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STRUCTURAL DYNAMICS TECHNOLOGY RESEARCH IN NASA

PERSPECTIVE ON FUTURE NEEDS

PREPARED BY AN AD HOC STUDY COMMITTEE
ON BEHALF OF THE OFFICE OF AERONAUTICS
AND SPACE TECHNOLOGY, RESEARCH AND
TECHNOLOGY DIVISION

APRIL 1979

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16 Abstract

The perspective of a NASA ad hoc study group on future research needs in structural dynamics within the aerospace industry is presented. It identifies the common aspects of the design process across the industry and establishes the role of structural dynamics in it through a discussion of various design considerations having their basis in structural dynamics. The specific structural dynamics issues involved are identified and assessed as to their current technological status and trends. Projections of future requirements based on this assessment are made and areas of research to meet them are identified.

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PREFACE

An Ad Hoc NASA Study Committee was organized in the Spring of 1977 to provide a perspective for NASA's long range Structural Dynamics Technology Program planning. The membership of the committee is shown in Appendix A. This document represents the initial output of the committee and is primarily a report to the NASA Office of Aeronautics and Space Technology. The committee believes that the report can also serve as a focus for discussion among structural dynamicists and other interested technologists in industry, government, and academia. It is viewed by the committee as a living document which will be updated periodically.

The committee's approach was to determine industry viewpoints by visiting a select number of companies, to formulate individual committee member perspectives, and to formulate a NASA perspective through committee deliberations and further interaction with the technical community through professional societies. The committee made the following visits:

Rockwell International Space Division	-	March 28, 1977
Northrop Corporation	-	March 28, 1977
McDonnell Douglas Corporation Douglas Aircraft Company	-	March 29, 1977
Rockwell International, LA A/C Div.	-	March 29, 1977
Pratt & Whitney Aircraft	-	September 19, 1977
Sikorsky Aircraft	-	September 19, 1977
Boeing Vertol Company	-	September 20, 1977

Host company participants in the discussions at each of these visits are shown in Appendix B.

A preliminary draft of this document was reviewed by several members of The Flutter and Dynamics Council and the AIAA Structural Dynamics Technical Committee. They are also listed in Appendix B.

This report presents a comprehensive review of the role of structural dynamics in the design process and an assessment of structural dynamics. It provides a delineation of structural dynamics issues and research needs. Considerable emphasis is placed on the design process because the committee visits to industry revealed clearly that the capability to account for structural dynamics early in the design process is needed.

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INTRODUCTION

Structural dynamics plays a key role in the design of aerospace vehicles since many of the technical considerations on which design decisions are made involve structural dynamics issues. The design process is continuously changing to accommodate new demands placed on it by increasing sophistication in the end products, necessitated by increasing user requirements. The role of structural dynamics in the design process can therefore be expected to change also. It is important that the research community and those involved in the planning of advanced product development anticipate and to some extent control these changes so that future needs can be effectively met. This report attempts to provide an assessment of potential future needs of structural dynamics technology and areas of fruitful research necessary to provide those needs.

A general viewpoint of the design process is first presented. Although the process varies widely depending on the end product and on the organization producing it, there is an underlying framework which is common throughout the aerospace industry. The viewpoint expressed here establishes a generally valid framework within which the role of structural dynamics is described. The design considerations with strong structural dynamics technology implications are discussed relative to this framework. The discussion continues with a state-of-the-art review of specific structural dynamics thecnology issues which underlie these design considerations, and is followed by a prognostication of future requirements based on current trends.

Research needs to meet the anticipated requirements are presented as a list of rather general research areas under two categories. The generic category identifies those requirements which will primarily enhance the

the basic tools of structural dynamics technology, while the applications category represents requirements for more effective utilization of the basic tools in resolving design related issues and problems. Priorities among these research requirements are not included in the report.

ROLE OF STRUCTURAL DYNAMICS IN DESIGN PROCESS

Design Process

The ultimate goal of structural dynamics technology in the aerospace industry is to support the design of industry products by assuring structural safety, functional adequacy, and service durability of the products. The product development occurs in three phases - the design phase, the manufacturing phase, and the service phase. Structural dynamics and other disciplinary technologies are required primarily to support activities within the design phase which collectively are referred to as the Design Process, although it is not unusual that requirements arise in the service phase. The Design Process varies with individual products and with the organizations producing them. There is, however, a unique and common set and sequence of events in all forms of the process - concept formulation, preliminary design, detailed design, and design validation.

