Propulsion System and Airframe Structural Integration Program

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The requirements for propulsion system and airframe structural integration are outlined. The deficiencies in current practice are discussed and emphasis is placed on joint airframe and engine company participation in developing a comprehensive integration plan that will result in well defined system interfaces and a high level of risk awareness. Structural analysis programs applicable to propulsion system and airframe integration analysis are discussed including input automation and substructuring capabilities. Examples of propulsion system and airframe math models and typical substructures are presented including static structure and rotating components. The importance of propulsion system loads is discussed. Applications of general purpose structural analysis programs such as NASTRAN to propulsion system structure are given.

Introduction

THE great success of modern jet aircraft has led to evolutions in design which have improved their safety, efficiency, and reliability. Both the airframe and propulsion systems have grown in size. These are not mutually independent developments, as more often than not an advance in one area leads to a critical condition in some other area.

From the structures point of view, the increased emphasis on efficiency, and the increase in size of the propulsion system has been very significant. Higher temperatures required for improved performance have put greater demands on materials and components and has led to often costly propulsion development problems. The increase in size of engines and related propulsion system components has increased the structural flexibility and resulted in propulsion system vibration and case/rotor interference problems.

These are not just engine manufacturer's problems because often the developmental problems do not emerge until the propulsion system is attached to the airframe and put into the real flight environment. The engine and its associated components (inlet, cowling, exhaust nozzle, reversers, installation, and thrust structure) which make up the propulsion system are generally not fully integrated and structurally verified until flight testing begins. This has been due in part to the lack of a well defined propulsion system/airframe integration responsibility between engine and airframe companies. The undeclared philosophy has seemed to be that the engine was so stiff compared to the airframe that it could be treated as a rigid appendage. This approach to propulsion system/airframe structural integration has recently changed due to problems encountered on the large jets and the American SST. However at least two major obstacles remain.

One is that a comprehensive plan for propulsion system/airframe integration has not existed, spelling out the procedures, timing, and the information required by the respective participants. Even if realistic ones exist, specifications, criteria, and standards are meaningless if the appropriate analyses and tests are not conducted to give a reasonable assurance of meeting them. A second obstacle and one that is being overcome rapidly is the inconsistency that exists between the math models and the analyses and procedures for structural integrity analysis of propulsion system components. Again, this is not the problem of a single participant in the co-operative development of an airplane propulsion system.

This paper relates primarily to this second problem and presents the results of preliminary planning and analysis which is intended to present a frame of reference in which the airframe and engine companies can begin to develop a systematic and comprehensive propulsion system/airframe integration plan. Much of the material is presented as flow charts and may be new only insofar as it applies to propulsion system technology.

A great deal of the information contained in this paper is associated with the basic engine which may seem strange coming from an airframe company. It is justified on the basis that the airframe company in commercial airplane development is the systems integrator and must, therefore, understand all components of the system. Secondly, the airframe company is continuously involved in engine evaluation to ensure that the best engines go on the airplane.

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Program Scope and Objectives

It is for the reasons outlined in the Introduction that the Propulsion and Airframe Structural Integration Program (PANSIP) was instigated. This program in its simplest connotation is an audit system for ensuring that the components of the propulsion system and related airframe structure function as a structural unit. In its broadest connotation it is a systematic and comprehensive working plan for propulsion system/airframe structural integration from the early stages of development through flight testing and beyond.

An objective is to give stronger consideration to the propulsion system structure early in the development cycle. This is illustrated in Fig. 1 which sketches an airframe/propulsion system development program. It emphasizes that structural integration must be part of the preliminary system sizing and systematically carried through the design and developmental phases. Figure 1 is intended to emphasize, further, that there has to be a coordinated management approach between the engine and airframe companies to assure well defined system interfaces and a high level of risk awareness.

Structural Analysis Background

The PANSIP program is built primarily within the context of large, general purpose structural analysis programs

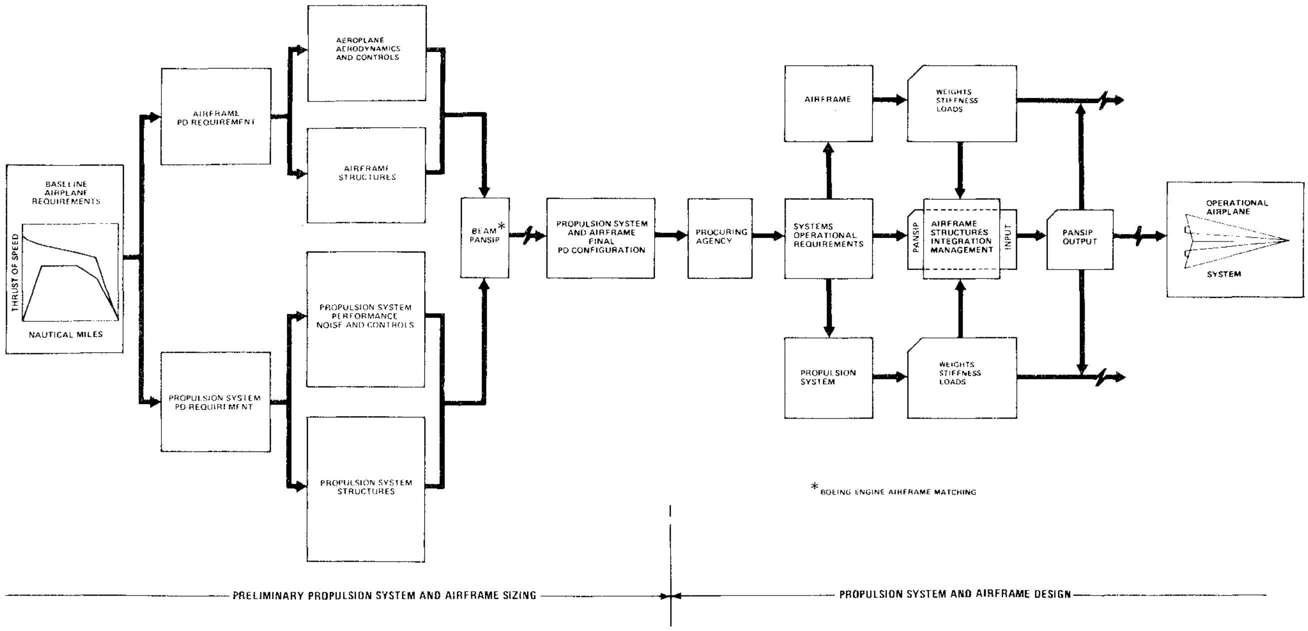

Fig. 1 Propulsion system and airframe structural integration program—PANSIP.

