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TECHNICAL NOTE

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IMPORTANT RESEARCH PROBLEMS IN MISSILE AND

SPACECRAFT STRUCTURAL DYNAMICS

1961

Prepared by M. V. Barton in collaboration with the
NASA Research Advisory Committee on Missile
and Space Vehicle Structures

NASA Headquarters
Washington, D. C.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

An attempt is made to indicate the research studies which should be vigorously supported in order to provide necessary information for the solution of structural dynamic problems of missile and space vehicles. The problem areas are discussed in terms of the disciplines or functions required in their solution. Among the latter are: (1) interactions of the complete system and the environment, (2) criteria for design conditions and performance, (3) interactions of aerodynamic forces with flexible structures, (4) motion of liquids, (5) vibration, (6) impulsive loading and transient responses, (7) guidance and control, (8) testing, and (9) materials considerations. In addition, some correlation is provided for identifying the problems in terms of the environmental conditions in which they occur.

INTRODUCTION

The purpose of this report is to identify the problems associated with the dynamics of missile and spacecraft structures which require organized analytical and experimental research to enhance our understanding of the phenomenological aspects of the problems. The report is addressed to the scientific community at large, to solicit their attention and assistance in this effort, and to governmental and industrial programmers for recognition of the impact of these problems on their program and support for timely initiation of the necessary research.

The term "dynamics" is used in its broad context of the nature and effects of time-dependent phenomena, encompassing the response of, and the effects on, structures and vehicle components resulting from vibration, shock, and impact, and involving any combination of inertial forces, elastic forces, control forces, air pressures, fluid pressures, radiation pressures, temperature effects, magnetic fields, and gravitational fields. The report thus supplements the review of research problems in advanced flight structures design which was published as an NASA Technical Note (ref. 20).

In organizing the material in this report, an early decision had to be made on the method of organizing problem areas, that is, by the principal specializations or disciplines used in problem solution, or by the environmental conditions in which the problems arise. The first classification was chosen as the arrangement of greater probable significance for the majority of the report's audience. For cross reference, organization of the problems by the latter classification appears in appendix L.

The source material of this report is the experience of the members of the NASA Research Advisory Committee on Missile and Space Vehicle
Structures and their colleagues. The membership of the Committee is given A
in appendix A. Inputs provided by the members were collected, analyzed, 6
and edited by a task group comprised of M. V. Barton (chairman), M. E. 2
Alper, A. L. Erickson, W. Nachbar, and R. S. Shorey. The task group 0
acknowledges with gratitude the important stimulation and guidance contributed by Prof. E. E. Sechler, chairman of the Committee, and the editorial assistance of Mr. Milton J. Berg of Space Technology Laboratories, Inc., and Mr. G. E. Nitzberg of NASA Ames Research Center.

CONCLUSIONS

In any survey such as this report, to determine areas of research that need emphasis, there is strong motivation to establish a relative priority among the dozens of problems thus illuminated. However, when one attempts to determine relative importance among problem areas, based on a description of the areas alone, there is a basic difficulty in that the reasons for importance lie outside this level of abstraction. Part of the importance of a problem at any given time is the importance of its particular applications. The importance of a problem, or need, is also related to the implications of an improved solution to the problem; for example, how much is the end-item improved by getting a better answer to the problem, to what extent does the end-item rely on an improved solution, and to what extent are alternate solutions possible?

For this reason, the missile and space vehicle structural dynamic problems have been grouped, in this report, in terms of the technological knowledge required for their solution. Although each of the problems included was originally identified with particular applications, the recommended research programs should not be narrowly constrained to only those applications. This manner of defining problem areas is an essential part of the research process.

Highlights of some of the research programs have been arranged in categories (which will have varying degrees of importance to different groups of people) without assigning relative importance emphasis, to provide guidance in individual assessments of the most profitable utilization of manpower and facilities resources and of funds for needed expansion of these resources. The categories chosen are:

I. Basic Problems Needing Continuing Research
II. Supporting Effort for Future Research and Design
III. Specific Problems of Major Importance
IV. Research Objectives

I. Basic Problems Needing Continuing Research

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The problems included in this category are fundamental in nature and extremely broad in their ramifications. It is important, therefore, that program objectives not be restrictive, since to specify and detail a "payoff" would change the direction of the program and the nature of the effort to such an extent that much of its potential would be sacrificed. The real payoff for this type of work is in the accumulation of a body of scientific knowledge which finds application in the solution of many related technical problems, only some of which can even be named at this date. To find a worthwhile area for fundamental research effort, one must look not for problems but for ignorance. This program attacks ignorance. The payoff will be knowledge.

Dynamics of solids.- For the purpose of this discussion, the dynamics of solids encompasses energy absorption, deformation, and fracture processes in materials. Consideration of internal inertia forces also becomes important when the rate of load application is very high, and also during rapid fracture, in such problems as pressure vessel design, meteoroid impact and explosive forming.

Since real solids are never perfectly elastic, when disturbances are propagated through them some of the mechanical energy is converted to heat through various mechanisms known collectively as internal friction. The nature of internal friction is not well understood, and its study on a molecular level should lead to a better understanding of the relations between molecular structure and macroscopic physical properties of solids. Another aspect of structural behavior affecting stress-wave propagation is mechanical relaxation of the material. It has been found that stress waves whose natural periods are close to the relaxation times are severely attenuated in passing through a material. Further attenuation is afforded by the temperature gradients set up by dilatational extensions and compressions, which, together with the finite thermal conductivity of the solid, provide another mechanism for the dissipation of mechanical energy as heat energy.

In addition to the elastic waves, shock waves and plastic waves may be generated and have been observed experimentally. The study of shock wave generation and propagation in metals is still in its infancy. Theoretically, the surface has only been scratched, and only a few experiments have been reported. Although considerable work has been done on the propagation of elastic and plastic waves in one dimension, and upon the propagation of a variety of waves along free surfaces and interfaces, the propagation of plastic waves in two- and three-dimensional situations is of considerable interest.