In the concept formulation stage the need for the product is established from studies and analyses involving economic and/or national welfare considerations. These also serve to define the desired missions or uses for the product. A number of candidate gross configurations of the product are next established based on the desired missions and performance estimates using statistical and trend data. Feasibility studies of economic and technical nature are then made to reduce the number of candidate configurations to a

few serious contenders. For these, a set of performance specifications and design criteria is generated for use in the preliminary design stage.

Preliminary design considers the configuration and sizing of major components or subsystems. It includes detailed performance analyses, and trades between performance and mission requirements for each contending configuration. These analyses occur in a highly iterative process which terminates only when a reasonable convergence condition is obtained wherein predicted performance matches mission requirements. During preliminary design, sufficient data is generated to permit valid comparisons among contending configurations and the selection of one to proceed through preliminary design into detailed design. Developmental testing is often required to support this activity. Typically, the preliminary design effort culminates in a mock-up model of the product or selected components.

The detailed design stage takes the preliminary design product and develops it further into detailed drawings (or equivalent) of all components, assemblies, subassemblies and individual parts. These become inputs to tooling and manufacturing activities.

Design validation is the stage at which the final design is shown to meet all critical design specifications and performance requirements. It involves both analytical and experimental activities including prototype testing.

During all stages of the process design decisions are made based partly on technical considerations many of which involve structural dynamics issues. Some of the more important considerations are discussed below.

Dynamic Loads:

This is a critical design consideration for most aerospace products. In launch vehicle and spacecraft design the response of the structure to lift-off

or boost rocket engine impulse as well as aerodynamic and acoustic excitations generates internal loads which are usually critical for structural sizing. Therefore, the design process in the preliminary design stage involves several iterations through a sequence of activities comprising: Excitation Environment Prediction, Loads Prediction, Structural Sizing, and Structural Response Computation.

In aircraft design, dynamic loads arising from atmospheric turbulence and/or gusts and from flight maneuvers represent an important (and often critical) airframe design loading condition. For helicopters, rotor blade design loads are dynamic in nature: They depend on the rotor aerodynamics, blade dynamics and control system dynamics. These loads often govern the operating envelope limits of the vehicles. Landing gear designs are based on dynamic loads as are the drive-train and gearing designs of helicopter transmissions.

Stability

Structural dynamics underlies a variety of potential instability phenomena which must be avoided in the design of the products. Flutter is the most critical instability mode which must be considered in the design of aerodynamic surfaces. Aircraft wings, empennage and control surfaces and helicopter rotors can exhibit a variety of flutter modes under different flight conditions and the design process must ensure that these conditions fall outside the normal operating envelope. For helicopters, the choice of the rotor system (articulated, hingeless, bearingless, etc.) is often governed largely by stability considerations. Coupled system type instabilities for helicopters such as ground resonance, and air resonance must also be avoided through proper

design considerations. Turbine engine compressor and fan blades and discs are also susceptible to flutter instabilities which, in the past, have been responsible for major redesigns of new engine developments. They have since become a major design consideration.

In landing gear design a dynamic instability condition known as "shimmy" must be considered.

POGO in liquid fuel launch vehicles - an instability condition involving dynamic coupling between structural vibration modes and hydraulic pressure fluctuations in the propellant feed system and combustion chamber - was responsible for major design modifications of early boosters including Thor-Agena and Titan II. It has since become a major design consideration on new vehicles. Special design procedures have been adopted on the Apollo and space shuttle program developments to avoid POGO.

Ride Quality

Ride quality considerations in the design of aeronautical vehicles aim at ensuring that passengers and crew are subjected to the least possible amount of discomfort, particularly in turbulent or gust environments. The discomfort results from excessive vibration, excessive noise or a combination of both. The ability of the flight crew to operate the vehicle effectively is also impacted by the vibration and noise environments. These considerations are particularly critical in helicopter design where the rotor and transmission gears, as both vibration and noise sources, combine to create a very hostile environment for passengers and crew.