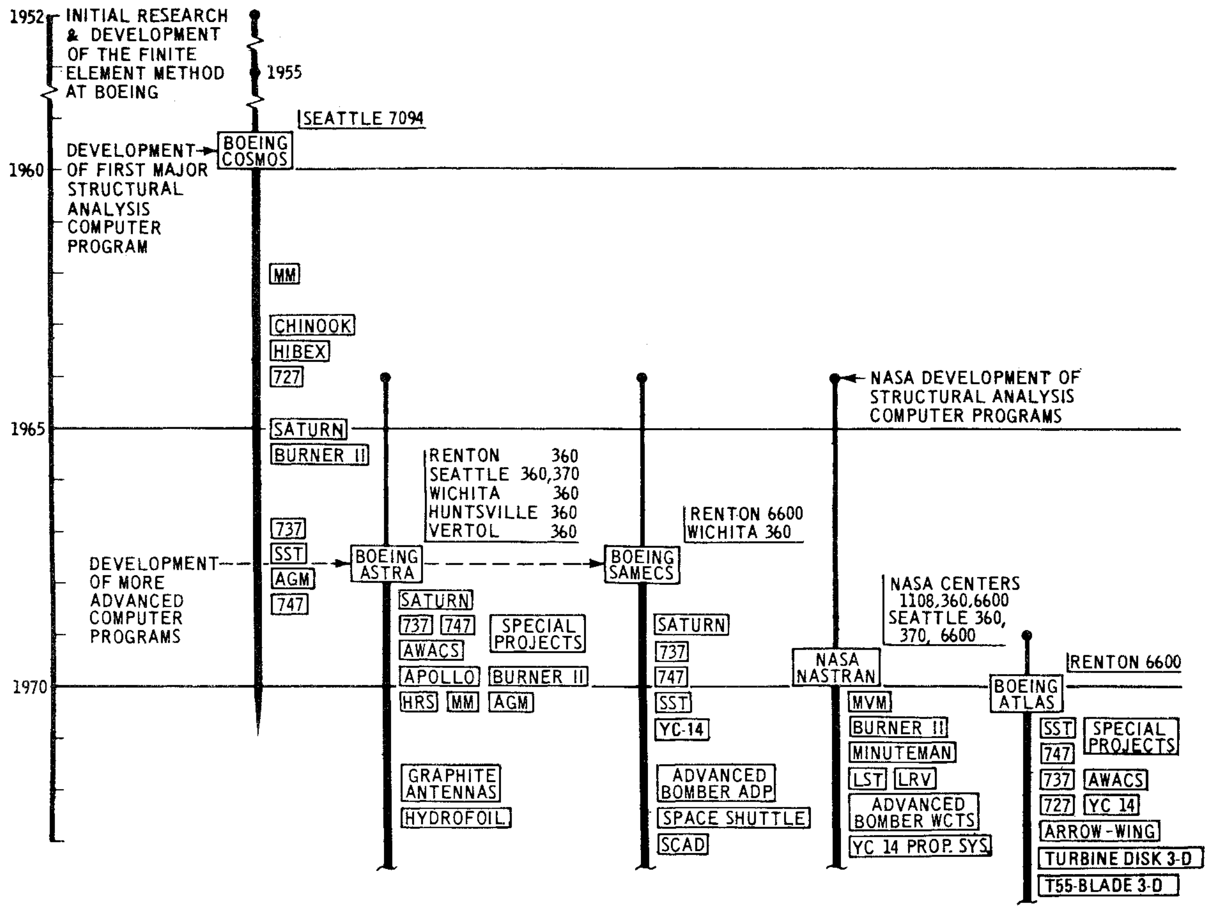

Fig. 2 Development and usage of major structural analysis systems at Boeing.

such as ASTRA,[1] ATLAS,[2] or NASTRAN.[3] It is, therefore, felt appropriate to digress momentarily and review briefly finite element program development and usage at The Boeing Company as illustrated in Fig. 2. This background will help to put the PANSIP program in perspective.

Structural Analysis at the Boeing Company

Some of the earliest finite element work originated at Boeing in 1957 with the publication of the work by Turner et al.[4] Subsequently this approach to structural analysis has been adopted in varying degree by every major indus-