The passage of a transient disturbance through a polycrystalline material will modify the structure of the metal if the disturbance is sufficiently strong. Examination has revealed that the principal deformation modes (grain distortions, slip, bending, and twinning) observed under conventional static loading are also observed in impulsively loaded metals. However, the prevalence, distribution, and occurrence of these various deformation modes are found to be markedly different for static as contrasted to impulsive loading. For example, there is evidence that under intense impact loading, local heating may be sufficient to cause phase changes in the material, and any subsequent failure may be modified accordingly. There are, on the other hand, many instances in which failure has occurred in the material without any phase change. The yield phenomenon has received wide attention under static and low speed loading conditions. Unfortunately, yield stress is dependent on many environmental factors other than material structure, such as local temperature and pressure, crystal structure, preworking, and rate of deformation. Such dependence is clear from models of dislocated plastic flow, and it is possible that more fundamental properties can be formulated eventually on the basis of such a model.

Nonlinear dynamics.- This subject is high on any research priority list from several points of view, ranging from a desire to fully utilize nonlinearities for more effective design to a desire to eliminate nonlinearities from design so as to simplify analysis and testing for design verification. Achievement of either goal can be attained only by complete understanding of the mechanics of nonlinear dynamic behavior and the acquisition of practical analytical techniques for solving problems involving such behavior. Some examples on nonlinear phenomena on which considerable research remains to be done are:

Dynamic behavior of visco-elastic and composite materials
Effects of creep of materials
Amplitude-dependent responses of structures
Thermoelastic behavior of structures
Damping mechanisms
Dynamic instability phenomena

Each of these problems, in varying degrees, importantly affects the confidence with which a dynamics analyst can evaluate and predict the performance of a vehicle design. If his analytical model contains only simplifying assumptions on nonlinear behavior of materials and structural geometry, then confidence in his results is low and a greater burden is placed on the test engineer. Research into these nonlinear problems should also improve the sophistication of vehicle design, resulting in effective, purposeful employment of nonlinearities to achieve specific design objectives, such as landing shock alleviation, vibration isolation and acoustic attenuation.

Scaling laws.- The practical limit in full-scale dynamic testing has probably been reached in SATURN, so that greater emphasis must be placed on testing dynamically valid models. Here again, we do not yet have sufficient knowledge to adequately model stiffness, damping, and nonlinear behavior. Present discrepancies in frequencies and mode shapes between model tests and full-scale tests demonstrate the need for greater sophistication in either the model or the test conditions, or in both.

II. Supporting Effort for Future Research and Design

Among the deficiences which handicap current missile and space vehicle design is a lack of knowledge about the dynamic environments which must be survived for successful achievement of missions. It is apparent that considerable effort is required to obtain significant information about these environments, and that most of it is attainable only from in-flight measurements.

However, it is important to balance the desire for large or very thorough flight experiments with the realities of experiment costs and flight program lead times. The latter is particularly important in planning the measurement program. For example, if an experiment were designed to provide information for use in the design of an interplanetary probe planned for late 1966, it would have to be flown and the data evaluated by mid-1963 to affect preliminary design and basic configuration, or in early 1964 to effect such relatively minor changes as small increases in material thickness. Now consider the lead time before even the experiment can be flown. If a Scout is to be used, there will be several months to evaluate data and, as a minimum, 12 months to design, build, test, and prepare the vehicle for launching. For a large experimental package on a Thor-Agena, the lead time would be a minimum of two years, based on acquiring the launch vehicle and scheduling range time for launching.

Considering all the effort required to obtain data from one flight, certainly every possible element of information should be extracted to contribute to a body of authoritative data on the dynamic environments to which vehicle, component, and materials responses must be sought by research, analysis, design, and testing. To achieve these ends, consideration should be given to creating some standardized vibration recording and telemetering system that can be flown on the vehicle upper stages which will be used often by NASA and the Armed Forces. Instantaneous values of acceleration should be measured continuously at as many points as is practical and, if telemetry bandwidth is limited, in-flight data reduction should be used. This system should be designed for use on every possible flight for the next 10 years. For maximum effective utilization of the information obtained, a central data analysis group should be established to collect, analyze, and disseminate the information and to plan future data-gathering programs.

III. Specific Problems of Major Importance

In contradistinction to the first category of research problems, those discussed here can be identified with specific current needs and their solutions would have many immediate applications in missile and space vehicle designs now in being and under development. Although there has necessarily been some work undertaken in connection with particular design problems, there is great need for concerted research in the broad aspects of these problems to arrive at generalized solutions suitable for many applications.

The appendixes contain some detailed discussion of these problems and it is certain that at least an equivalent volume could be filled in more discussion, since they are so broad in their scope and in their influence. For the present purposes it will be sufficient to identify these problems within the context of current needs, although the research required and the results to be sought are broader in scope. Selection of these problems to be thus highlighted out of the many included in the appendixes is indeed based on the broadness and the timeliness of their influence on planned future missile and space vehicle programs, such as lunar and planetary probes and manned space flight. Once again, no implication of relative importance should be attached to the order of their listing.

(1) Interaction of aerodynamic and hydrodynamic forces with an elastic structure (buffeting, sloshing).

(2) Landing shock control (landing in nonatmospheric environment, water impact, etc.).

(3) Transportation and handling dynamics.

(4) Dynamic buckling of shells due to transient pressure fields (including the influence of superimposed vibration).

(5) Microparticle impact of shell structures (this is also related to the research discussed in Section I).

(6) Behavior of fluids under zero-gravity conditions.

IV. Research Objectives

The required results of the research outlined in this document can be summarized in two broad objectives, Systems Interactions and Design Criteria.

<u>Systems interactions</u>.- The complex interactions of all the significant factors, such as structural flexibility, propellant sloshing, aerodynamic forces, control characteristics, staging, etc., which affect the dynamic behavior of missile and space vehicle systems must be taken into account by generalized system dynamic analyses to determine performance, trade-offs, and general system characteristics. Research is required to provide authoritative information on the many parameters involved in such analyses and to refine the analytical techniques, including the incorporation of such factors as:

(1) The aerodynamic and structural effects of clustered bodies.

(2) Long-time effects of fluid motions, internal forces, radiation pressures, and thermal gradients in zero gravity fields.

(3) Adaptive control systems and nonlinear devices.

<u>Design criteria</u>.- Of the three parts of a dynamic study, namely, the environment (including the loads), the calculations of the responses of the structure to the environment, and prediction of the ability of the structure to withstand the environment, the first and last are concerned with the establishment of the structural design criteria. Emphasis should be placed on the dynamics elements of design criteria, such as, for example, the provision for rational methods for the determination of engineering failure under dynamic conditions and the specification of suitable values of displacement, stress, load, or other measures of satisfactory performance.

