnetic tapes.

A more detailed description of the physical structure of the Level 2.01 FLEXSTAB System can be accomplished by contrasting Level 2.01 programs to those of Level 1.01. Then, current government and industrial users of Level 1.01 can more easily visualize Level 2.01 FLEXSTAB. To further facilitate this contrast, Level 2.01 programs have been segmented into the same four analysis sections as before and individual program acronyms of Level 1.01 are maintained wherever possible. Since these program acronyms have been in active use for more than three years, it is hoped most readers will have some familiarity with the terminology of Level 2.01 FLEXSTAB.

Specifically then in the Airplane Definition section of Level 2.01 FLEXSTAB, the Geometry Definition (GD) and the associated CALCOMP program (GDPLOT) of Level 1.01 have been combined in Level 2.01 to facilitate the conversion of the scaled configuration drawings of the aircraft into the spatial mathematical descriptions required by the subsequent downstream programs of Level 2.01. The Aerodynamic Influence Coefficient (AIC) program of the Level 2.01 System is structured to include both the steady and low-frequency unsteady aerodynamic programs of Level 1.01. The Internal Structural Influence Coefficient (ISIC) and Normal Modes (NM) programs and the External Structural Influence Coefficient (ESIC) program of Level 1.01 have been modified to provide structural data to mathematically represent 15 types of flight control sensors. In the airplane Stability Evaluation Section of Level 2.01, the Stability Derivative and Static Stability (SD+SS) and the Characteristic Equation Rooting (CER) programs of Level 1.01 have been combined to facilitate the controls-fixed aircraft analysis. In the position previously occupied by the CER program of Level 1.01, a new Linear Systems Analysis (LSA) program for controls-free aircraft analysis is included in Level 2.01. The Level 1.01 FLEXSTAB Time Histories (TH) program is modified so that Level 2.01 may analyze the response of controls-fixed and controls-free flexible aircraft that are perturbed by deterministic gusts or control surface disturbances. The remaining Graphical Display programs of Level 2.01, i.e., Elastic Axis Plot (EAPLOT), Normal Modes Plot (NMPLOT), and Pressure Distribution Plot (PDPLOT), and the Auxiliary programs of Level 2.01, i.e., Corrected Aerodynamic Influence Coefficient (CAIC), and Structural Loads (SLOADS) are only slightly altered from their Level 1.01 FLEXSTAB form.

The net cost/effectiveness of these changes from the Level 1.01 to Level 2.01 FLEXSTAB, as well as the contracted and the in-house modifications to the CDC computers at WPAFB, is shown in Figure 3. Initially, the Level 1.01 FLEXSTAB, as implemented at WPAFB in February 1973, required 17 workdays, 72 manhours, and 18,000 computer resource seconds to perform a single design point analysis of a high aspect ratio aircraft using a moderate sized math model that consisted of 200 aerodynamic influence coefficients (AIC's). A computer resource second is defined to be the total of the Central Processor seconds added to one-half the Input/Output seconds (CP + 1/2 IO).

Presently, the Level 2.01 FLEXSTAB analyses require substantially less workdays, manhours, and computer seconds at WPAFB. As an example, the Control Criteria Branch performed a conceptual design analysis (Reference 7) of a Spanloader aircraft, Figure 4, inspired by the Lockheed Spanloader presented in Reference 8. This in-house analysis required approximately 3 workdays, 5.7 manhours, and 10,000 computer resource seconds. In fact, a substantially greater number of Level 2.01 FLEXSTAB analyses were performed, at approximately 1/2 the computer costs of the Level 1.01 FLEXSTAB analyses. An examination of the differences in the workdays indicates that 10 days were removed due to the purchase of a second CDC 6600 computer for WPAFB. The remaining 8 days were reduced to 3 via the streamlining of the program and the specialization of the System to the computer software of the CDC computer system at WPAFB. The reduction in the expended manhours can be attributed to several things. Approximately 20 hours of the reduction can be attributed to experience gained in using the System over the past two years. The major manpower savings is accomplished in the operation of the ISIC program due to the creation of an interface program that simplifies the input of elastic axis and lumped mass locations, thus eliminating user-generated errors. Manpower savings were also accomplished in the GD and SD+SS programs by rewriting the input data formats to highlight redundant data inputs and to redefine the input data.

Analysis and Evaluation Capability of Level 2.01 FLEXSTAB

The basic analysis and evaluation capability of the Level 2.01 System is substantial, being best illustrated by detailed descriptions of what each major program in the System will do. In general, the Level 2.01 System estimates the static and dynamic stability and control parameters of controls-fixed and controls-free flexible aircraft over a Mach number range of 0.0 to approximately 3.5. The System is applicable to complex, three-dimensional aircraft configurations, e.g., vertical tails located on the outboard portions of the wing, T-tails, nacelles suspended from struts, and close-coupled canards and wings. The steady aerodynamic theory of the System is an advanced version of the method developed by Woodward, Tinoco, and Larsen (Reference 9), in which constant pressure vortex panels, constant strength source panels, line doublets, and line sources represent the linear potential flow aerodynamics about the flight vehicle. In addition, the aerodynamic program of the System contains a recently-developed (Reference 10), low-frequency unsteady aerodynamic approximation that extends the basic steady aerodynamic method to the calculation of unsteady aerodynamic derivatives, e.g., $\dot{\alpha}$, $\hat{q}$, $\dot{\delta}_S$, $\hat{\beta}$, $\hat{r}$ and $\hat{p}$ derivatives, as well as the "generalized modal aerodynamics." The low-frequency approximation is unique in that it has the same general, three-dimensional capability of the steady aerodynamics method at both subsonic and supersonic speeds. This feature eliminates the redefinition of the influence coefficient geometry with Mach number and also the "diaphragm region" of the existing Mach Box supersonic method.

There are two structural influence coefficient methods within the System. One method is based upon the elastic axis/lumped mass approximation usually employed on high aspect ratio aircraft. In this method (ISIC and NM programs of Figure 2), the structure of the aircraft is replaced by a connected configuration of beams with specified bending and torsional stiffness properties. This math model is used to calculate the stiffness and the flexibility matrices, the aircraft inertial characteristics, and the invacuum vibration eigenvalues and eigenvectors of the free-free structure. The structural and inertial matrix coefficients are transformed into a mathematical format that is compatible with the steady and unsteady aerodynamic influence coefficients. Once the aerodynamic and structural influence coefficients exist in a compatible numerical format, the subsequent programs in the System can calculate the stability and control parameters of the rigid and flexible aircraft.

The second structural influence coefficient method in the System (ESIC program of Figure 2) contains numerical routines that accept influence coefficients from an "external" finite elements programs, such as NASTRAN, and then converts them to a form compatible with the aerodynamic influence coefficients. Thus, ESIC provides the System user with an accurate structural influence coefficient representation of the aircraft that is most useful in the advanced design cycle of aircraft development.

As noted before, the aerodynamic and structural influence coefficients are summed for the static and dynamic aeroelastic stability and control calculations by the other programs in the System. These System programs (SD+SS, LSA, and TH programs of Figure 2) calculate the stability and control derivatives, the static and dynamic stability, the aerodynamic loads on the maneuvering aircraft, and the deformed shape of the flexible aircraft. The SD+SS program of the System (Reference 11) allows for initial conditions of non-accelerating dynamic motions consisting of constant-magnitude, angular pitch, roll, and yaw rates and linear translational rates, singularly or in combination. The engine gyroscopic effects are included at the user's option. Once the initial conditions of motion are defined in SD+SS and the trim or specified shape of the aircraft defined, the analyses of symmetric, asymmetric, or coupled perturbation dynamic motions is possible using (1) a characteristic equation rooting method, if the perturbation equations are linear ordinary differential equations, or (2) a Runge-Kutta integration method of the TH program, if the differential equations are nonlinear or the system is excited by deterministic gust and control disturbances.