The ultimate goal of these considerations is to ensure that the final product meets FAA standards or the customer's requirements, where FAA standards

are either less stringent (for commercial vehicles) or are inapplicable (as for military aircraft). With today's technology this assurance is usually not realized before the prototype qualification stage. In the early design stages the immediate goal is to avoid coalescence of resonances between the airframe and the major excitation sources, and to develop vibration control devices and noise attenuation treatment concepts to be judiciously applied during prototype testing.

Controls/Structure Interaction

In the past several years the interaction between automatic control systems and structural dynamics has emerged as an important design consideration in the development of modern aircraft, space transportation systems, and spacecraft. This contrasts with earlier design procedures in which the vehicles were treated as rigid bodies from the viewpoint of control system synthesis and evaluation. Justification for this approach resided in the fact that the overall vehicle mechanics was governed primarily by the low frequency rigid body dynamics with the higher frequency flexibility effects adding only secondary motions which could be controlled passively with inherent or added structural damping. As the vehicles have become more flexible due to continuing advances in structural efficiency the relative magnitudes of the rigid body and flexible dynamic forces (which are always coupled) have become comparable. In addition, control systems are being used increasingly to perform other functions besides guidance, e.g. stability augmentation, which are highly influenced by the flexiblity effects.

Earlier considerations were aimed at accounting for the structural dynamics effects in the design of the control systems. Failure to simultaneously consider the feedback effect of the control system on the structural dynamics is now recognized as a major defficiency. It can result in serious

unanticipated development problems as for example an instability mode (involving control system/structural dynamics interaction) which was encountered on the YF-16 program during flight testing. Currently efforts are in progress within several aerospace companies and research organizations to develop the base technology for addressing in the early design stages this interaction. The technology cuts across at least three erstwhile well-defined disciplines; flight controls, structural dynamics, and aerodynamics.

Durability

Durability considerations include assessments of lifetime performance and of service life of critical components. In aircraft turbine engines, for example, seal wear from rubbing due to large rotor vibrations and case distortions from airframe-nacelle interactions produce increases in running clearances which result in significant performance losses within the first few hours of engine operation. These are anticipated during design and controlled through rotor bearing placement and nacelle support design. The fatigue life of critical components such as helicopter rotors and transmissions, engine fans, turbines and combustors, and control actuators, under steady cyclic and transient dynamic loads is an important design consideration.

ASSESSMENT OF STRUCTURAL DYNAMICS

Current Practice

In applying structural dynamics concepts to the design considerations as outlined above, a number of topics must be effectively addressed. They include structural modeling, environmental modeling, analysis and synthesis, and design validation.

Structural Modeling

As used in this report, structural modeling refers to the process of converting a physical structural system into an equivalent idealization amenable to complete characterization using accepted engineering principles, and of applying these principles to establish a set of mathematical relations for subsequent evaluation by numerical procedures during "analysis." The finite element method represents the current state-of-the-art for structural modeling. It is well established in the aerospace industry as a standard procedure for natural vibration mode analysis. Canned computer codes based on the method, such as NASTRAN, are readily available and are routinely used for the purpose. There are, however, major drawbacks in their application. They generally require a fairly detailed definition of the structure as a starting point. As such they are not well suited to the early preliminary design stage where only the gross attributes of the structural configuration are known. The modeling process involves the generation of large quantities of data defining the geometrical coordinates, material properties, and loading conditions for a large number of elements and modes. Until recently, this has been a time consuming manual operation. Currently, many aerospace companies are adapting interactive graphics techniques to this activity with resultant reductions in the modeling time by a significant amount.

The skill required to create a finite element model is, on the surface, fairly simple. This has been beneficial in promoting the widespread use of the method. Unfortunately, it has also encouraged usage by inexperienced personnel and resulted in poor models and instances of erroneous design predictions. A good dynamics model requires a high degree of skill on the part of the modeler. One of the problems facing many aerospace companies

today is the scarcity of that level of skill within the industry. The mathematical relations involved in the method are tractable as long as linear behavior is presumed. When geometric and/or material nonlinearities are included, they become so complex as to make the method of limited use as a design tool.