Among topics requiring investigation are:

(1) Better statistical definitions of loading, such as for transportation.

(2) More satisfactory methods for assuring reliability.

(3) Behavior of shell structures, both pressurized and unpressurized, under a variety of dynamic loads.

(4) Establishment of meaningful requirements for equipment and mechanical components.

NASA Headquarters,
Washington, D.C., January 8, 1962

APPENDIX A

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APPENDIX B

GENERALIZED SYSTEM DYNAMICS

Generalized system dynamics studies cover the interaction between a total system and its environment, and the behavior of a total system resulting from dynamic interaction between components or subsystems. The impetus for making thorough generalized system studies arises from the fact that the loads which govern the design of the system, and of subsystems and components, usually result from some system dynamics problem. Definitions of conditions and occurrences during a vehicle mission, and trade-off studies between subsystems become meaningful only when treated in generalized system analyses.

LAUNCH CONDITIONS

Booster loads may be greatest during ground transportation or while the booster is on the pad, due to ground winds and vortex shedding. Many weapon systems of the future will undoubtedly employ silo-launched missiles. For design purposes, the dynamic effects of this complex environment must be readily determined to enable selection of optimum arrangements of flight and ground systems. This requires that the environment be known or predictable and that means of using it in the dynamic analysis are developed. Consideration of dynamic response of structures to engine start transients must include effort to distinguish the effects of multisource energy inputs, that is, multimotor configurations, where actual tolerances on thrust level, build-up rates, and decay rates are of known significance. In this situation, simultaneous responses of separate elastic components will be reacted into a common structure. In addition, relative evaluation of clustered bodies as compared with a functionally singular body design is hampered by inadequate analytical techniques. Effort is required to develop reasonable mathematical models for use in calculations of mode shapes and frequencies as a prerequisite to meaningful response calculations.

ATMOSPHERIC FLIGHT

The dynamic effects encountered during atmospheric flight include, among others, servo-elastic problems and the coupling of forcing environments with steady, or almost steady, environments. The response of the structure-servo control-engine system (including nonlinearities) to disturbing forces is a major problem requiring attention. Another problem is the interaction of strain (thermally induced or from applied loads) and the response of the structure induced by noise, unsteady aerodynamics, internal pressure fluctuation, etc. The effects of mass variation, fluid sloshing, structural heating, point of thrust application (liquid vs. solid propellant engines), thrust vector control systems, engine-out operation in multiengine systems, and resonances in engine mounts are all complicating factors which should be included in the generalized systems dynamic analysis. Dynamics of stage separation may be responsible for significantly reducing the reliability of multistage vehicle systems. An extension of standard structural dynamics analytical methods to include the effects of small forces due to the actuation of separation devices, and gas dynamic effects, is needed to analyze both the transient loads and vehicle dynamic responses.

Prediction of equipment shock and vibration is usually based on a highly idealized environment. Components are frequently structurally supported in a complex manner, resulting in nonlinear response to inputs. Analytical means for predicting component environments, given the general vehicle environment and the vehicle structure, are badly needed. Vibration transmission through complex structures must be studied in addition to the varied sources which provide the energy input.

SPACE FLIGHT

Very little is known about the loads on structures and the structural response in a zero-gravity space environment. Small forces which are normally neglected can become important and must be considered. Radiation pressure, magnetic effects, rotating machinery, and circulating fluid in power conversion systems are sources of this type of force. The structures involved may have very low natural frequencies, and although the control systems will provide small control forces, they will be required to operate for many months.

ENTRY

Atmosphere entry and landing problems also require comprehensive study from a systems viewpoint. The atmospheric conditions require consideration of heating problems. On the other hand, aerodynamic forces can be used for attitude and approach velocity control. There is a design trade-off in three areas: attitude control, altitude (or approach velocity) control, and landing shock alleviation. Some pressing problems in this area include providing shock alleviating structure which is also a radio frequency window; or providing a means of shedding the protecting structure after a hard landing so that experiments can be performed and communications can be established. The systems dynamics problems of attitude, velocity and shock control, and structural interactions during and immediately preceding the landing impact of a soft lander are also major problems, particularly in planetary soft landing. Here, the atmosphere adds heating and all the other aerodynamic problems; but it also offers more alternative methods of solution. The choice can be made easier if the detailed behavior of the various parameters can be studied in advance in system studies which provide a basis for comparing the alternatives.

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APPENDIX C

STRUCTURAL DESIGN CRITERIA

The interactions of two factors are considered in establishing structural design criteria: (1) environment including applied loads, and (2) ability of the structure to withstand the environment and the loads, or the design allowables. The latter factor includes a proper consideration of the environment and the response of the structure to that environment.

The environment to be considered consists of loads originating from external sources such as aerodynamic loads, acoustical noise, etc., loads induced internally such as engine noise transmitted mechanically, internal pressure, and control system forces. Additional environments that must be considered are thermal effects, effect of a hard vacuum, and radiation effects.

Of particular concern are those time-dependent loads for which "allowables" must be expressed either in terms of dynamic buckling of columns or shells, actual rupture of material, peak dynamic hydraulic pressures in vessels, critical conditions for panel flutter, limiting deflections or deformations, local deflections, or perhaps others that might be considered as failure conditions for a vehicle and its mission. When the primary loading terms of the environment are time-dependent, the determination of structural resistance requires a complete understanding of the dynamic behavior of the structure.

LOADS

Studies should continue on the dynamics of entire missile structures, including the effects of the time history of the parameters from attachment to the launch complex through first boost separation. Refined criteria should be established for in-flight loading imposed on both rotating and nonrotating vehicles.

Criteria are needed for the design of space structures that are as lightweight as possible while still embodying the required resistance to destruction. As usual in flight vehicles, the desire for minimizing weight is in opposition to the desire for maximizing safety, and we need to determine the trade-off relationships between weight and resistance to failure for various realistic loading conditions. It is expected that environment research will eventually lead to probability tables and curves for varying magnitudes of environmental loading, such as gust loads, number of impacts and size of meteoroid particles per unit area per unit of time or distance, radiation intensities, etc.