The Stability Derivative and Static Stability (SD+SS) program also contains numerous options that connect the Level 2.01 FLEXSTAB to the existing experimental and semi-empirical methods of analysis. As an example, the stability and control data measured during wind tunnel tests of rigid force and hinge moment models of aircraft may be incorporated as tables of data, e.g., $C_L(\alpha, \delta_S)$ and $C_n(\alpha, \beta)$, or as derivatives at the trim point, e.g., C_{L_α} and C_{n_β}. If the wind tunnel measurements are unavailable, a semi-empirical method such as Datcom (Reference 12) may be used instead.

The Linear Systems Analysis (LSA) program of Level 2.01 FLEXSTAB is of particular interest to analysts of CCV-type aircraft. As implied previously, the computer mechanization of the routine engineering computations involved in CCV analyses improves the analysis cycle time and analysis accuracy, because the computer does not make mistakes due to fatigue or boredom. The specific CCV-type calculations that have been mechanized in LSA (Reference 13) are:

The construction of an LSA precompiler, that accepts user specified control system transfer functions as a ratio of high order polynominals in the Laplacian variable, and then internally rearranges these elements into a standard matrix format for Root Locus, Bode, Nyquist, and Power Spectral Density analyses.

The construction of accelerometer, rate gyro, angular position, air speed, and inertial velocity sensor equations as an integral part of the overall LSA calculations.

The construction of a Padé polynomial approximation of the gust and the turbulence penetration exponential, per user specified tolerances.

A built-in Von Karman Power Spectral Density model to represent the turbulence excitation of the flexible, controls-fixed and controls-free aircraft. The user may input his own turbulence model if he so desires.

Options that permit a user to "delete" or "reduce" selected invacuum modes via the MODAL TRUNCATION or the RESIDUAL FLEXIBILITY formulations that are discussed in the next section of this paper.

An option to punch on cards, in a standard format, the matrix equations of motion of the aircraft and the sensors for the user to input to flight simulators and other interfacing stability and control computer programs.

The input and output data of the programs are graphically presented by five CALCOMP programs that are interconnected to the main analysis programs of the System by overlay, cards, or magnetic tape (TAPE 99 in Figure 2). These CALCOMP programs present the geometric orientation of the aerodynamic and structural elements of the math model of the aircraft, the invacuum eigenvectors, the aerodynamic load distributions, and the time history responses.

Two programs in the Level 2.01 FLEXSTAB are intended primarily for design. One, Corrected Aerodynamic Influence Coefficient (CAIC program of Figure 2) is used to correct the aerodynamic influence coefficients for non-linear effects via correction factor matrices. The second, Structural Loads (SLOADS program in Figure 2), calculates the aerodynamic and inertial component loads along the elastic axes, if the beam structural math model is employed.

ESTABLISHMENT OF CRITERIA FOR THE APPLICATION OF LEVEL 2.01 FLEXSTAB

The Level 2.01 FLEXSTAB contains numerous user options that permit varied types of aeroelastic stability and control analyses. A unifying concept in the System is, that no matter which of the options are selected, one of the major results is the creation of the equations of motion using the aerodynamic, structural, and inertial matrices. These equations of motion, and the attendant sensor and loads equations, consist of three inter-related formulations, QUASI STATIC, RESIDUAL FLEXIBILITY, and MODAL TRUNCATION, that describe the dynamics of the controls-fixed and controls-free aircraft.

The industry surveys mentioned at the beginning of this paper indicated that all of the formulations were used to a degree, but that the QUASI STATIC and MODAL TRUNCATION formulations were the most common. As examples:

The XB-70 GASDSAS, B-52E LAMS, B-52E CCV, C-5A ALDCS, F-4 Survivable Flight Controls, F-4 CCV, F-111, and F-15 aircraft projects applied the QUASI STATIC and MODAL TRUNCATION formulations.

The initial AFFDL sponsored studies of a CCV-type bomber, transport, and fighter aircraft applied the QUASI STATIC and a combination of the MODAL TRUNCATION and RESIDUAL STIFFNESS formulations.

The SST design studies applied the QUASI STATIC, MODAL TRUNCATION, and RESIDUAL STIFFNESS formulations. The B-1 design studies applied the QUASI STATIC, MODAL TRUNCATION and RESIDUAL STIFFNESS formulations.

The industry and government have developed criteria for the selection of the QUASI STATIC formulation. However, there are few criteria to guide the selection of the other formulations of the equations of motion. The criteria are necessary because they:

Force the flight control analysis to be consistent with the flutter and structural loads analyses of CCV-type aircraft.

Provide a qualification for the associated handling quality and ride quality criteria studies.

Provide a rational to the USAF and the other government agencies to be used in the evaluation of competing CCV-type aircraft.

Identify the configuration development problems created by the application of each formulation.

Place upper limits on the complexity to be tolerated in CCV-type control systems that are designed using each of the approximate formulations.

Determine the risks associated with the relaxation of criteria.

The AFFDL Control Criteria Branch initiated a study in 1971-1972 to supply these criteria as part of the Development plan for Level 2.01 FLEXSTAB. As a first step, the six linear formulations of the equations of motion were identified and mathematically related using the notation of the FLEXSTAB documentation:

EXACT - The motion of the structure is determined by eigenvalue (root) and eigenvector (mode shape) solutions of the equations of motion for the elastic aircraft. The mode shape coordinates contain complex numbers. The accuracy of the solution is limited by the existing computerized routines that calculate the complex number eigenvalues and eigenvectors.

MODAL SUBSTITUTION - The motions of the structure are assumed to be related to the orthogonal, invacuum eigenvectors (mode shapes). The eigenvectors contain only real numbers.

RESIDUAL STIFFNESS - The mode shapes representing the elastic motion in the MODAL SUBSTITUTION formulation are separated into "retained" and "deleted" modes. The deleted modes are represented in the dynamic stability analysis as quasi static aeroelastic corrections, using a correction factor related to the deleted modes and the stiffness matrix of the free-free structure.

RESIDUAL FLEXIBILITY - Similar to the RESIDUAL STIFFNESS formulation, except the quasi static aeroelastic correction is related to the retained modes and the flexibility matrix of the free-free structure.

MODAL TRUNCATION - The deleted modes of the RESIDUAL STIFFNESS and

RESIDUAL FLEXIBILITY formulations are not represented by any correction factor. This is the most common dynamic aeroelastic formulation reported in the literature.

QUASI STATIC - The motions of the structure are assumed to be in-phase with the rigid body motions. The method is used primarily for the conceptual and preliminary design of handling quality and reduced static stability control systems for elastic aircraft with a wide frequency separation between the axis system motions and the structural deformations.

A contrast of the computational difficulties and the unique features of each of the formulations is found in Tables 1 and 2. As shown, the EXACT and MODAL SUBSTITUTION formulations consist of a large number of equations that must be solved simultaneously and, in most cases, their number precludes their use in the design of flight control systems. The RESIDUAL STIFFNESS and RESIDUAL FLEXIBILITY formulations provide equivalent numerical results, despite the differences in matrix formulation.

During the analytical studies to mathematically relate the various formulations, it became apparent that a general criteria for the selection of each formulation could be stated in terms of the major assumptions that are required to derive each formulation (Reference 14). These major assumptions are presented in Figure 5. An examination of Figure 5 reemphasizes that it is relatively easy to decide when the QUASI STATIC formulation is appropriate. However, the decision on the appropriateness of the RESIDUAL formulations or the MODAL TRUNCATION formulation is considerably more difficult. The difficulty arises due to the necessity to numerically evaluate the significance of the "structural spring forces," A8, and the "aerodynamic forces of structural deformation," A9 upon the performance of the flight control system.