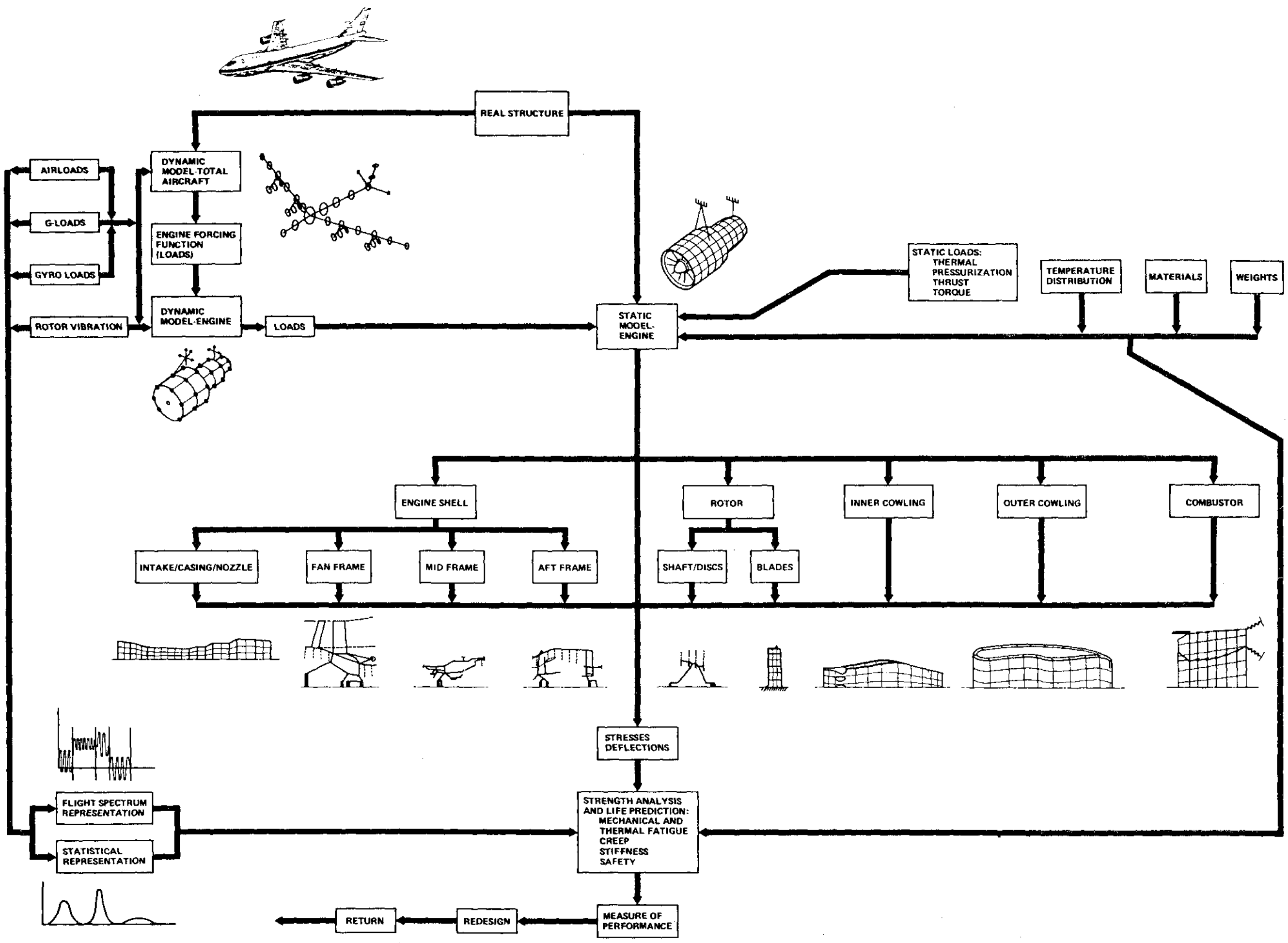

Fig. 3 PANSIP structural integrity analysis plan.

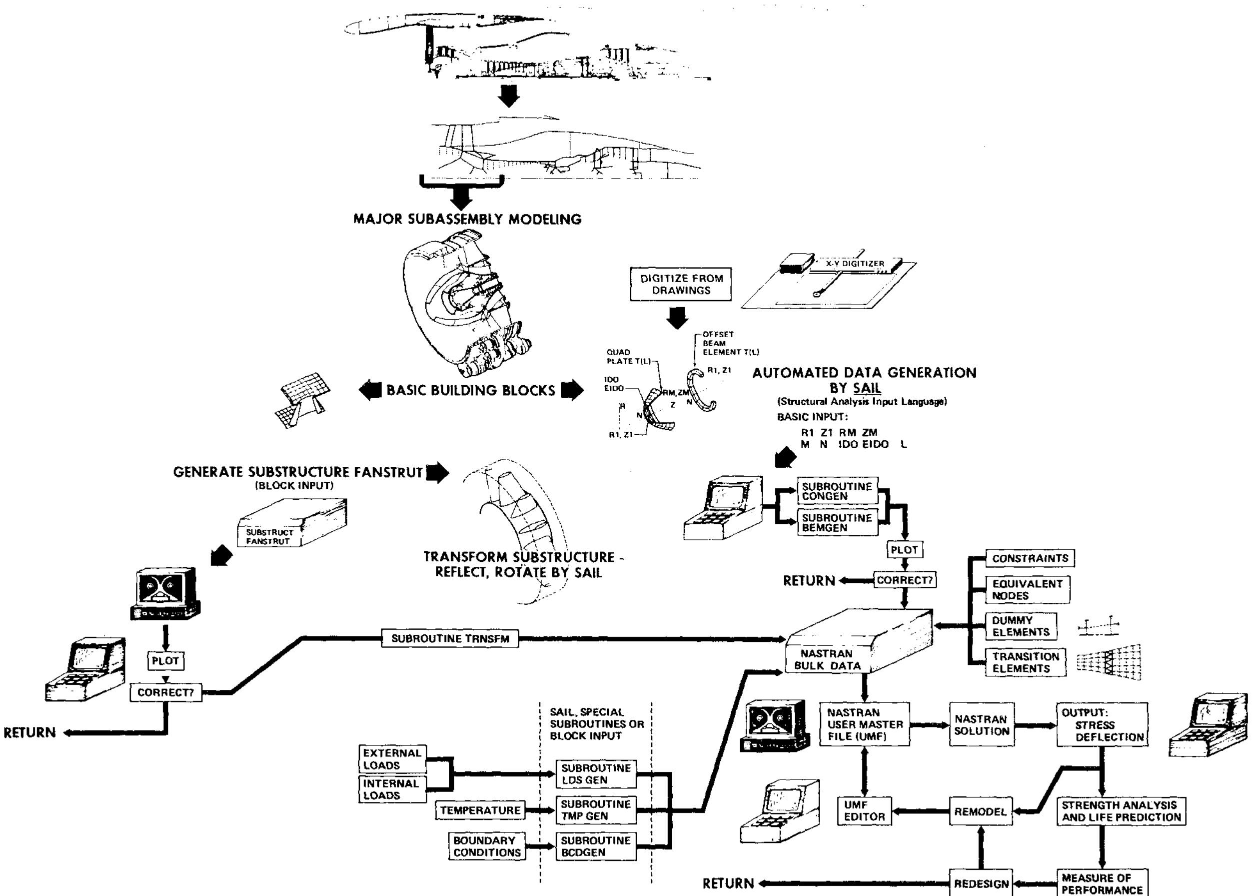

Fig. 4 Structural modeling of stationary components.