In many cases, the environmental conditions associated with various transportation modes, for example, truck, air, rail, and ship, design part of the missile structure itself. Better data on transportation environments will aid in more efficient designs. For analysis purposes, the environment should be specified independently of a particular vehicle design such as statistical descriptions of road and rail surfaces, axle motions, coupling impacts, ship motions, etc. The achievement of a simple equivalent transportation environment to be used in design criteria would be a valuable contribution.

RELIABILITY

The design of structures for high reliability is a requirement of increasing importance for space vehicles which must remain in space and be operable for long periods of time. Designing for reliability has a number of new aspects with several dynamic implications. For instance, the determination of appropriate dynamic factors of safety requires a new look at the definition and philosophy of "factor of safety." A design method is needed which will include a prediction of life expectancy or assurance of reliability, rather than some arbitrary factor. This is of particular importance for all types of vehicles subjected to repetitive loads, creep loads, or any of the dynamic loads which accumulate damage in the structure and eventually cause failure. Design criteria must take into account the expected number of cycles of repetitive load, the likelihood of load duplication during each cycle, as well as the probability of uniformity of material characteristics and fatigue properties. A critical review is required of all pertinent design criteria now being used to predict the reliability characteristics of structures.

In test specifications and in design procedures, factors are applied to insure a necessary level of reliability. The basis for such factors is quite arbitrary and, in many cases, may impose severe cost and scheduling penalties. Furthermore, simple vibration specifications generally do not account for impedance characteristics of a component of the structure to which it attaches. Much research is needed to define and specify vibration environments for design which are based on the degree of performance reliability and life expectancy required in a particular vehicle.

Another problem of importance to spacecraft reliability is the method of structural mounting or attachment of individual components. The method of mounting determines critically the vibrational and other dynamic environment of the component, and hence its lifetime (and vice versa). Unfortunately, in many cases the mounting is not designed by the structural designer. It is therefore important that simple design criteria be developed for use by the component designer, so that the structural designer can anticipate the use of proper mounting procedures.

STRENGTH

The most significant structural components of missiles and spacecraft are thin shells and pressure vessels. Appendix E of NASA TN D-518 (1960) contains a comprehensive discussion of the problems associated with these structural elements, with conclusions and research recommendations. For added emphasis, particular remarks in that report are paraphrased in the following paragraph.

Through the years much effort has been devoted to the problems of analytical structural mechanics and the great body of knowledge accumulated in the literature provides satisfactory solutions to many structural design problems. Effort should be continued, and probably expanded, to develop practical mathematical and probabilistic methods for analytical investigations of flight vehicle structures in fields of stress analysis, fatigue analysis, thermal effects, internal pressure effects, etc. In studies of heated structures, the effects of transient loads, including automatic control systems, fuel sloshing, and more complex loading should be pursued. These analytical methods must be broadened to include composite structures, and advanced materials. While refinements and improvements are both possible and desirable in many areas, there are others in which present methods for analysis and design are inadequate, serving only as a guide by which test articles may be built for verification or study. Testing in general is becoming more complex and expensive, and in some situations may be wholly impractical.

APPENDIX D

AEROELASTICITY

Aeroelastic problems, such as primary surface flutter and divergence, buffeting, panel flutter, etc., continue to be important in the design of missile systems, spacecraft boosters, and atmosphere entry vehicles. A large backlog of experience exists on flutter, but the hypersonic speed range is relatively unexplored. Similarly, temperature effects coupled with a fluttering system have not been defined. Panel flutter is presenting design problems on many new configurations, and very little is known other than "rule-of-thumb" fixes. Aeroservoelastic coupling has been overcome in all the current designs, but the increasing size of boosters, which will lower structural frequencies, plus the use of winged payloads or stabilizing fins, may make solutions more difficult on future vehicles.

GROUND WINDS

Ground wind conditions impose both drag loads and lateral loads due to shedding vortices. The hold-down structure and the afterportion of some first stage boosters are designed by the ground wind conditions, and research efforts in defining the wind environment and in refining methods of ground wind load analysis are urgently needed. Although a great deal of statistical data are available on magnitude of strongest winds and on vertical profiles of average winds, the spectral properties of strong winds are yet to be defined. Emphasis is also required on determination of the lateral forces arising from vortex shedding. A basic understanding of the underlying mechanics of the wind problem is needed, so that reliable analytical methods for treating the problem can be developed. This treatment must take into account the separate and combined effects of Reynolds number, tip effects, spoiler configurations, surface roughness, axial variations in diameter, and lateral structural oscillations.

PANEL FLUTTER

A problem of particular concern is panel flutter. Until recently the occurrence of panel flutter was seldom catastrophic and simple fixes were available. The current trend toward thin gage structures, particularly those with orthotropic properties for radiation-cooled designs, has led to a different situation. For such configurations, panel failure and the available simple fixes may defeat the purpose of the original design. Panel flutter analysis should be based on actual panel dynamic characteristics, rather than an idealized equivalent panel. Experimental techniques should be developed to properly simulate edge support conditions, pressure differences, thermal gradients, and other pertinent parameters in wind-tunnel tests for panel flutter. Little is known about the phenomenon of curved panel flutter in thin-skinned pressurized vehicles. Methods are needed to determine the behavior of typical structures, accounting for such variables as biaxial stress ratios, pressure-diameter-thickness ratios, small protuberances, etc. Development of methods for cylindrical, conical, and other bodies covering a broad spectrum of flight parameters is also needed.

LIFTING SURFACE FLUTTER

This aspect of the flutter problem has plagued the development of all vehicles that operate within the atmosphere. Since many space vehicles and all missiles will be operating in the atmosphere during the ascent phase and some in the entry period, flutter must still be considered as a definite design condition. To support missile and spacecraft design, continued effort is required to define the unsteady forces which can result in flutter of surfaces and bodies at hypersonic speeds. In particular, there has been some evidence that piston theory becomes unconservative at Mach number greater than 6, so continued effort in regard to both theory and experiment is in order. Flutter research is required on typical lifting surfaces above a Mach number of 3 to evaluate theoretical flutter methods applicable to advanced configurations and to establish flutter prevention design criteria for future systems.