Presently, most of the aeroelastic stability and control design methods in use in the industry do not possess the capability to evaluate these terms for their numerical significance to the dynamics of the flexible aircraft. In contrast, the Level 2.01 FLEXSTAB is specifically engineered and coded to provide the USAF with the capability to consider both formulations, and thus, to evaluate the numerical significance of A8 and A9 when applied to the design of any proposed aircraft. This new capability in Level 2.01 should provide additional information concerning the interaction of modern flight control systems with the structural dynamics of aircraft.

The aeroelastic stability and control parameters, to be calculated with the Level 2.01 FLEXSTAB during the check-out using the aircraft presented in Table 3, will provide more specific numerical criteria for the selection of either the RESIDUAL FLEXIBILITY or MODAL TRUNCATION formulations of Level 2.01 FLEXSTAB. The bomber/transport aircraft category is receiving first attention due to their significant aeroelasticity at all flight conditions. Once the numerical criteria are generated for this category, the fighter category of aircraft will then be considered. Here, the emphasis will be placed upon the unique fighter aircraft maneuvers that are comprised of large rates of rotation and high load factors.

FUTURE DEVELOPMENT OF LEVEL 2.01 FLEXSTAB

The Level 2.01 FLEXSTAB is nearing the completion of the first cycle of funding action that was intended to provide AFFDL and the USAF with the capability to perform basic analysis and evaluation of conventional and CCV-type aircraft. As mentioned previously, the contractor and the AFFDL Control Criteria Branch decided early in the program that the high risk technical areas should be identified prior to beginning the extensive engineering or programming work in these high risk areas of analysis. There are two areas of high risk that have been identified for AFFDL in-house and contractual studies in FY75-76:

The application of the low-frequency unsteady aerodynamics to the calculation of turbulence and gust induced aerodynamic forces.

The identification of a suitable test case to verify the engineering and the coding of Level 2.01 FLEXSTAB.

The test application of the low frequency unsteady aerodynamic method to the calculation of unsteady aerodynamic stability and control derivatives such as $C_{L_{\dot{\alpha}}}$, $C_{m_{\dot{\alpha}}}$, $C_{n_{\dot{\beta}}}$, $C_{\ell_{\dot{p}}}$, and $C_{m_{\dot{\delta}_S}}$ and the low-frequency, generalized aerodynamic forces has been "successful" to date. By successful is meant that "reasonable" correlation has been achieved on most test cases. The doublet lattice and the unsteady aerodynamic strip theory methods provide partial checks at subsonic speeds. At supersonic speeds there are no comparable theoretical methods that can represent the complex flow field around three dimensional aircraft configurations. Ideally, the Level 2.01 estimates should be compared to experimental data, as well as existing analytical data. However, the comparison to the experimental data will require the development of the parameter estimation method for flexible aircraft, to be discussed in the latter paragraphs of this section of the paper.

The low frequency unsteady aerodynamics have proven to be marginally acceptable to unacceptable for the calculation of atmospheric gust and turbulence induced aerodynamic forces. The problem in the Level 2.01 turbulence analyses is that the calculation of the Power Spectral Density of a parameter such as vertical acceleration due to vertical gusts, a_z/w_g, requires the integration of the square of the frequency domain representation of the a_z/w_g transfer function, multiplied by the turbulence Power Spectral Density. This integration over all frequencies does not converge due to the neglect of the higher order unsteady aerodynamic effects by the low frequency aerodynamics method. The contractor, Air Force Office of Scientific Research, and the Control Criteria Branch have studied the numerical problem in detail and identified the contributions of the individual terms of the transfer functions. There are four possible solutions:

Incorporation of the Kussner-Wagner functions per conventional design practices.

Addition of the doublet lattice aerodynamic methods for turbulence analysis at subsonic speeds.

Retention of the next higher order frequency terms in the asymptotic expansion of the unsteady aerodynamic potential flow equations.

Expansion of the unsteady potential flow equations for "large frequencies" and then "matching" of the low and high frequency solutions for intermediate frequencies.

The first option is the obvious short term solution for Level 2.01, since only a small increase in the computer costs is involved in using the System. The incorporation of the doublet lattice method into the System is attractive, since it has become an accepted design method. Unfortunately, this solution may require extensive modification of the System, and thus eliminate some of the unique CCV analysis options currently available, e.g., the inclusion of the forward speed degree of freedom in the dynamics, the multiple equation of motion formulations discussed in the preceeding section of this paper, and the very general initial conditions of motion. NASA has contracted to study this problem in detail. In addition, the Air Force Office of Scientific Research has funded fundamental studies related to the unsteady aerodynamics methods applied to stability and control analyses. The third and fourth solutions are theoretically interesting, but unproven mathematically. Regardless, the incorporation of the latter 3 solutions is a relatively long term process requiring several extensive program check cases. These check case data are presently being collected during studies at AFFDL using the existing Level 2.01 programs and will be available for the future unsteady aerodynamic improvements to the Level 2.01 FLEXSTAB. The incorporation of the Kussner-Wagner functions and the correlation of Level 2.01 FLEXSTAB analytical estimates to the C-5A or the B-52E flight test data has been planned for FY75.

As mentioned, a new computer program requires extensive verification of the engineering equations and of the program coding. The development of the 13 programs of Level 2.01 FLEXSTAB compounded the verification problems, in that the check data on aircraft technology integration and the check data on the correlation of existing design methods to flight test data is practically non-existent. Ample amounts of wind tunnel test data on rigid aircraft models are available, along with comparisons to the other analytical methods. These data verify only the steady aerodynamic methods. Some static and dynamic structural data from ground vibration tests are available, but test conditions and parameters are not entirely suited to computer program check-outs; often these ground tests do not have a comparable flight test counterpart. The static-elastic aircraft models, cantilevered from stings or struts during wind tunnel tests, provide excellent checks of basic static aeroelastic calculations, but again little data is presently available. The cable-mounted flutter models provide some verification of dynamic aeroelastic calculations, although cable friction and umbilical cord drag add incalcuable factors.

The Level 2.01 contractual test case consisting of the B-52E LAMS at Flight Condition Number 1 has provided mixed results. This is because the LAMS data were not intended for check cases for new computer programs and, thus, they were not qualified and correlated in any great detail to the results of the LAMS design methods. For example, the generalized structural damping added to each structural mode was not documented and has been assumed to be $\zeta = 0.03$ in the Level 2.01 check case. Additionally, typographical errors, such as sign errors in the summation of the LAMS feedback loops exist inadvertently in the formal AFFDL documentation. Numerous additional questions arise in the correlations between the results of the Level 2.01 FLEXSTAB and the flight test that cannot be answered because the basic LAMS calculations were not preserved.

To date, the AFFDL Control Criteria Branch has been unable to find a suitable operational aircraft that can check the Level 2.01 program to the degree desired. As such, the Control Criteria Branch has decided to select the best data from the aircraft and aircraft model wind tunnel tests that are presented in Table 3. Each aircraft or model checks an area of major calculation within the System. To whatever extent possible, the experimental data and the Level 2.01 analytical estimates will be compared to the estimates of the contemporary, parochial analytical methods. The contrast of the Level 2.01 calculations to the calculations of parochial design methods of the aerospace industry is particularly important, since it qualifies the inaccuracies of FLEXSTAB, while providing a historical background to measure the progress of research and development. The major contracted test cases are with the B-52E and the F-111 TACT aircraft and flexible model; the remainder are in-house check cases. The manpower and computer cost of the in-house effort, approximately 60,000 dollars, is considerably less than the costs of a single wind tunnel test of either a rigid or a flexible model of an aircraft.

It should be noted that the data collected during these check case studies of Level 2.01 are extremely valuable. The data provide a mathematical representation of the current USAF vehicles for AFFDL support to the System Program Office (SPO) and for the development of future analytical methods by AFFDL.