Aerodynamic and Environment Modeling

Modeling of the aerodynamics as well as the structure of aerospace vehicles is necessary because there is generally a strong interaction between the two. Aeroelastic analysis including flutter is a case in point. Environmental modeling of the external sources is needed for acoustic and gust response. For these purposes interest lies primarily in the unsteady component which interacts most with the structure.

Current methods of unsteady aerodynamics modeling include the doublet-lattice, mach box and the kernel function approaches. These are generally applicable to subsonic and supersonic flows for which linearization of the potential equations is feasible. In practice, however, they are generally restricted to steady harmonic motion and require empirical corrections when applied to control surfaces. In the transonic flow regime characterized by mixed subsonic and supersonic flows with shock waves, the nonlinear potential equations must be solved in their entirety by finite difference and other numerical techniques. This approach is not readily adaptable to flutter and other aeroelastic analyses because of solution time and cost. The need for more practical 3-D unsteady transonic analysis methods applicable to flutter is quite real.

Analysis

As indicated earlier, analysis involves the numerical evaluation of the mathematical relations resulting from the modeling activity. Today, most structural analysis methods are computer based and most are oriented toward the finite element modeling application technique. Although almost all practical formulations of the method are based on linear assumptions, they are quite often applied to nonlinear analysis through piecewise linearization and stepwise numerical methods.

Dynamic analyses are performed either in the frequency domain or the time domain. Natural vibration modes analysis and dynamic stability roots both require eigenvalue solutions. Examples of time domain response and stochastic solutions are gust response, dynamic loads determination, and nonlinear stability solutions.

The eigenvalue methods are currently well established and their applications are quite routine. Standard time domain methods using time-marching numerical integration are, on the other hand, plagued by problems of numerical instability and error propagation. They require considerable care in their use and in the interpretation of results. The problem of long computational times for finite element analysis applies to both types although it tends to be most acute in the time domain solutions. Contributing factors are the large numbers of degrees-of-freedom (DOF) associated with finite element modeling and the large numbers of integration steps required for the time domain solutions. Modal synthesis methods are extensively used in this regard as a powerful means of drastically reducing the number of DOF in time domain analyses. Also, finite difference approaches combined with simultaneous equation solution methods are often used as alternatives to

the time-marching numerical integration methods.

Responsiveness of current dynamic analysis methods to the design process is very poor in the preliminary design and early detailed design stages when frequent design changes are being made and thus necessitating frequent reassessment of performance, reliability and durability attributes. The major problem here is that in many companies, finite element analyses and company management data processing systems do compete for computer time and resources through automatic priority scheduling procedures for efficient job batching. The big finite element job with its large requirements for CPU, core and disk storage, and magnetic tape input/output, frequently receives no better than overnight turnaround priority in the process. Following execution, it takes several hours more before the results are interpreted to provide an assessment of the design changes proposed more than 30 hours ago. Further delays are incurred if the results are to be used as inputs to other disciplinary assessments such as aerodynamic performance, control effectiveness, propulsion efficiency, noise attenuation, etc. This pace is much too slow for the current design process. There is a need, therefore, to reduce the analysis flow time by at least an order of magnitude in order to be responsive to the need.

In the late design and qualification stages, the analysis issue from a responsiveness point of view is not so much the flow time, but rather the logistics of integrating the various disciplinary analyses into a single coordinated design support role. The various disciplinary design analysis methods generally have been developed independently and are designed to be exercised independently. Obvious interfaces with the other disciplines are accommodated in the form of data transfers. Thus, the various analyses

must be done sequentially and often iteratively, and design optimization is handled piecemeal within each discipline rather than from a global consideration of all design parameters.

To improve the responsiveness of technical analyses to the design process, many companies are taking advantage of dramatic advances in computer technology. Computer graphics systems are being adapted to the preparation of finite element input data and to the post processing of analysis results for more effective extraction and interpretation of the vast wealth of technical information present. The availability in recent years of inexpensive minicomputers with sufficiently large memory (1000 K), adequate precision (32 bit), and computational speeds approaching those of the multi-purpose mainframes, has spurred considerable interest in the implementation of finite element procedures on minicomputers. Computer aided design systems with integrated multi-disciplinary analysis capabilities are operational at the major companies. They are complemented by design, research and development task groups with representation from the major disciplines - aerodynamics, structures, controls, propulsion, computer science, etc.