An extension of theory to the determination of hypersonic unsteady aerodynamic coefficients for low-aspect-ratio wings, including body, and wing and body combinations, is required. Flutter stability equations may contain nonconstant coefficients and nonlinearities because of time-variant and nonlinear aerodynamic coefficients. Work is required to extend current efforts for the approximate solution of these equations. Chordwise bending modes must be considered in the aeroelastic analysis of thin, low-aspect-ratio wings. Quasi-steady and indicial methods of flutter analysis for these advanced configurations must be developed to include effects of dynamic pressure, temperature, and Mach number.

BUFFETING

Another severe dynamic problem is transonic buffeting, particularly on long, slender launch vehicles with a bulbous payload. The random input forces to rigid bodies have been measured on a few configurations. The data available present information on the amplitude and frequency content at local stations. Information is needed concerning the correlation of these fluctuations, both peripherally and longitudinally. In addition, the possibility of coupling due to structural response exists and needs clarification. Two types of structural response need studying: one involving bending in free-free modes of the vehicle, and the other the coupling due to local response of the shell structure; with recognition of the fact that in regions of first and second stage attachment, stress loads from either or both types of structural response can occur. In atmospheric flight, the forces associated with atmospheric disturbances, such as gusts and wind shear, and the forces associated with the relatively long period motion associated with vehicle stability should have special attention. In particular, the indicial force functions on bodies are of particular interest in booster design (equivalent to the Wagner function or the Kussner function on wings).

ENTRY

Reentry vehicles are going to be required to make more and more sophisticated maneuvers. Both ballistic-type vehicles, like nose cones, and lifting reentry-type vehicles, such as might be used for manned reentry, will be expected to be able to correct their trajectory during reentry. In order to enable the required maneuvers, some kind of control fins or other aerodynamic surfaces will have to be included on the vehicle. These control surfaces will be subjected to reentry heating as well as to the aerodynamic forces which they are there to produce. Therefore, the structural dynamic problems will be both those associated with the vehicle as a whole and the more local ones associated with the control surfaces. Aerothermoelastic effects are also particularly associated with such reentry aids as the para-glider. Any such device, which is a very flexible, light structure subjected to both the heating of reentry and the aerodynamic forces of hypersonic flow, probably embodies the most critical aerothermoelastic problem that can be considered. Aerothermoelastic problems associated with atmosphere entry are severe because extreme heating produces temperatures very near, or actually equal to, the melting point or boiling point of the surface material. The material is then at minimum strength and stiffness and is likely to be on the verge of collapse or flutter. Indeed, it appears that these aerothermoelastic problems are among the most difficult problems now confronting structural dynamicists.

APPENDIX E

FLUID DYNAMICS

Some of the fluid dynamics problems that affect the structural design of missiles and spacecraft are: propellant sloshing, propellant utilization, and "zero-g" effects. The interactions between the fluid, the structure and the control system have important implications in the design criteria for the structure and even the vehicle configuration.

Propellant sloshing has been recognized for several years as a problem in the design of liquid propelled vehicles. Extensive effort has been expended by various agencies but a great deal of work remains to be done. Theoretical and experimental work has been limited to the consideration of tanks of geometrically simple designs. Multiple tank configurations have not been studied in any detail nor have the systems interactions of propellant motion with vehicle control systems, structures, and other subsystems. The use of clustered propellant tanks, multistage missiles with off-loaded upper stages, and larger, more complex systems makes further work imperative. Considerations must also be given to the trend toward more flexible tanks and their interactions with fluid motions. Experimental and theoretical work should be extended to consider more complex excitations including rotation. The study of damping devices and means of installing them in thin-walled tanks should be extended. Configuration studies of tankage systems may result in new design concepts. The peculiar characteristics of cryogenic fluids should be investigated, including the effect of rapid cooling of the pressurizing gas and the resultant effect on structural dynamics behavior as well as pressure system design.

Effective means of insuring high utilization of propellants is essential, in order to avoid penalties in the form of large amounts of unused propellants, and to be able to predict and rely on repeatability of thrust decay transients. Two important areas of study for solutions to these problems are low-level sloshing and the formation and behavior of vortices, including the effective use of baffles. The use of expulsion bladders is another promising means of reducing residual fuel and is being considered for small noncryogenic propulsion systems. Work should be extended to include cryogenic systems. The effects of these bladders on the sloshing and vortexing behavior of fluids should be studied and their effectiveness in reducing reserve requirements should be determined.

An understanding of the behavior of fluids in low or zero gravity fields is important for the successful design of upper stage and spacecraft propulsion systems. Considerable research on this problem is currently being pursued or proposed. Experimental techniques include drop tests, aircraft flying ballistic trajectories with free floating research packages in the cabin, and sounding rockets with fluid dynamic experiments in the payload compartment. The maximum time available at zero gravity conditions varies from a few seconds in the drop tests to 20 seconds in airplane flights to 5 minutes in Aerobee sounding rockets. The zero gravity studies under way are directed toward:

(1) Developing techniques for venting cryogenic tanks

(2) Understanding the transient behavior of contained liquids

(3) Developing techniques for settling the ullage bubble for engine start after a zero gravity coast period

(4) Understanding the mechanism of heat transfer to liquids

(5) Developing liquid transfer techniques for thermodynamic power systems

(6) Developing techniques for measuring the amount of liquid in a tank during coast or very low thrust periods

This work should be continued, and extended to study the effects of zero gravity conditions on the forces applied by the fluid to its container.

APPENDIX F

VIBRATION

Structural vibration involves the interaction between exciting forces, structural internal forces, and inertial forces. The exciting forces can arise from several sources, such as mechanical shaking, propulsion pressures, aerodynamic pressures, and so forth, and can be periodic or random in nature. The structural forces may consist of elastic or inelastic restoring forces, damping forces, or others. In general, the problems associated with vibration are concerned with the understanding and definition of the force inputs, the responses of the structure to the inputs, and evaluation of the behavior of the system to judge its performance suitability. Additional research effort is required in all of these areas.

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Continued effort is required to develop techniques for the measurement and calculation of the structural dynamic characteristics, such as modes, frequencies, and damping, of complex systems. New problems will arise with the use of large boosters consisting of many bodies clustered together, in the use of inflatable structures made of thin membranes, and in composite structures such as propellant filled cases in which there is a combination of elastic and visco-elastic materials. Structures which are designed to have very high damping will probably involve the development of new techniques for analysis; the effects of extremes of heat or cold on the structures' nominal characteristics must be considered; and the effects of variations of mass with time must also be taken into account in more sophisticated analyses of system characteristics.