In addition to funding the unsteady aerodynamics improvement and the additional B-52E and F-111 TACT test cases, AFFDL Control Criteria Branch has decided to begin studies in four areas directly or indirectly related to Level 2.01:

Modification of the System to allow the analysis of sting- and strut-mounted flexible models that are tested in wind tunnels.

Creation of a structural loads analysis module that interfaces with the System and that provides a numerical measure of the effectiveness of the CCV control system. This necessitates the study of the sensor equations that are appropriate to each of the math models of the dynamics of the aircraft.

Creation of an optimal control synthesis module that may be interfaced with the System.

Creation of a parameter estimation method for flexible aircraft to provide experimental check data for Level 2.01 from flight tests of aircraft.

In FY75-76, the Control Criteria Branch will study the difficulties involved in adding the capability for the analysis of static aeroelastic models that are tested in wind tunnels. Conceptually, this modification to Level 2.01 requires relatively minor changes to the System: the elimination of the "inertia relief" and the "free-free flexibility matrix" calculations in ISIC/NM, ESIC, and SD+SS programs (Figure 2) that are required for aircraft, but not for static aeroelastic models. The F-111 TACT flexible model serves as a check case for this modification, as well as an element in the overall System verification discussed previously. Pressure data will be incorporated into the analyses of the F-111 TACT flexible model and aircraft to further facilitate the numerical checks of the coding.

The FY75 studies will also investigate and define the form of the loads analysis equations that reflect the improvements or the degradations to the structural loads due to the operation of the CCV-type control systems. This study will include an investigation into the elastic correction factors on the accelerometer equations of motion found in the QUASI STATIC and the RESIDUAL FLEXIBILITY math models of flexible aircraft dynamics.

The incorporation of the optimal control synthesis methods as a feature of the Auxiliary Programs of the Level 2.01 FLEXSTAB is currently being studied in-house by the Control Criteria Branch (Reference 15). The aerodynamic program (AIC program of Figure 2) is particularly attractive in this study, in that it formulates the equations of motion in the time, Laplacian, and frequency domain of mathematical analysis. This uniqueness of Level 2.01 FLEXSTAB means that most if not all of the useful optimal control synthesis methods can be interfaced with Level 2.01 FLEXSTAB. This work by the AFFDL Control Criteria Branch is closely coordinated with the Active Controls Aircraft Office at NASA/ARC to ensure that funding duplication is avoided and that independent work by the AFFDL and NASA is available to all. The FY75-76 study in optimal control will use the C-5A as the test case.

The application of parameter estimation methods to flexible aircraft is receiving substantial attention from the Control Criteria Branch (Reference 16). There are several motivating factors that force the development of this type of Auxiliary Program for the Level 2.01 FLEXSTAB . First, the comparison of the steady and unsteady aerodynamic parameters, experimentally determined by flight tests, to the analytically calculated values, is essential to ultimately verify the accuracy of Level 2.01 FLEXSTAB, or any other aeroelastic analysis program. Without these types of verification to qualify the precision of the analytical estimates of the aerodynamic parameters of importance to CCV design, the innovative use of CCV concepts may be penalized by design risk factors that are assumed to be too large. Since the existing parameter estimation methods treat the aircraft as a "rigid" vehicle, a new method must be developed.

Second, the practical necessity of removing all excessive structural weight, whether through conventional design practices or through active control systems, has resulted in vehicles that are more aeroelastic than previous vehicles with similar operational missions. To a degree, all flight vehicles, including fighter aircraft, are aeroelastic. The degree of aeroelasticity depends upon the particular flight condition (Mach number, dynamic pressure, and mass distribution) at which measurements or observations are made. In order to minimize the technical risks involved in the design of these type of high performance vehicles, a prototype or a pre-production vehicle is often constructed prior to committing a large amount of resources to a production vehicle. The SST aircraft are obvious examples. The intent of the prototype vehicle is to demonstrate that the design meets all the mission objectives. This demonstration entails flight tests of the prototype to verify the math models employed in the design and to isolate any configuration problems that would be objectionable in the production vehicle. Again, since the existing parameter estimation methods treat the flight vehicle as a "rigid" structure, they eliminate the possibility of explicitly identifying important aeroelastic parameters that affect the response of the aircraft. This reason further necessitates the development of a parameter estimation method for flexible aircraft.

The effort in parameter estimation consists of both in-house and contractual work planned through FY78. As a first step, the Control Criteria Branch is developing an in-house program that is based upon the maximum likelihood method. The test data for this program will consist of B-52E CCV flight test data that will be selected to minimize the anticipated numerical problems discussed in Reference 16. The B-52E CCV analytical start-up data for the in-house method has been generated using the Level 2.01 aerodynamic and structural finite element representation presented in Figure 6. A contracted effort will compare the B-52E CCV aircraft analytical model to flight data estimated by a method being developed by a contractor. Both groups of these parameter estimates will be correlated to flight test data measured during the tests of the dynamic response of the B-52E to step, ramp, and sinusoidal motions of the control surfaces. As part of the in-house effort, the ISIC and NM programs of Level 2.01 FLEXSTAB will be evaluated relative to the methods applied to the B-52E CCV aircraft by the contractor. The purpose of the evaluation is to identify any inaccuracy that could be introduced in the in-house developed parameter estimation method due to the theoretically calculated values of the generalized mass and stiffness and of the invacuum mode shapes.

The next phase of the effort will involve investigating the high risk/high payoff areas of parameter estimation of flexible aircraft and further developing a production computer program. The final phase of the effort will include an extension of the linearized methods to nonlinear analyses.

CONCLUDING REMARKS

The Level 2.01 FLEXSTAB Computer Program System has the potential to meet most of the immediate needs of the AFFDL and the USAF for an analysis and evaluation tool of conventional and CCV aircraft. Its capability for varied aerodynamic and structural finite element representations of the controls-fixed and the controls-free aircraft provides versatility and allows cost/effective analyses at the conceptual, preliminary, and advanced design levels of aircraft development. The modular independence of the thirteen programs that comprise FLEXSTAB facilitate improvements to the aerodynamic, structural, dynamic, and flight control program elements. In fact, several USAF and NASA efforts are presently underway or planned to enhance FLEXSTAB to create an increase in capability for the Level 3.01 FLEXSTAB System.

Of particular importance in Level 2.01 FLEXSTAB is the availability of the QUASI STATIC, the MODAL TRUNCATION, and the RESIDUAL FLEXIBILITY formulations of the dynamics of aircraft. These multiple formulations provide a further capability for cost/effective analysis of the dynamics of both the controls-fixed and controls-free flexible aircraft. The numerous options in the Level 2.01 programs, for the inclusion of experimental data to improve accuracy, and for the interface of output data to flight simulators, optimal control synthesis methods, and parameter estimation methods, should make the Level 2.01 programs a key element in the development of the flight control systems of future military aircraft.

The AFFDL Control Criteria Branch and other organizations are currently applying Level 2.01 FLEXSTAB to the analysis and evaluation of all categories of military aircraft. This accrued experience is available to other interested organizations through a liaison officer in the Control Criteria Branch. This officer is responsible for any request to the AFFDL for a copy of the Level 2.01 FLEXSTAB programs, for monitoring the successes and failures of other Level 2.01 users, and for answering user questions. Presently several contractors and government agencies are taking advantage of the service.

Most promising is the decision by the Mechanics Department of the Air Force Institute of Technology (AFIT) to use the Level 2.01 FLEXSTAB programs and documentation as an illustrative tool to teach the intricacies of combining technologies during the design of modern aircraft. These USAF students provide valuable, constructive criticisms to the AFFDL Control Criteria Branch. Their related thesis work should provide new and often innovative ideas that could be incorporated into future Levels of FLEXSTAB. Finally, their background in finite element programs, such as FLEXSTAB, prepares them for the tasks of following the contractors of the USAF during the conceptual, preliminary, advanced design, and flight test phases of new aircraft development, or during the contractual modification of operational aircraft.