The accuracy of dynamic analyses is an issue of great importance. In vibration mode analysis, only a few (typically less than ten) of the lowest frequency modes can be predicted with reasonable precision (10% or less error). The precision drops off quite rapidly with increasing frequency, making it undesirable to even attempt computation of the higher modes. Thus, modal synthesis applications must necessarily be limited to a truncated set of natural modes giving rise to questions of convergence and accuracy in those applications.

Non-linear analysis methods are presently not widely used in dynamic analyses. Several factors are responsible for this. First, the need for these methods has in the past been quite infrequent: it has been possible most of the time to design structures with sufficient strength and stiffness such that under all the operating conditions considered in the design process, the behavior is well represented by linear methods. Secondly, and due partly to the reason above, there does not exist a library of proven, general purpose non-linear methods. Thirdly, the abundance and versatility of linear methods -- particularly in numerical analysis, coupled with the large computational capabilities of modern day computers, have encouraged the adaptation of linear methods to the analysis of non-linear phenomena whenever they have arisen. Thus the incentive to develop or apply non-linear methods has not increased appreciably in spite of recent trends in the design process which have necessitated consideration of non-linear phenomena such as crashworthiness, controls-structure interactions and deployment dynamics of large space structures.

Numerical instability and error propagation problems associated with the stepwise algorithms employed in the numerical methods have somehow been amplified by the non-linearities to the extent that practically all the on-going research and development efforts in non-linear mechanics and methodology are devoted to the establishment of techniques for controlling these problems in applications.

Synthesis and Optimization

As used in the literature, structural synthesis refers to the systematic modification of a structural system in order to achieve some optimum condition. Typically, minimum weight has been considered the desired optimum condition (objective function) with deliberate concessions being made for such factors as stiffness and strength (constraints). In the current design environment, synthesis procedures consist of iterations of detailed structural

analyses (weight, stress, dynamics) followed by re-sizing of selected components, or elements, based primarily on the judgments of experienced designers and analysts. The major weakness of the process today is that the analysis phase takes so long that the experienced personnel are having to frequently wait on the analytical results rather than vice versa.

Testing

Full-scale and scaled model testing of aerospace products is an integral part of the design process. In the aircraft industry, wind tunnel testing of scaled models is used extensively in the preliminary design stage to help establish the candidate configurations. Subsequently, throughout the design, additional wind tunnel tests are made to generate design input data and to validate analytical predictions.

The structural dynamics issue in these tests is the proper scaling of the models in order to faithfully reproduce the true aeroelastic characteristics inherent in the design. While the scaling laws are fairly well established, the process of reproducing analytical stiffness and mass distributions in the physical model is a highly specialized art-form practiced only by a few companies. The future health of these companies is of great concern to the aircraft industry.

Laboratory tests of aircraft structures and space vehicles are also conducted generally as part of the design validation process. The static load test is used to validate the strength of the design by the application of static equivalents of expected dynamic loads. Vehicle vibration tests are used to validate analytical mode shapes and frequencies. The major issues with the static testing are the determination of the equivalent loads and their experimental simulation. The method of excitation of natural modes in vibration tests is one of the important technical issues. A common issue in

both static and vibration tests is the proper usage of the test data. Traditionally, the data have been used to generate comparisons with analytical predictions. Invariably, discrepancies arise necessitating adjustments to the mathematical model to minimize them. Systematization and full utilization of all the available data in this adjustment process appears to be an important issue.

PROJECTIONS

Design Process

The design process will continue to change as it has in the past to accommodate the constantly increasing requirements for improved performance, reliability and durability in the design products. The products will become more complex as more advanced technology is incorporated. The need to meet specific performance requirements in the final product will mean that each activity of the process must be more accurately assessed as to its effect on the final product performance. This in turn will require greater interaction among the various disciplines and technologies that support the process. The process will thus become increasingly more dependent on performance predictions at all stages and across all technical and management disciplines. Domestic and foreign competition for product sales or applications will tend to impose even more stringent scheduling requirements.