Research on how to avoid unstable combustion and intermittent separation in nozzles which are overexpanded needs continuing effort. In addition, consideration of dynamic response of structures to engine thrust variations must include effort to distinguish the effects of multiengine configurations where actual tolerances on thrust level, buildup rates and decay rates are of known significance. In this situation simultaneous response of separate elastic components will be fed into a common structure.

The literature indicates that the relation between random input and random response can be determined analytically provided the relations between nonrandom input and response are known. For the nonrandom case, considerable analytical work remains to be done in unsteady aerodynamics, fuel sloshing, and structural damping.

It is suggested that many flights of all types of vehicles should be instrumented to obtain records of vibration environment from engine start to final separation. The method of instrumenting in order to obtain the correct information is critically important because the information must not only indicate local strain and/or deformations but must also be able to locate the origin and cause of the input. It seems that at least four types of information would be needed, local strains, accelerations, some pressures, and probably angle of attack. It also appears that time histories of the signals will be needed in order to have some hope of determining the source of any specific response.

The problem of acoustic excitation deserves considerable attention from the viewpoint of the structural effects produced. This problem is aggravated in the case of the enormous boosters for space vehicles now under development. Such excitation will be capable of inducing failures even in substantial structural elements, to say nothing of the many space vehicle components which, because of their necessarily flimsy character, are in great danger of failure during launching. We have not developed the ability to predict near-field sound levels of different type rocket or turbo-power plants by analytical methods, and must depend upon actual field tests. At the present time, the structure design is based on estimated data and is merely proof tested. It is essential that flimsy structures be adequately supported or packaged so that the acoustic loading does not induce fatigue failures. The problem is one of design with proper consideration to the vibration response of the structure or mounted component. Proper mounting, together with proper fatigue design, will result in a reliable structure. Research is needed into acoustic fatigue tolerance levels of current and future structural element combinations. The effects of added environments and loadings, such as temperature and steady-state stress, must be determined. Design criteria for sonic fatigue must be improved to produce adequate structures. There should also be investigations for control of propulsion noise at its source, by isolation and suppression devices, to reduce acoustic structural loading.

Research is also needed to improve methods of predicting aerodynamic noise, particularly at supersonic and hypersonic speeds. In addition to noise generated by flow separation and fluctuating shocks in the neighborhood of the boundary layer, emphasis should be placed on base pressure fluctuations in the wake of a blunt body. In addition, because launching of space vehicles may occur at altitude, the effects of noise must be studied at altitude as well as on the ground. These studies should be coordinated with those of noise effects on boosters and tanks, on ground support equipment, and on personnel, for they are directly related to the need for improved noise suppression techniques.

It is highly desirable to obtain, by analysis, the sound level distribution for a given flight vehicle system and then be able to analyze the sound propagation effects on and through the structure, so that more efficient structures can be designed. In regard to rocket engine noise, an immediate effort should be devoted to publishing noise data obtained during firings. Measurements around large rockets are of particular interest for the purpose of verifying available noise prediction methods.

APPENDIX G

SHOCK AND IMPACT

The problems associated with shock and impact are generally concerned with the sudden or impulsive applications of loads or displacements, the impingements between bodies, and the transient responses and wave propagation in structures. There are many areas for which research is required to establish useful design parameters for missile and space vehicles, including the definition of the exciting forces or shock spectrum, the analysis of the structural responses, and the establishment of criteria of acceptable performance.

The importance of the meteoroid impact problem has been recognized and progress has been made in the ability to propel particles to higher velocity, with 30,000 feet per second having been attained, and somewhat higher velicities apparently attainable. Mean meteoroid velocities are probably on the order of 70,000 feet per second, so that the need for obtaining higher velocities is extremely important and should be pursued with a maximum of effort.

An equally important objective is the determination of the meteoroid hazard by the use of space experiments. The exposure of test surfaces in order to assess the mechanics of the damage incurred has been suggested. It now appears appropriate to include consideration of the type of experiment that can obtain velocity and density information in order to establish the accuracy of the various estimates of this space hazard.

Of major concern to the dynamic design of space structures will be the effect of meteoroid penetration and partial penetration on stressed structural elements. This requires the ability to analyze stress wave propagation in shells and composites both parallel to the surface and through the thickness. Both elastic and inelastic effects must be included. Methods must be developed which will quantitatively predict the behavior of practical structures to impulsive loads of microseconds duration. It is also important to investigate the effects of impact in fluid-filled containers simulating liquid propellant fuel tanks and liquid metal radiators. Also of interest are the effects of penetration of pressure vessels. There appears to be little design-type information of a basic nature regarding the explosive failure mode in pressure vessels and its limits as affected by the pertinent configuration and materials parameters. The boundary separating the case of simple puncture and the case of explosive failure may be affected to some extent by the dynamics of impact.

The problem of water entry has been of interest in the areas of torpedo development and ship slamming. The interest continues in these fields and is arising in some new areas associated with rocket development. These areas are:

1. Design of data recovery systems.

2. Design of manned vehicles such as Mercury and Dyna-Soar which may land in water under emergency conditions.

Methods are required which will allow a quantitative prediction of the pressure history over the entire surface of the body from the time of first impact through the time that flow is established. Existing theoretical approaches assume that piston theory applies for the first period after impact and that expanding disk theory applies after flow is established. These methods are crude and fail to predict the pressure distribution during the time flow is developing. Analytical techniques should be developed which account for fluid compressibility, surface wave generation, and the establishment of flow. The method should be flexible enough to permit the evaluation of the effect of interaction between the fluid and structural deformation. The pressure-time relationship on bodies entering water at velocities up to 1,000 feet per second should be measured experimentally and correlated with analysis. Serious efforts will be required to develop test methods and instrumentation for the quantitative measurements required.

The attenuation of impact loads on land surfaces requires further study of devices such as crushable structures and inflated shells. In the area of inflated shells more advanced analytical solutions are needed to predict with greater accuracy the behavior of these shock attenuation devices.

Many thin-shelled structures, such as fuel tanks, are subjected to various types of pressure pulses arising in connection with engine starts, pressure buildup in launching from silos, internal tank pressure variations, and many others. Studies should be made to determine the nature of these pulses and then to establish methods for determining the response of the structures and modes of failure, such as buckling, under these conditions.