REFERENCES

1. Stauffer, W. A., Lewalt, J. G., Hoblit, F. M., "Application of Advanced Methods to Design Loads Determination for the L-1011 Transport," Journal of Aircraft, Vol. 10, No. 8, August 1973.

2. Rowan, J. C., Burns, T. A., "Aeroelastic Loads Predictions Using Finite Element Aerodynamics," AIAA Paper 74-106, Presented at AIAA 12th Aerospace Sciences Meeting, 30 January-1 February 1974.

3. The Boeing Commercial Airplane Company, "A Method for Predicting the Stability Characteristics of Control Configured Vehicles," Boeing Documents D6-41095-1, 2, 3, 4, November 1974. To be released as an AFFDL TR in November 1974.

4. The Boeing Commercial Airplane Company, "A Method for Predicting the Stability Characteristics of an Elastic Airplane," Boeing Documents D6-41064-1, 2, 3, 4, 5, August 1974.

5. Dornfeld, G., Schaeffer, D., [Richardson, T.], "Approach to be Used for Linear Analysis for AFFDL Contract F33615-72-C-1172, " Aero Coordination Sheet AERO-490, 21 June 1972.

6. The Boeing Company (Wichita, Kansas), "Aircraft Load Alleviation and Mode Stabilization (LAMS)," Boeing Document D3-7901-1, September 1968; also AFFDL-TR-68-161.

7. Schwanz, R. C., "Stability and Control Analysis of a Spanloader Aircraft," AFFDL TM 74-67-FGC, February 1974.

8. Lockheed <u>Southern Star</u>, 10 January 1974.

9. Woodward, F., Tinoco, E., Larsen, J., "Analysis and Design of Supersonic Wing-Body Combinations, Including Flow Properties in the Near Field: Part I - Theory and Applications," NASA CR 73106, 1967.

10. Brune, G., "Low Frequency Approximation in Unsteady Aerodynamics," <u>Journal of Aircraft</u>, Vol. 6, No. 5, September - October 1969.

11. Hink, G., Reference 3, D6-41095-3, November 1974.

12. Anonymous, <u>USAF Stability and Control Datcom</u>, Flight Control Division, Air Force Flight Dynamics Laboratory, October 1960 (Revised 1972).

13. Bills, G., Reference 3, D6-41095-3, November 1974.

14. Schwanz, R., "Formulations of the Equations of Motion of an Elastic Aircraft for Stability and Control and Flight Control Applications," AFFDL-FGC-TM 72-14, August 1972.

15. Stockdale, C., "Effect of the Equation of Motion Formulation on the Optimal Control Problem," AFFDL TM to be released in 1974.

16. Schwanz, R., Wells, W., "Estimation of Elastic Aircraft Parameters Using the Maximum Likelihood Method," Paper presented at the Symposium on Parameter Estimation Techniques and Applications in Aircraft Flight Testing, NASA Flight Research Center, 24-25 April 1973.