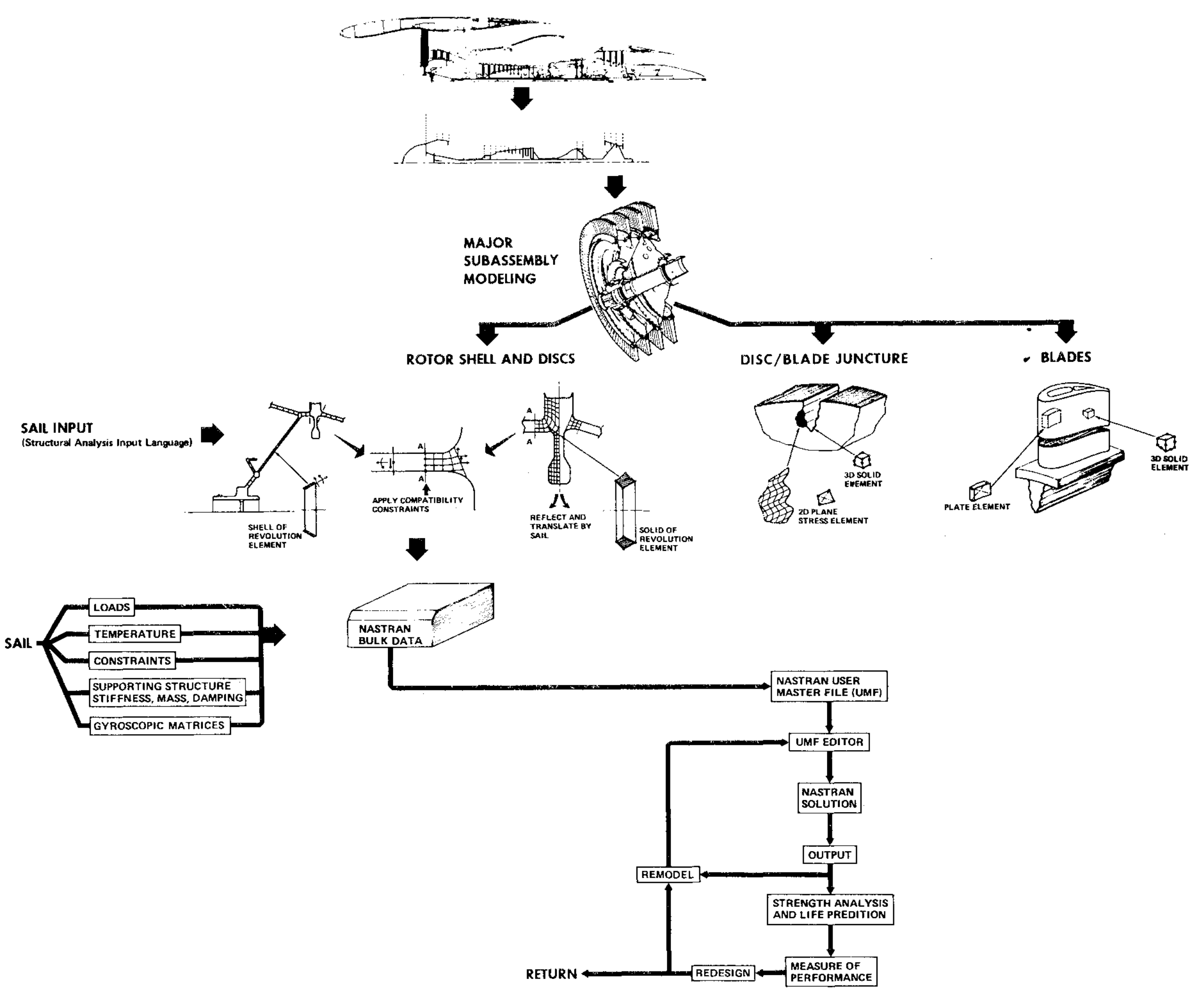

Fig. 5 Structural modeling of rotating components.

try involved in structural design. Boeing has developed three of the major, large-scale computer programs in current use in the industry. COSMOS[5] (Comprehensive Option Stiffness Method of Structural Analysis) was developed in 1961 and is still in use today. It has been used to analyze a large variety of space and aircraft structures as noted. The ASTRA (Advanced Structural Analyzer) Program is the COSMOS replacement, incorporating many advanced features including modular design, a comprehensive input language, substructuring, and many broadened capabilities. The SAMECS[6] (Structural Analysis Method for Evaluation of Complex Structures) program was developed primarily for use on complex airframe structure, notably the American SST, where it underwent extensive development.

The ATLAS program is the SAMECS replacement and is a highly efficient program tailored to the CDC 6600 computer. It was designed for use in an integrated airplane design system. It contains a 3-D isoparametric element of up to 44 nodes which has been used recently for turbine disk and blade analysis.

Boeing acquired the NASTRAN program in 1969 and since that time has conducted a comprehensive capabilities study and used it on several hardware programs including those illustrated. NASTRAN has been selected as the structural integration tool in the PANSIP program because of its broad capabilities, including substructuring, and its common availability to the engine and airframe manufacturers and governmental agencies. This permits a free exchange of structural information in a common language. An auxiliary program to enhance substructure analysis in NASTRAN has been developed called SPAN[7] (Substructure Partition Automation for NASTRAN).

Structural Analysis Input Language

Early in the development of second generation finite element analysis programs such as ASTRA, the need was recognized for a general purpose input language, i.e., as opposed to special purpose FORTRAN program, for generating grid points and elements for example. This input language should be general enough to encompass all of the basic input including grid points and elements, loads, and boundary conditions. It should have data transformation capability, it should be flexible to permit varied input such as tabular data; and it should be simple, and easily accessible to a person with little or no computer programing background.

The Structural Analysis Input Language (SAIL) was first developed for the ASTRA program and a similar language called SAIL II[8] has been developed for the NASTRAN program and is readily available to the structures analysis community at large. Without going further into the details of the SAIL II language, its advantages may be summarized as follows: it shortens schedules, saves labor, reduces chance of error, and makes data preparation a challenging and enjoyable job.

PANSIP Structural Integrity Analysis Plan

To give an overall picture of what the PANSIP program encompasses, a series of five illustrative figures, Figs. 3–7, is provided that illustrates the program elements.

PANSIP Overall Structural Analysis Plan

Figure 3 depicts the overall plan for the structural integrity analysis of the airplane propulsion system. The basic elements are loads, structural modeling, analysis, and failure analysis and life prediction. Dynamic loads data is calculated from a simulation of the total propulsion system including airframe components. Vibration frequencies and load factors are derived from a structural dynamic model which may be derived by reducing the basic detailed static model. The static model is a detailed finite element simulation and may be built up from independent substructures. This has the advantage of greater flexibility and cost saving in the modeling and analysis, particularly as related to major components such as the strut, inlet, or engine.