Computer aided design technology appears to provide the only logical means of coping with this evolution. It is already widely used for design drafting with considerable improvement in cost and schedule over conventional board drafting. It has proved to be a more effective and convenient means of storing design information as compared to conventional design drawings, and interfaces efficiently with automated manufacturing equipment. It is currently

being extended into the technical computations areas where direct interface with design data in storage is helping to eliminate some time consuming manual data preparation starting with design drawings.

From current trends, it can be readily projected that the design process will become increasingly dependent on the computer. All design information will reside in the computer and accessed on a controlled basis by all design support personnel. Systematic procedures will be developed for updating this information periodically throughout the design with the final data interfacing directly with tooling and manufacturing activities. Analytical tools will be developed or modified to interface directly with the data base. Computer network systems will provide remotely located segments of the design team with access to the design data and also handle communications among team members irrespective of their geographic locations.

Modeling

Good mathematical modeling for dynamic analysis will continue to require considerable analytical skill and a great amount of practical experience. The aerospace community will need to make a concentrated effort to develop and maintain personnel with the necessary skills and experience.

The training of young engineers has to emphasize the fundamental understanding of both the dynamic behavior of structural systems and the mathematical techniques used in analyzing these systems. Industry must take steps to discourage the use of analysis tools as black boxes into which one feeds data and receives data in return without adequate appreciation of what takes place in between. Developers of analysis methods will have to "build in" aids to guide users in the proper usage of the methods.

The finite element modeling technique will continue to be the primary tool, although it will tend to operate in a hybrid mode in which finite difference and other discretization schemes for non-structural modeling (e.g., aerodynamics, acoustics, propulsion, controls) are integrated in a single analysis tool. The "super-element" concepts based on sub-structuring techniques will need to be developed further for application to the very large structural systems anticipated for future space applications.

Simpler modeling approaches (equivalent beam, frame, plate or truss representations) will continue to be needed in the early preliminary design stages where the structural configuration has not matured sufficiently to permit the creation of a meaningful state-of-the-art finite element model. This is where experience in modeling becomes such a significant factor. Means for transferring this experience from one generation of designers to another will require some research and formalization.

The need for unsteady transonic aerodynamics modeling techniques applicable to flutter, general aeroelasticity and active control analyses, will become more critical with the flexible and lighter aircraft configurations being studied for improved energy efficiency and direct operating cost goals. For rotorcraft applications, these models must be capable of depicting complex phenomena such as dynamic stall, rotor wakes and blade-vortex interactions.

Needs exist and will grow in developing semi-empirical modeling methods for the acoustic environments of aeronautic and space structures, and for atmospheric turbulence.

Analysis

The responsiveness of dynamic analysis in the preliminary design phase of the design process must be significantly improved if the pertinent dynamic

issues are to be effectively addressed. The role of these issues in the design process has been shown to be crucial. It can be expected to become even more so in the future as a result of current trend towards increased structural flexibility and the attendant increase in structural dynamic interactions with external environments and on-board controls/propulsion systems.

To meet these needs both the analysis methods and the way they are used will have to undergo major changes. Analysis techniques must be developed in which fairly simple models are used in the preliminary design stage and systematically upgraded in size and detail, as the design matures, into that required for design validation. The use of dedicated computer facilities for dynamics and other design support analyses appears to be a viable solution to the response problem, and can be expected to become economically feasible if advantage is taken of the developments in the minicomputer and microprocessor fields - increasing capabilities at decreasing costs. The dedicated facilities will have to operate in an interconnected computer complex environment so as to promote the needed multi-disciplinary interactions.

As to the analysis methods themselves, the single major deficiency currently is in the non-linear mechanics representation. It is unlikely that the general purpose computer program, as we know it today, can be made to provide this capability in an efficient manner, because of the variety of non-linear phenomena to be handled. In the long run, it can be expected that microprocessor technology will provide the means of modeling each problem on an ad hoc basis. It can be further anticipated that there will at that time be efficient mathematical solution techniques for various classes of non-linear equations. In the interim, the needs are to establish a classification scheme for known and anticipated phenomena, and to develop a specialized

modeling framework and an efficient solution routine for each class.