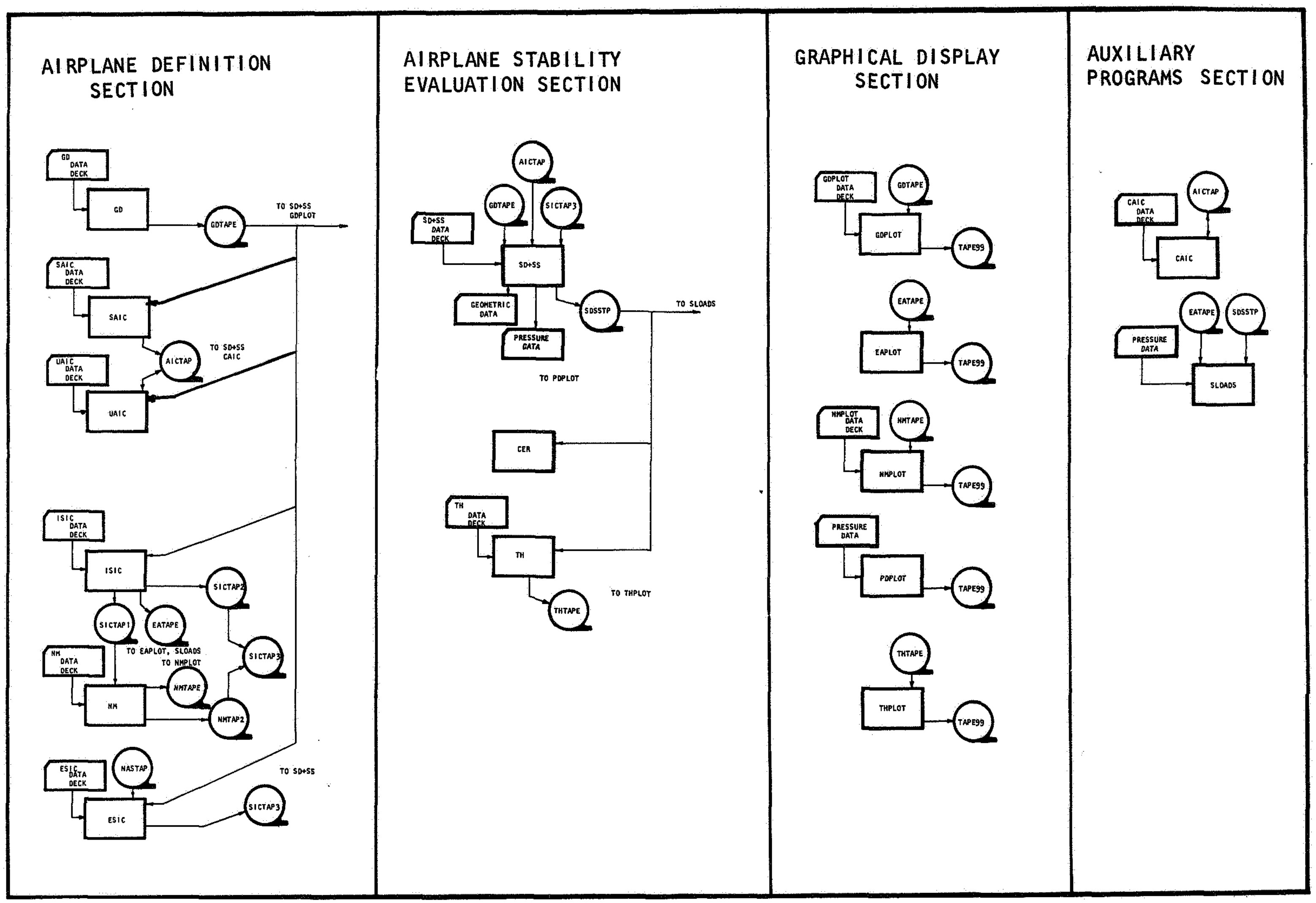


Figure 1. Level 1.01 FLEXSTAB Computer Program System

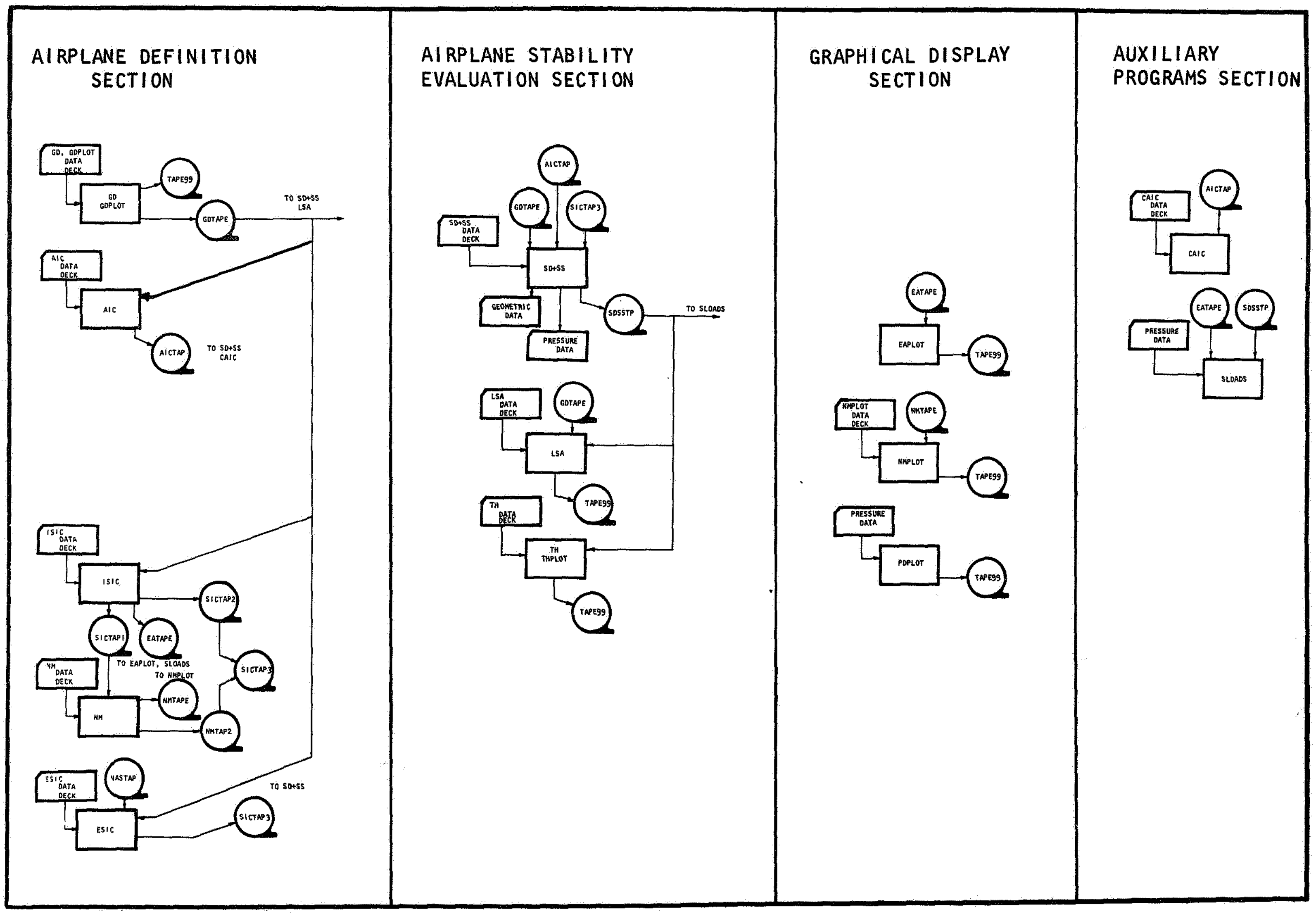
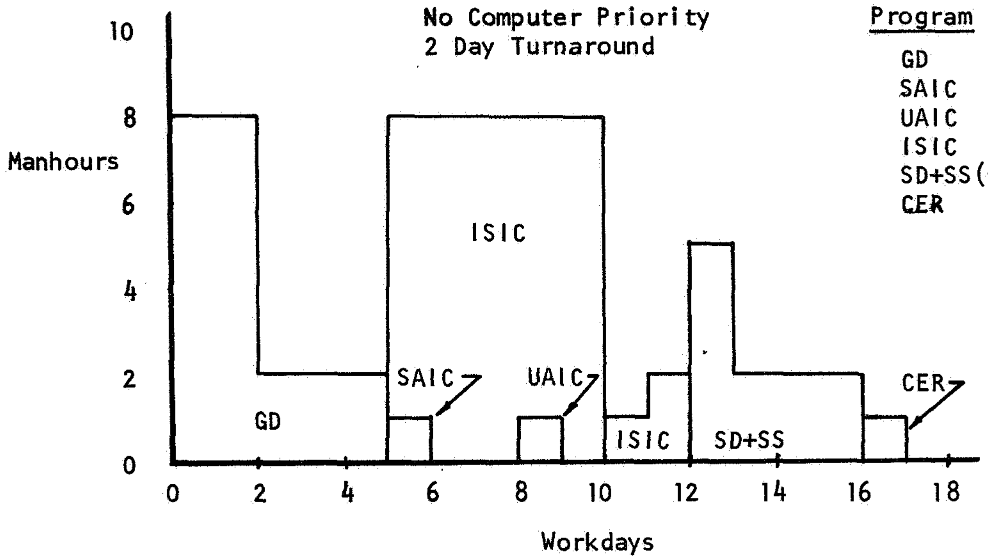


Figure 2. Level 2.01 FLEXSTAB Computer Program System

200×200 AIC ANALYSIS
ONE ENGINEER/ONE AIRCRAFT CONFIGURATION
ONE ANALYSIS POINT (M, q, Wt, STATICS, DYNAMICS)

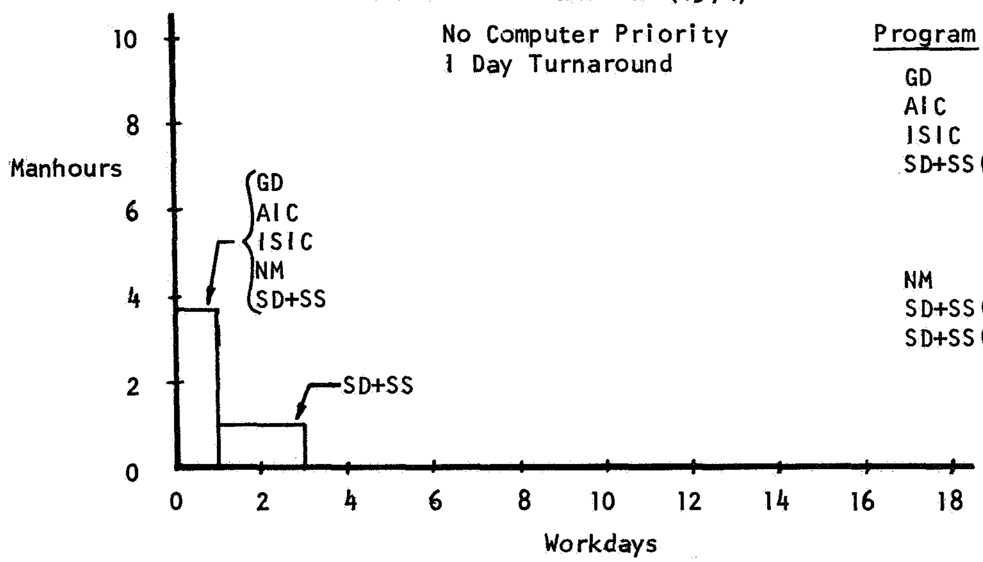
(QS) - QUASI STATIC
(MT) - MODAL TRUNCATION
(RF) - RESIDUAL FLEXIBILITY

LEVEL 1.01 FLEXSTAB (1973)



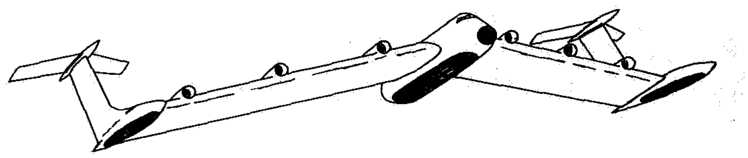
Program	CP + IO/2(sec)
GD	30
SAIC	4,000
UAIC	2,000
ISIC	8,000
SD+SS(QS)	4,000
CER	100
	18,130