The substructuring approach[9] to structural analysis permits independent analysis of a portion (substructure) of a structure, by which this portion is characterized in terms of information (stiffness, displacement, forces) on its boundary. Integration then in the context of substructuring means joining the different substructures at their common boundaries to accurately characterize the interaction of the total system. Also, with accurate boundary stiffness one can accurately characterize boundary supports for analysis of isolated components such as conical shell seal mounts rather than relying entirely on engineering judgment or considering the "worst case" condition.

Substructuring as used here also encompasses the use of modal data to characterize structural interaction which has been called component mode synthesis.[10] This technique is very useful for predicting coupled dynamic behavior (vibration, frequency response) using frequencies and mode shapes (either analytical or experimental) of individual substructures.

Propulsion System Stationery Structure Modeling

Figure 4 illustrates the approach to modeling the propulsion system stationery structure. Because of the axisymmetry or cyclic symmetry of most of the engine structure, automation of the modeling is particularly easy. The automation technique is based on the SAIL II language, described earlier. An example of an engine fan frame is shown whereby half of one strut is idealized, then by use of the SAIL II built-in transformation subroutines, it is reflected, rotated, and joined with other structure to generate the entire fan frame substructure.

Digitization of geometry is used where practicable as illustrated in the example of stiffened conical segment generation in Fig. 4. The digitizer is linked directly to the computer operating system. Upon selection of mesh size, grid point, and element numbering schemes, modeling can proceed directly from digitization of engineering drawings after which almost immediately the mathematical model is projected on the screen for checkout. Also, digitization of stiffener cross sections is linked through a section properties generator and beam element generator to model the circumferential stiffening beams.

In practice, complete verification of a structural mathematical model, not including loads, involves: check on basic coding and input data (i.e., spelling, punctuation,

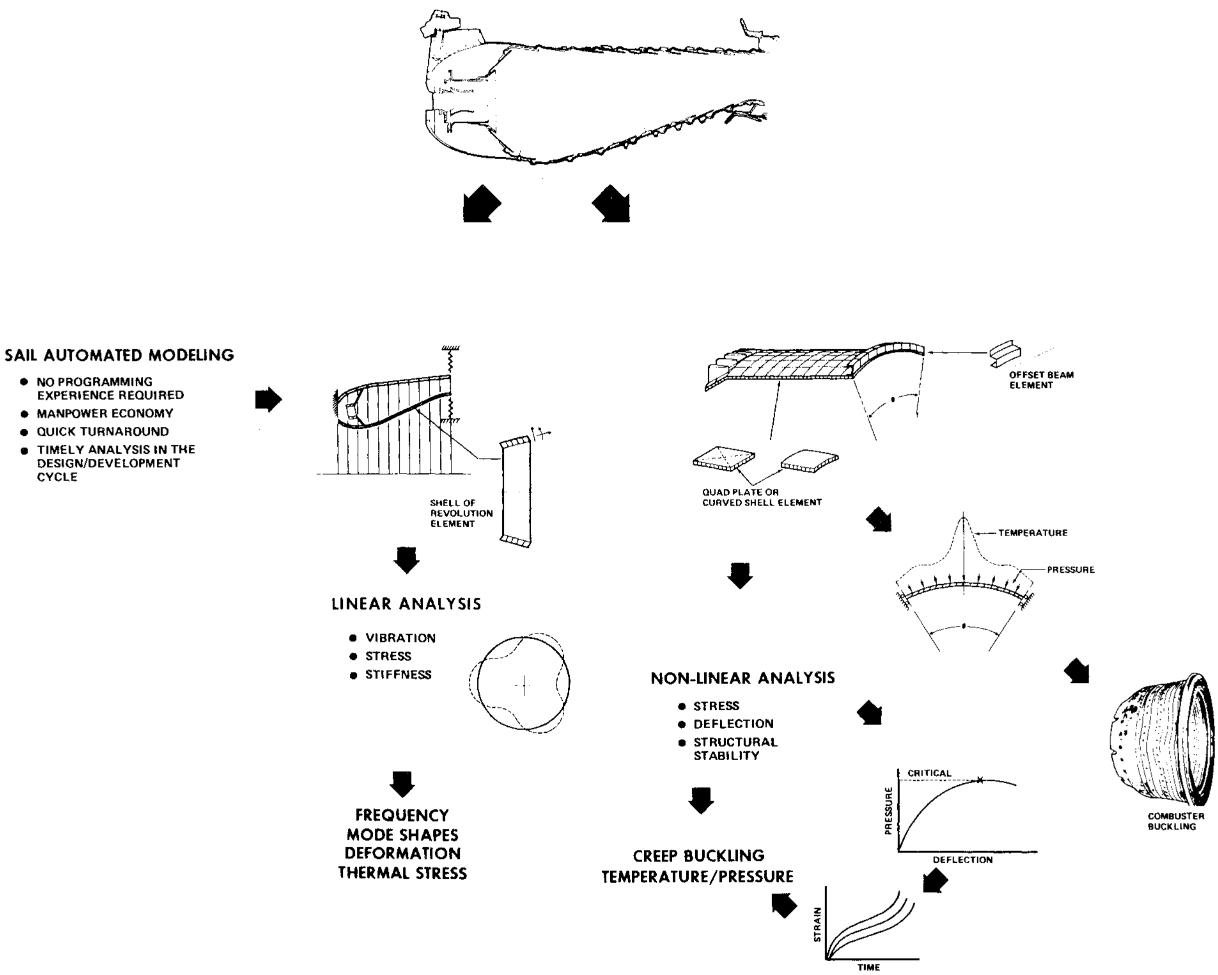

Fig. 6 Structural modeling of combustor.