For the linear analysis methods, improvements are needed primarily in the manner of their computerization and applications. Efficiency improvements will continue to be made in numerical algorithms, computer program architecture will be modularized and analysis outputs will be streamlined and structured to provide the user with maximum flexibility in the formulation and solution of specific problems.

Synthesis and Optimization

Synthesis procedures will become more automated in the sense that the interaction between decision making by the designer and analysis computations by the computer will be accommodated in the computerized tools. These tools will also cater to the needs for multidisciplinary optimization in which all design constraints and associated trade penalties are duly considered in arriving at an optimum design.

Testing

The major development to be expected in this area is a more widespread use of component testing in contrast to the total system testing as the basis for design validation. This is recognized as a necessary requirement in the development of large space structures which cannot be assembled for testing in the earth's gravitational field. It is obvious that this approach will necessitate that the test results feed into as well as complement analytical validation procedures.

RESEARCH NEEDS

Listed below are a number of broad areas of research activity and objectives which are considered necessary to meet current and future design support needs. These have been identified from an assessment of the current state-of-the-art and from projections of current trends, as discussed earlier. They are not in any priority order, nor are they meant to be all inclusive or specific as to actual research tasks. They are grouped into two categories: Generic and Applications Research.

Generic research is that aimed primarily at the improvement and extension of the basic tools of structural dynamics. Applications research on the other hand seeks to enhance the procedures by which the basic tools are applied in the design process, or to use the tools in the investigation of design problems.

Generic Research

Modeling

- o Dynamic Finite Elements: Development of finite elements in which all inertial effects (gyroscopic, centrifugal, coriolis, etc.) are accounted for.
- o High Frequency Dynamics Modeling: Feasibility investigation of alternatives to finite element and modal synthesis approaches (e.g., statistical energy distribution).
- o Mixed Discretization Models: Development of techniques for compatible interfacing of finite elements with finite difference and other discretization schemes in modeling for structural interactions with aerodynamics, hydrodynamics, and control elements.
- o Math Model Correlation and Validation: Development of techniques for systematic updating of math models to improve correlation with test data.

- Unsteady Aerodynamics: Development of transonic and viscous non-linear potential flow methods that are computationally efficient and suitable for aeroelastic analyses.
- Structural Damping: Feasibility studies for the replacement of equivalent viscous damper and complex stiffness approximations by more realistic (of actual mechanisms) models.

Analysis

- Advanced Numerical Methods and Computational Algorithms: Development of improved methods which exploit such features as matrix bandedness and symmetry (normal or skew) to increase computational speed.
- Non-linear Analysis Methodology:
  (1) Classification of non-linear phenomena of significance in design process on the basis of their governing equations, and the establishment for each class of necessary and/or sufficient conditions for the existence of solutions, and the uniqueness and boundedness of such solutions.
  (2) Development of efficient and accurate numerical methods for the solution of specific classes of non-linear problems.
  (3) Development of experience data base of experimental data and benchmark analytical solutions for use as design aids.
- Empirical/Statistical Methods Using Experimental Data: Establishment and maintenance of comprehensive data bases and reliable prediction methods for acoustic, turbulence, fatigue life, etc.
- Minicomputer and Microprocessor Based Tools: Development of cost effective dedicated systems for rapid turnaround analyses.

Testing

- o Modal Testing; Continued improvement of testing methods, acquisition and reduction of test data, and use of test results.
- o Wind Tunnel Testing:
  - (1) Innovative usage of facilities for validation of analytical methods and investigation of phenomena not amenable to analytical treatment.
  - (2) Continued effort to improve quality of tunnel measurements.
- o Flight Testing:
  - (1) Expanded usage for technology development purposes through carefully planned piggyback experiments on design validation programs.
  - (2) Continued activity to improve quality of flight data and the extraction of useful information from data.
- o Instrumentation; Continual development and improvement of dynamic transducers and associated instrumentation.

Applications Research

Modeling

- o Simplified models for Preliminary Design: Development of simplified models for preliminary design of specific products coupled with extensive calibration of such models against more detailed models.
- o Modeling Standards and Criteria: Development of modeling standards and criteria for specific product classes to aid in the professional growth of young dynamicists.
- o Finite Element Model Output/User Interfaces: Incorporation of secondary state variables such as kinetic/strain energies, linear and angular momentum, to assist in interpretation of analysis results.