LEVEL 2.01 FLEXSTAB (1974)

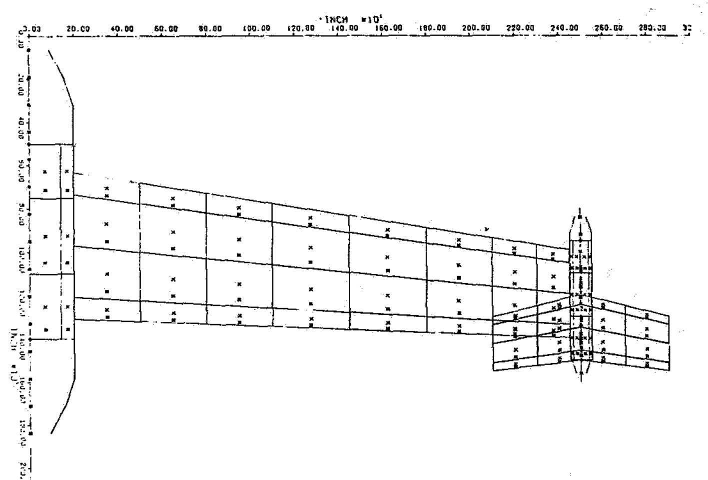


Program	CP+IO/2(sec)
GD	19
AIC	2,655
ISIC	937
SD+SS(QS)	1,321
	4,932
NM	308
SD+SS(MT)	1,952
SD+SS(RF)	2,950
	10,142

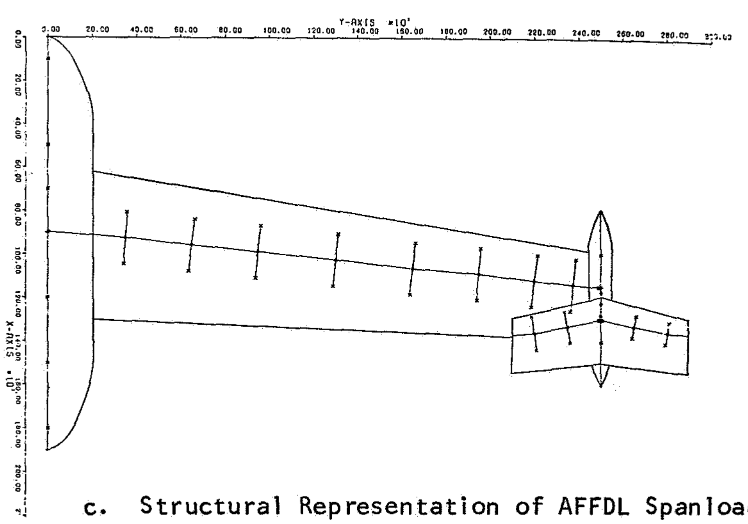
Figure 3. Costs for Aeroelastic Stability and Control Analysis at WPAFB



a. Lockheed Spanloader Aircraft



b. Aerodynamic Idealization of AFFDL Spanloader



c. Structural Representation of AFFDL Spanloader

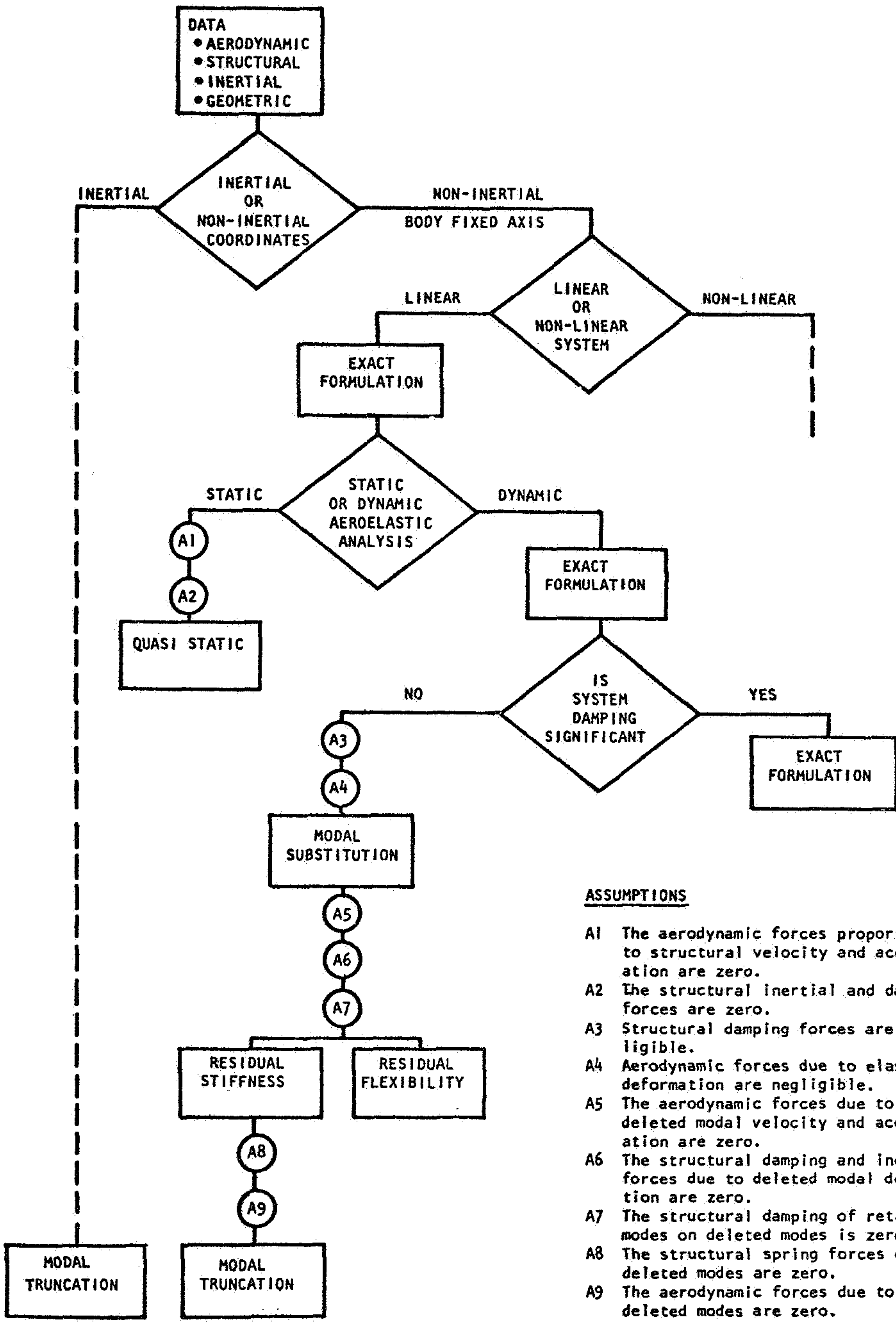
Figure 4. Application of Level 2.01 FLEXSTAB to Conceptual Design Analysis of a Spanloader Aircraft

Table 1. Computational Difficulties Associated with the Linear Formulations of the Equations of Motion

METHOD	ECONOMICS		EIGENVALUE ROUTINE		STRUCTURAL DATA REQUIRED
	PROGRAM SIZE	PROGRAM RUN TIME	REAL NUMBER	COMPLEX NUMBER	
EXACT	LARGE	?	-	LARGE	[K]
MODAL SUBSTITUTION	LARGE	?	LARGE	LARGE	[K]
RESIDUAL STIFFNESS	MEDIUM	LONG	LARGE	MEDIUM	[K]
RESIDUAL FLEXIBILITY	MEDIUM	LONG	MEDIUM	MEDIUM	[K] AND [C]
MODAL TRUNCATION	MEDIUM	MEDIUM	MEDIUM	MEDIUM	[K]
QUASI STATIC	SMALL	SHORT	-	SMALL	[K]