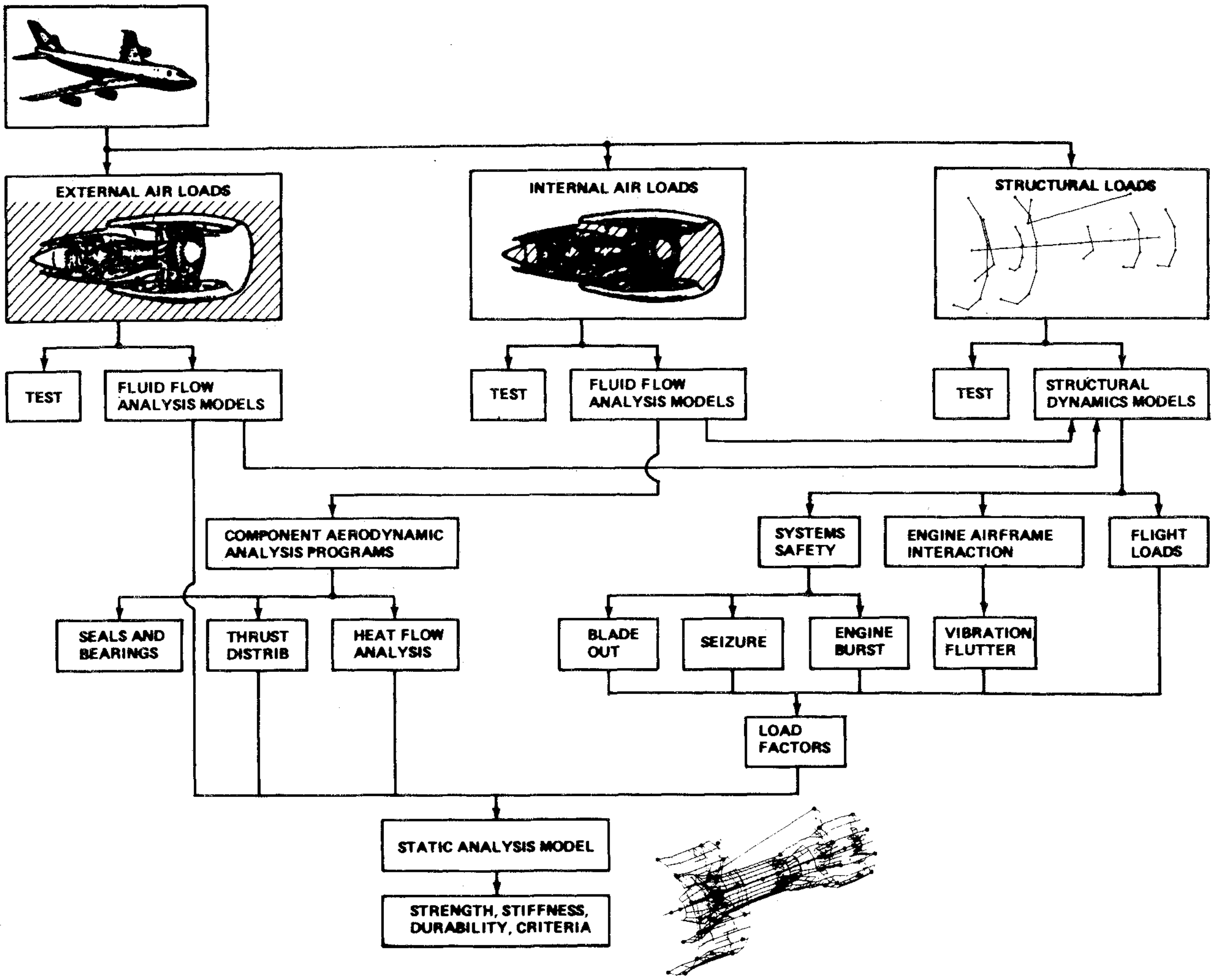

Fig. 7 Propulsion system loads.

FORTRAN grammar); check on structural geometry and grid point/element topology; check on structural stiffness response to load to reveal singularities, multipoint constraint, and boundary condition deficiencies; a check which should include stress and deformation plots and an equilibrium check. The latter step which requires essentially full program execution is often neglected until a valid run is attempted which more often than not gives disturbing surprises. A systematic checkout of loads is also required for the introduction of loads into the structural model where these are of an extensive nature, as in the case of airplane aerodynamic loads.

Propulsion System Rotating Structure Modeling

Figure 5 is essentially a continuation of the previous figure and illustrates what is believed to be a reasonable approach to modeling propulsion system rotating structure including airfoil and disk components. The detailed structural analyses of rotor components are required as part of case/rotor clearance and rotor-fragment containment studies[11] which also come under the scope of PANS-IP. Generally, the nonlinear effect of centrifugal forces must be included which in the context of NASTRAN would require a two step solution in the NASTRAN solution block.

Math models of the types illustrated here are authentic idealizations of the real structural item and can be compared to a test item limited only by the ability to simulate the exact loading and environment. These abstract "test" models can be quickly altered, they can be loaded in any way, they never fail and can be preserved economically for quick utilization at any later date.

Modeling of high-speed rotating structures generally requires the inclusion of spin stiffening and Coriolis' acceleration forces. MacNeal[12] has developed these terms in a finite element matrix format for the linear analysis case, and these matrices have been introduced via the direct matrix input feature of NASTRAN.

Combustor Modeling

For completeness in illustrating structural modeling, the combustor is included in Fig. 6 although it is essentially structurally isolated from the other major engine components. The structural durability of the combustor however is of particular interest since it is subject to extreme operating environment and is a high frequency maintenance item. It is believed, therefore, that detailed structural analysis could be of benefit in improving its design and durability.

Propulsion System Loads

The determination of propulsion system loads is that of utmost importance in propulsion system/airframe integration. The introduction of realistic loads including aerody-

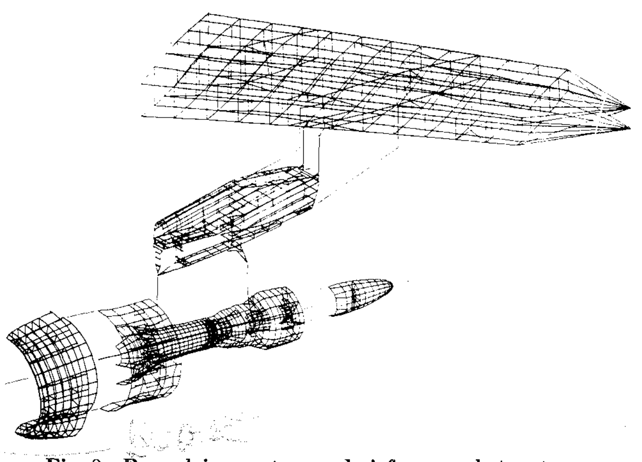

Fig. 8 Propulsion system and airframe substructures.

namic, thermal, and mechanical loads requires a broad application of technical disciplines.

A schematic of what constitutes propulsion system loads from one point of view is shown in Fig. 7. The blocks labeled "test" are not expanded upon since the primary purpose here is to present an analytical rationale. From this viewpoint the loads are classed as: external airloads—primarily nacelle pressure distributions; internal airloads—internal engine stage by stage pressure, thrust and torque loadings and transient temperature distributions; and structural loads—flight and engine operation induced static and dynamic loads including vibration, gyroscopic, and inertia loads.