Analysis

- o Integrated Design Analysis: Structuring of Dynamic analysis tools for effective interfacing with other disciplinary tools - aerodynamics, controls, propulsion - in integrated design analysis applications.
- o Design Loads and Criteria: Continued improvement of methods for the establishment of design criteria and the determination of design loads. Particularly important in rotorcraft airframe and space vehicle payloads design.
- o Design Optimization and Structural Synthesis: Extension of analysis methods to include structural synthesis and design optimization capabilities.

Design Problems

- o Low Frequency Dynamic Loads for Launch Vehicle Payloads: Development and validation of quick response and reliable prediction methods.
- o AircraftManeuver Loads: Development of capability of analytically simulating the maneuvers in order to determine critical loading conditions.
- o Helicopter Rotor Loads: Development of accurate aeroelastic prediction methods capable of supporting the design process for a variety of rotor configurations. They should be capable of dealing with both main rotors and tail rotors.
- o Turbo-Machinery Dynamics, Aeroelasticity and Hydroelasticity: Development of comprehensive methods for prediction of the steady and unsteady environments (aerodynamic, hydrodynamic) of major components and the resulting dynamic response, including flutter, stall and surge phenomena.
- o Aircraft Buffet and Gust Loads: Accumulation of flight data and development of empirical/statistical prediction methods.

- Vibroacoustic Testing/Analysis: Establishment of data base and use to develop improved prediction methods.
- Helicopter Ride Quality: Development of design procedures and supporting analysis methods for achieving low vibration, low noise helicopters and other rotary wing aircraft. This includes the development and effective application of vibration control devices and systems.
- Aircraft Flutter Suppression: Development of design procedures, supporting analysis methods, and experimental data (wind tunnel and flight) in support of flutter suppression of clean wings and wings with stores, using both active and passive techniques.
- Structure-Controls Interactions of Large Flexible Structures: Development of analysis methods and their use in studies of guidance and control of large flexible space systems.
- Design Validation of Large Space Structures: Development of alternatives to conventional ground testing for design validation.
- Deployment/Assembly Dynamics of Large Space Systems: Conduct of analytical and experimental studies to validate candidate concepts.

CONCLUDING REMARKS

The committee perceives the role of structural dynamics in the design process to be crucial. However, it also perceives that this role is not being fully played in current practice mainly because the structural dynamics considerations are not addressed early enough in the design process. It attributes this situation to a lack of proven simplified analytical methods and design data bases suited to the early preliminary design activities. A number of the recommended research areas are aimed specifically at remedying this by providing reliability and application speed improvements in simplified modeling and analysis techniques with emphasis on synthesis, and by enhancing experience data bases that serve as design aids.

In the design validation stage, the committee perceives some need for improved reliability of prediction and experimental qualification, primarily through more effective treatment of nonlinear phenomena. Beyond this, it perceives even greater needs in the procedures for the application of basic analytical and experimental methods. The recommended research areas address this from several aspects such as integrated design analysis, design optimization and design validation of large space structures. These issues are equally applicable to the late preliminary design and detail design stages during which trades are constantly being made among the various design requirements, both technical and economic. Other needs for detailed design include adequate resolution of specific problems which tend to hamper the making of valid comparisons among decision options on a uniform intellectual basis. The major ones are included in the recommended "design problems" research areas.

The committee recognizes that many of the recommended research areas are being addressed in ongoing research within NASA as well as elsewhere. Their inclusion here is not to be interpreted as reflecting any perceptions by the committee of deficiencies or inadequacies in such programs; The committee did not address itself to an assessment of ongoing research, because it considered this to be outside the scope and purpose of this study.

This report provides a general framework and categorization scheme that are valid throughout the industry and suited for long range planning purposes. As an input to NASA's long range planning, it provides a basis for an assessment of ongoing research, which the committee believes to be a logical follow on to this study. From such an assessment, true deficiencies in technology can be identified and prioritized. These together with considerations of budgetary, staffing, and national interest issues would provide the basis for the establishment of near term research emphasis and far term broad objectives.

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APPENDIX A

Ad Hoc Study Committee

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APPENDIX B

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