Table 2. Unique Features of the Formulations Describing Lightly Damped Aircraft Dynamics

METHOD	ADVANTAGES	DISADVANTAGES
MODAL SUBSTITUTION	PERMITS COMPLETE ANALYSIS OF LIGHTLY DAMPED AIRCRAFT MOST ACCURATE	LIMITED TO LINEAR OR PIECEWISE LINEAR SYSTEMS SLOWEST, MOST COSTLY
RESIDUAL STIFFNESS	REDUCED: NUMBER OF UNKNOWNS ANALYSIS CYCLE TIME COMPUTING COSTS	NEGLECTS DYNAMICS OF DELETED MODES REQUIRES ALL INVACUUM MODES
RESIDUAL FLEXIBILITY	SAME AS RESIDUAL STIFFNESS REQUIRES ONLY INVACUUM MODES OF INTEREST	REQUIRES FREE-FREE FLEXIBILITY MATRIX
MODAL TRUNCATION	SAME AS RESIDUAL FLEXIBILITY COMMON ANALYSIS TECHNIQUE	NEGLECTS STATICS AND DYNAMICS OF DELETED MODES
QUASI STATIC	FASTEST, LEAST COSTLY	NEGLECTS ALL DYNAMICS OF STRUCTURAL MOTION LEAST ACCURATE



ASSUMPTIONS

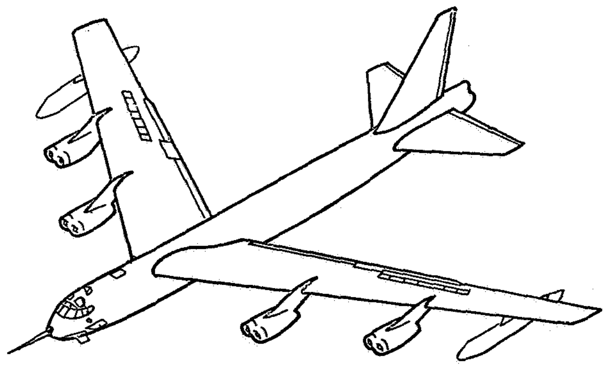
- A1 The aerodynamic forces proportional to structural velocity and acceleration are zero.
- A2 The structural inertial and damping forces are zero.
- A3 Structural damping forces are negligible.
- A4 Aerodynamic forces due to elastic deformation are negligible.
- A5 The aerodynamic forces due to deleted modal velocity and acceleration are zero.
- A6 The structural damping and inertial forces due to deleted modal deformation are zero.
- A7 The structural damping of retained modes on deleted modes is zero.
- A8 The structural spring forces of deleted modes are zero.
- A9 The aerodynamic forces due to deleted modes are zero.

Figure 5. General Criteria for the Selection of the Formulation of the Equations of Motion in Level 2.01 FLEXSTAB

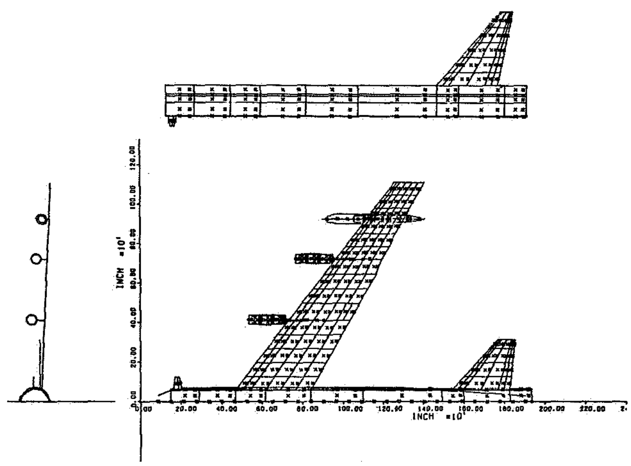
Table 3. Initial Level 2.01 FLEXSTAB Check Case Aircraft, AFFDL In-house and Contract

TEST CASE	THEORETICAL											SEMI-EMPIRICAL				DETERMINISTIC GUST/CONTROL		RANDOM TURBULENCE	
	GD	AIC	ISIC	NM	ESIC	SD+SS(R)	SD+SS(QS) SD+SS(MT) SD+SS(RF)	LSA(R)	LSA(QS) LSA(MT) LSA(RF)	TH(R)	TH(QS) TH(MT) TH(RF)	CAIC	SD+SS(QS) SD+SS(MT) SD+SS(RF)	LSA(QS) LSA(MT) LSA(RF)	TH(QS) TH(MT) TH(RF)	TH(R)	TH(QS) TH(MT) TH(RF)	LSA(R)	LSA(QS) LSA(MT) LSA(RF)
Check Original NASA/ARC																			
707	•	•	•	•						•	•		•		•				
YF-12 (M<1.)	•	•			•	•	•												
YF-12 (M>1.)	•	•			•	•	•												
Bomber/Transport																			
B-52E LAMS	•	•	•	•		•	•	•	•	•	•		•	•	•	•	•	•	•
B-52E CCV	•	•	•	•		•	•	•	•			•	•	•		•	•	•	•
C-5A ALDCS	•	•	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•
CCV KC-X	•	•	•	•		•	•												
Strategic Bomber (M<1.)	•	•	•	•		•	•	•	•			•	•	•				•	•
Strategic Bomber (M>1.)	•	•	•	•		•	•	•	•			•	•	•				•	•
CMW Strategic Bomber (M<1.)	•	•	•	•	•	•	•	•	•									•	•
CMW Strategic Bomber (M>1.)	•	•	•	•	•	•	•	•	•									•	•
Fighter Aircraft																			
F-111 TACT (M<1.)	•	•			•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
F-111 TACT (M>1.)	•	•			•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
TACT FLEX MODEL (M<1.)	•	•			•	•	•					•	•						
TACT FLEX MODEL (M>1.)	•	•			•	•	•					•	•						
F-15 CMW	•	•			•	•	•	•	•				•	•					
YF-16 CCV	•	•			•	•	•	•	•			•	•	•					

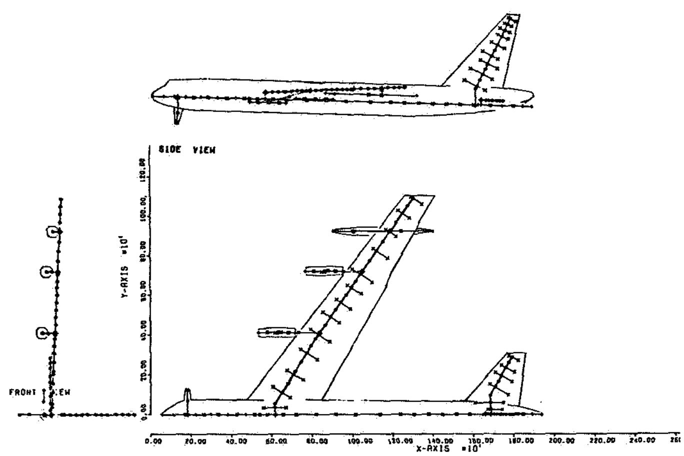
(R) RIGID ANALYSIS
(QS) QUASI STATIC ANALYSIS
(MT) MODAL TRUNCATION ANALYSIS
(RF) RESIDUAL FLEXIBILITY ANALYSIS



a. The B-52E CCV Aircraft



b. Aerodynamic Idealization of B-52E CCV



c. Structural Idealization of B-52E CCV

Figure 6. Application of Level 2.01 FLEXSTAB to the B-52E CCV Aircraft