Internal engine loads, particularly as they pertain to pressure distribution and transient thermal conditions, seems to be a very difficult problem. The indeterminate nature of seal leakage and running clearances, compounded by complex flow patterns are apparently the major obstacles to predicting accurate and detailed internal engine loads. It is believed, however, that the ability to predict the detailed structural deformations throughout the engine, including rotor/case clearances could substantially contribute to understanding the problem.

In relation to structural loads, the structural dynamic load factors based on a rigid propulsion system can be very unrealistic and unconservative. An example was the American SST propulsion system which was 40 ft long and had flexible body vibration frequencies in the range of the wing vibration frequencies. Furthermore, propulsion system installation design requirements may dictate statically indeterminate engine mounting, in which case engine flexibility must be accounted for, even for basic static loads determination.

Applications

The remainder of this presentation is examples of propulsion system modeling and analysis. The objective is to illustrate what is believed to be the minimum level of modeling detail required and a sampling of results which have been obtained.

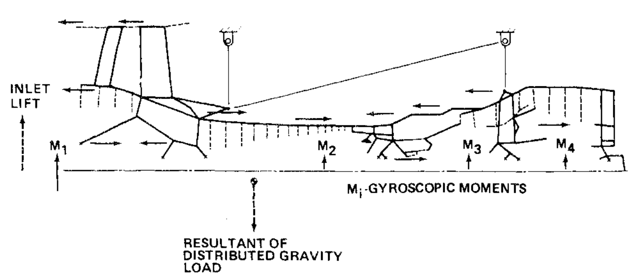

Fig. 9 Propulsion system static loads simulation.

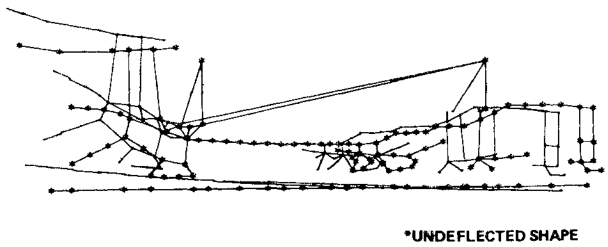

Fig. 10 Deflections under thrust load.

Although considerable quantitative data has been generated, engine and airframe company proprietary information agreements prevent a free dissemination of much of the data. Also lack of engine test information is a problem. In the near future extensive analysis-test correlations will be carried out which will help to establish the requirements of the techniques proposed here for propulsion system analysis. The validity of the methods has already been established through many test analysis correlations of a great variety of spacecraft and airframe problems. The techniques used here are not new; however, they have not been applied as intensively to airplane propulsion system technology as to other aerospace systems.

It should be pointed out that the math models shown and the analysis results are not necessarily related to any one propulsion installation nor to the same engine in a given installation. Some of the data including the engine ovalization analysis-test correlation were obtained early in the 747 program. Also the vibration results shown may not reflect the total system detail required to correlate accurately with a real installation.

Figure 8 shows math models generated by the techniques which were outlined in the preceding charts. The engine model is a high bypass ratio fan jet engine used for the largest airplanes. This model is symmetric, made up essentially of quadrilateral plate and beam elements, and includes frames, flow passage cones, and a beam-lumped mass representation of the rotors. Multipoint constraints are used to model bearing housings as rigid rings which are coupled to the rotor by scalar spring and damper elements. Figure 8 also illustrates the typical, major substructures of a propulsion system. The basic static stiffness models are shown from which the dynamics models are derived.

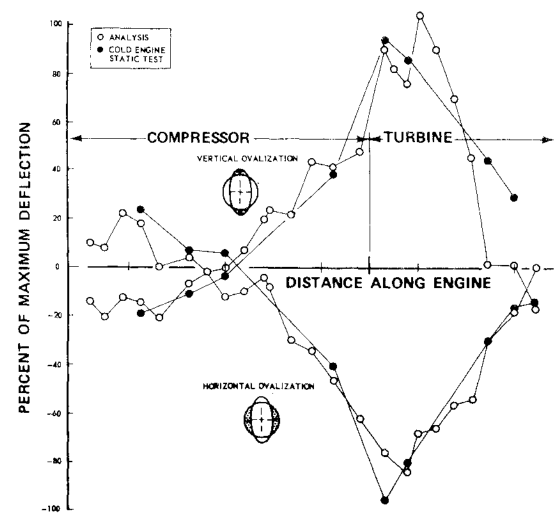

Fig. 11 Engine case ovalization study.

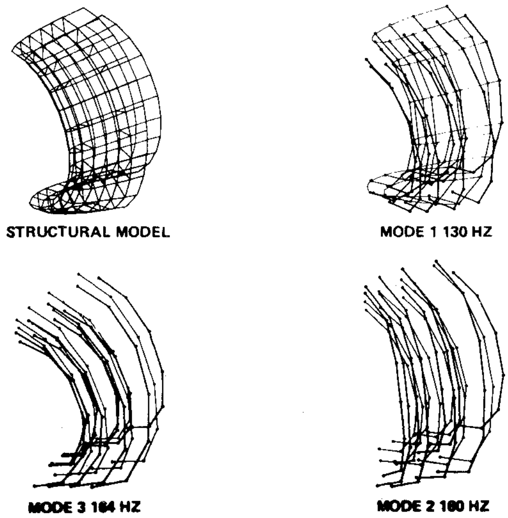

Fig. 12 Inlet vibration analysis.

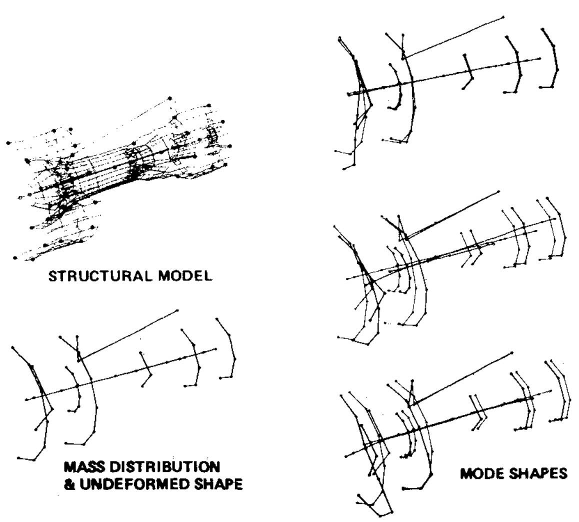

Fig. 13 Engine vibration analysis.