Considerable authoritative data are required on the nature of transportation and handling loads such as occur during truck, rail, air, and ship transportation and the associated handling. Studies of methods for structural protection from these dynamic environments should be conducted. Also of interest are the conditions and requirements for moving a vehicle over an alien surface, such as that of the moon. Terrain and unusual gravity effects are factors to consider in the study.

Experimental and analytical studies are required to establish methods and conditions for the determination of response of structures having nonlinear stiffnesses. Of particular interest is the possibility of using nonlinear devices for shock isolation.

APPENDIX H

GUIDANCE AND CONTROL

The interaction between structural vibratory motion and the control servo system has become increasingly difficult to control. When bending resonances are very close to the bands of frequencies to which the controls respond, a troublesome situation results. It is apparent that a dual approach to these problems is necessary, with the structural dynamicist becoming fully aware of the potential solutions offered by controls refinements, as well as the need for more sophisticated dynamics analysis of the problems. For instance, for large and heavy boosters with greater length-to-diameter ratios, particularly those in clustered configurations, rigid body dynamic stability consideration alone is inadequate for control system design. The structural flexibility effect may dictate the requirement for sensor locations, control gains, and, at times, the choice of control law for system stability. The loads experienced by the structure in flight are also strongly affected by the control system as well as the vehicle flexibility. Current practice of aeroservoelastic analysis has been based on relatively simple concepts, for example, treatment of the problem as a linear system with constant coefficients, operation under a simple control law, and subject to an environment in the form of a statistical envelope. Full appreciation of the interaction problem requires further work in more sophisticated analysis of the problem, in refining methods of solution, and in parametric evaluation of results. Complete representation of the physical problems requires exacting specification of all inputs that affect the dynamic system, for example, the structure, the external environment, the control system, the internal mass characteristics, etc. The structure description should include thermal effects, both transient and steady-state, as well as nonlinearities due to large deflections. Refined aerodynamic representation should be available for transient motion throughout the speed range, for large angles and for accelerated flight. The control system description should include dead spot, hysteresis, limit-stop property, and any adaptive characteristics present. The effect of internal motions of stored mass, particularly for liquid propellants, and the effects of mass depletion require consideration. The formulation which includes the above considerations will result in a set of nonlinear simultaneous differential equations with time-variant coefficients. Research effort should be devoted to developing practical mechanized solutions for such problems. Inasmuch as the aeroservoelastic interaction is highly time-dependent, a review of conventional criteria for system stability is urgently needed. The damping in displacement response may be entirely different from that in acceleration response. The requirement for positive damping at all instants of flight may be overly restrictive and may unnecessarily penalize the system design. If loads or guidance requirements are the quantities to impose the ultimate limitations on system responses, then an instantaneous divergence may very well be acceptable. Before such an approach can be adopted, however, research must be devoted to a much more refined definition of disturbance environment such as wind shear and gust in appropriate statistical form.

On the other hand, the efforts of the structural dynamicist might be aided if it were possible to design a control system that can regulate the structural dynamics. If the gimbal actuator can respond enough to cause problems, the same actuator can reasonably be used to introduce corrective action, if it knows what action to take. This implies sensors capable of measuring the undesired bending motions, and introduction of this information into a control box to damp the motion by gimbal manipulation. Although this is clearly a controls problem, it is tied into the structural dynamics problem and its solution would remove some of the vehicle design constraints.

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APPENDIX I

DYNAMIC TESTING

Dynamic testing of flight structures and models increases in importance as configurations become more complex, stiffness decreases due to increased emphasis on weight efficiency, and more detailed results of dynamic analyses are required in response to increased emphasis on reliability. Some of the important and obvious reasons for dynamic testing are to provide proof of new analytical techniques; to determine quantities needed in analysis but not obtainable analytically, such as the stiffness of a structure at elevated temperatures and equivalent structural damping, or an effective structural impedance; to uncover problems inadvertently overlooked; and to provide proof of performance. Both testing techniques and test requirements are areas which require extensive development.

In the area of testing techniques dynamic model testing should be studied. Model testing is needed for the many repetitive tests designed to increase understanding of dynamic behavior when prototype testing is impractical. It is useful as a time- and money-saving device in more limited programs. Research in this area is needed to determine the adequacy of current model fabrication techniques and to develop new methods of fabrication and testing. Correlation between model and prototype testing is required to indicate areas requiring further study and to suggest the optimum utility of model techniques.

The techniques used in testing are dependent on the equipment available. Some of the pressing needs for equipment include a high powered, random vibration generator with sufficient flexibility to provide shaped, mean-squared acceleration spectra over a wide frequency band. A shaker or shaker system capable of exerting large forces at low frequencies is required for testing large structures having low natural frequencies. It should be able to provide both random and clear sine wave excitation. The ability to perform vibration testing in a vacuum should be provided. Flight instrumentation, telemetry, and on-board data reduction equipment should be developed to permit making adequate flight vibration measurements. Acoustic generators are needed for sonic fatigue testing. Heating structures during ground vibration tests is desirable as is the instrumentation technique needed to measure the frequencies and mode shapes of hot structures.

The method of mounting structures during vibration tests must also be studied along with the interaction between structure, shaker, and control system to insure complete understanding of what is being done in ground vibration testing.

Test requirements and testing philosophy for structures and components at both the system and subsystem level must be re-evaluated continuously in the light of past experience. Ground testing, flight testing, and analysis should be correlated whenever possible to determine the adequacy of current test techniques and requirements. Research should be started to determine whether simplified test procedures can be formulated which will still insure adequate testing.

Criteria for the flight evaluation of structural integrity must be improved and techniques for completely testing large vehicles on the ground should be developed. The results of this study should then be integrated so that adequate combinations of ground and flight tests may be determined.

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APPENDIX J

MATERIALS PROPERTIES

The importance of the interaction between the dynamic characteristics of structures and materials properties is evident. The significance of materials development in structural design suggests that it is desirable for structures and materials engineers to work closely together to produce improved materials having the properties most needed for structural design. It is hard to demonstrate that until recently there has been any substantial cooperation between materials developers and structural designers. There are two outstanding examples of this lack of cooperation: (1) Because the structural designer has not communicated the importance of low material density to the materials developer, there has been no real effort to develop low-density structural materials; (2) because it admirably suits his purposes, the developer of materials has so concentrated on the "modulus of rupture" test that the structures man has not been able to use materials of potential merit, for meaningful mechanical property data have not been available. Increased cooperation between materials developers and structural users should be immensely profitable in obtaining improved structural materials. To begin with, the structural designer must define clearly the desirable material properties for the various flight applications. The following sections present some of the more promising areas of research and development for materials properties required for mitigation of dynamics problems.