Figure 9 is an illustration of the nature of the static loads representation that has been used in typical propulsion system deflection studies. This includes a rather gross distribution of thrust as indicated by the horizontal vectors which are distributed around the circumference. A more detailed distribution, including torsional loads appears out of reach at the moment as no systematic calculation of the internal loads is available. The gravity loads are distributed over the entire structure. Static gravity loads as well as the static treatment of gyroscopic loads includes rotor modeling to account for redundant bearing systems.

Figure 10 is a computer plot of the static deformation of an engine under a typical thrust load condition. The detailed deformations throughout the engine structure are not evident since the scale was determined by the gross engine deflections. Much can be learned about propulsion system structural behavior from this level of analysis. In recent studies, the engine case/rotor clearances were mapped for the entire engine under a variety of load conditions. Studies are now being formulated to determine the effect of engine location and installation design on specific fuel consumption.

Figure 11 is a correlation of analysis and test data for a mechanically loaded, cold engine structure. The results substantiate the accuracy of refined analysis techniques even for "stiff" engine structure undergoing relatively small deformation.

Of great importance in propulsion system/airframe integration is the analytical prediction of dynamic behavior, such as critical rotor speeds and overall propulsion system vibration. Restricted models which do not account for the total propulsion system structure including airframe mounting structure are often deficient in predicting critical behavior. Vibration analysis can be very useful in guiding propulsion system vibration testing in revealing modes to look for and in determining the magnitude of damping. Figure 12 illustrates typical vibration analysis results for an inlet. This particular analysis used 229 grid points and extracted 152 frequencies and mode shapes each for the symmetric and antisymmetric boundary conditions.

Figure 13 shows the vibration analysis of a large high bypass ratio engine. The mass model included 51 lineal masses, 7 rotary inertias, and retained 151 freedoms from the static stiffness model. A total of 120 symmetric modes and 120 antisymmetric modes were extracted. An attempt was made to use the Guyan reduction method which is built into the NASTRAN analysis system. Excessive run times influenced a decision to revert to the mass lumping technique with no mass matrix reduction. A method[13] has recently been introduced in conjunction with NASTRAN for eigenvalue extraction which precludes gross lumping and selective reduction of the static model.

A final significant point relative to vibration analysis should be made. That is, an authentic idealization of the propulsion system such as shown in Fig. 13 will provide vibration data that may be difficult or impossible to obtain with traditional beam, mass, spring representations, particularly where shell modes of behavior are prevalent. Further, accurate results can be obtained without excessive "tuning" or dependence on test data.

Conclusions

It is believed that the methods proposed here and the implications for their use is a valid approach to propulsion system and airframe structural integration analysis. Success in doing this requires the cooperative effort of all participants in the airplane development program.

Through a better understanding of the propulsion system/airframe structural response, using modern structural analysis techniques, it is believed that significant improvements can be made in operational performance such as thrust-to-weight ratio, specific fuel consumption, and reliability. Further, improvements in propulsion system development cost and schedule are envisioned by providing more reliance on analysis techniques early in the development cycle to verify designs and to guide test programs.

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Rapid Verification of Engine Rotor and Case Flexibilities by a Modal Comparison Algorithm

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A computation technique has been developed at Pratt & Whitney Aircraft (P&WA) in which localized dynamic flexibilities in an assembled rotor or case can be rapidly determined from experimental mode shape and frequency data. A dynamic mathematical model of the structure is developed with empirical flexibility terms assigned to mechanical joints such as flanges, splines, couplings, etc. The vibratory response of the structure is measured in laboratory tests and compared with calculated values. Agreement between calculated and experimental mode shapes and frequencies is obtained by a computerized random search technique, which determines the flexibility terms that produce the best match between experimental data and calculated values for all of the vibration modes compared. The technique was developed for rotor critical speed applications, but it may be applied to any simple or complex beam type structure.

I. Introduction

THE emphasis on a lightweight, high-performance design for advanced turbojet engines has required the designer to use mechanical joints (flanges, splines, couplings, etc.), which are significantly different from earlier designs. These new joints influence the dynamic response of the structure and, consequently, affect the engine's sensitivity to unbalance, stall loading, and maneuver deflections. To verify the adequacy of the joints before an engine test, the designer must conduct design verification tests to corroborate his predicted flexibilities. These test results must be interpreted and the impact on design performance evaluated in time to make design modifications if necessary. The sophisticated mathematical models, which are required to accurately compute the engine dynamic response, should therefore be arranged so that the data from design verification tests can be readily incorporated and the data's impact quickly evaluated.

The subject of this paper is the rapid incorporation in an existing math model of joint flexibilities derived from structural test data. A computational technique has been developed in which flexibilities that occur at mechanical joints in an assembled rotor or case are determined from laboratory mode shape tests. In this technique, empirical flexibility terms assigned to mechanical joints (flanges, splines, couplings) are used in the initial calculation to compare with experimental data. Flexibilities are then varied, if necessary, by computerized calculation until the best match is obtained between calculated and experimental mode shapes. The result is a math model, with joint flexibilities defined, that accurately describes the dynamic stiffness and mass distribution of the assembled rotor or case.

The use of this technique has considerably reduced the time necessary to adjust the math model to account for local flexibilities, which may not have been accurately predicted during the design phase. Perhaps more importantly, it has shown that a rather subtle change in the overall stiffness of an assembled rotor due to localized joint flexibilities can cause a significant increase in the vibration response. This is illustrated by an example problem on a high-pressure compressor rotor.

II. Technique

A. Methodology

1) Math model development

A large number of vibratory systems in engineering are described by what is commonly known as a lumped mass mathematical model of the true physical system. This model can be used to determine the natural frequencies, mode shapes, forced response, etc., of the physical system and will accurately duplicate the system if local joint flexibilities are known.

To develop the math model, the structure is represented by a series of stations connected by massless beam sections of cylindrical, conical, or plate elements. The stations are chosen to coincide with concentrated masses, span ends, and locations of geometry change. Each station is assigned a mass and a mass moment of inertia, which includes the beam inertias as well as those for concentrated masses such as disks or gears. From these properties and the material characteristics, bending and shear flexi-

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