Five outstanding examples of special material properties needed are: (1) internal damping, (2) impact resistance, (3) resistance to crack propagation, (4) resistance to meteoroid penetration, and (5) shock energy absorption.

Investigations are needed to identify optimum methods for determination of energy absorption and transmission characteristics of varied materials. Definition of damping characteristics as a function of such parameters as temperature, pressure, geometry, joining techniques, and combinations thereof would result in more flexibility in optimization of structure design. Most common structural materials have a relatively small amount of inherent internal damping. This does not mean that materials may not be developed which have a relatively large amount of internal damping combined with adequate strength and stiffness to be useful as structural materials. For example, the foamed plastics may be formulated to have large internal damping combined with reasonable stiffness and strength. Proper combinations of foaming (as in sandwich cores) with structural properties may result in composite materials useful for a number of structural vibration problems which would otherwise be difficult to solve. Another possibility is the use of rather flimsy core members which, under vibration loads, tend to buckle and unbuckle, would provide a form of internal damping. The entire field of development of structures and materials with internal damping for solutions to vibration problems is relatively unexplored, and potentially fruitful.

Materials with high resistance to impact are not as novel as those with high internal damping. For years, some civil engineering structures have required materials which could withstand rather violent impact. An essential difference between such structures and space vehicles or missiles is that the latter do not necessarily have to be in perfect shape after withstanding the impact since they are not intended for reuse. Therefore, for vehicle use, materials which can provide impact resistance even though suffering permanent deformation may be of great value. Thus, the path seems to lie along the development of materials with extremely high ductility combined with a high work hardening characteristic.

The dynamics of crack propagation, particularly in structures such as pressure vessels, is of great importance in space vehicle design. Cracks may be initiated by a meteoroid puncture or, more commonly, by fatigue, but control of propagation of the crack is extremely important. It would seem that materials with a low notch sensitivity, or perhaps having a low sound velocity, are desirable. Of particular importance are crack-resistant materials for cryogenic temperatures, for which the selection is very limited at present. The development of materials with suitable dynamic properties at very low temperatures is essential.

Although data are not available on material penetration by particles at meteoroid velocities, there is evidence that the depth of penetration is probably related to the density and Young's modulus of the material. Low density is probably of greater value than stiffness, so it is conceivable that new, low density materials may be developed specifically to provide increased resistance to meteoroid penetration, as in a space vehicle "bumper" design.

Another dynamic material property of great importance to structural engineers is the phenomenon of the strength increase of a large number of structural metals with increased strain rates. When additional test data can be made available for materials at various strain rates, methods can be developed for incorporating this knowledge into design criteria and structural analysis.

The problem of shock attenuation on landings is a problem of concern. Crushable material is a very efficient shock absorber, but it is difficult to attain significant attenuation in more than one direction.

APPENDIX K

SPECIAL PROBLEMS

The rapid pace of advancements in space exploration and return has created several special problems which do not lend themselves to classification by the categories used in this report. Some of these problems are discussed herein, and the list will inevitably grow with time.

ERECTABLE STRUCTURES

The necessity for post-launch area enlargements or erection of antennas, reflectors, collectors and drag devices, and boom-mounted sensors creates special problems for the structural designer, who must work closely with the controls designer. Since these structures will generally be large and flimsy and will require accurate, rapid control, the design principles and concepts must be arrived at jointly. Experimental and analytical studies should be initiated on the modes and effects of vibratory oscillations of large, light-weight structures, simulating the free-free state in vacuo. The reactions of these devices on the parent vehicle, particularly those designed to minimize the atmosphere entry aerodynamic heating problem, are discussed below.

PASSIVE ENTRY AIDS

Parachutes, ribbon chutes, paragliders, and "ballutes" are attractive devices which can be used passively, except for initial deployment, to aid a body to survive atmosphere entry and landing on a planetary surface. These aids induce a number of dynamic structural problems. For example, the opening of the drag-brake or the deployment of the paraglider will produce a sudden load on the spacecraft. This load will be transmitted through shrouds or similar devices and will be reflected upon the entry aid itself. The resulting problems are both structural and aerodynamic in nature because, if a suitable design of shroud lines and entry aids is not made, an instability could be produced comparable to a slow flutter or oscillation which might be catastrophic. This same type of instability is observed in parachutes, for example, in the lower reaches of the atmosphere. The stabilizing or destablizing effects of these aids during the aerodynamic regime in which they are used are important. In planetary entry, time of descent is an important design parameter and must be known or predictable for all these devices, even in an atmosphere whose properties are only partially known. The dynamic behavior of the body-aid combination just before landing is also important since it influences design of impact protection devices and mounting of equipment in the vehicle.

NUCLEAR PROPULSION SYSTEMS

Nuclear reactors cause rather unique design problems because the experimental tests that can be conducted are extremely limited both by the cost of systems and by the radioactivity that results after running, which makes it difficult to inspect components, take corrective action, and continue testing. It therefore becomes necessary to increase the amount of dynamic analysis of the structures and improve the analytical methods many-fold over those required for nonnuclear power sources. It also means that improved simulation devices are required to study the dynamic characteristics of parts affected by the reactor without encountering the problem of radioactivity. Some of the problems that will be encountered and that require study are: fuel element flutter and vibration; thermal stress and fatigue effects; servo control mechanisms in the nuclear and thermal field of the reactor; and thermal effects on surrounding components resulting from nuclear radiation.

BIO-DYNAMICS

The dynamics of the animal body in a zero-g condition, or in a rotating system designed to provide an artificial gravity, must be studied along with the biological or physiological responses of animals. An analytical study of this problem is bound to be helpful in showing ways in which man can perform his normal functions in this new gravitational environment. In particular, the effects of Coriolis forces in the rotating environment will require considerable study, leading to meaningful ground training of men in centrifuges to prepare them for the new environment.

In addition, there are many situations in which people are a part of a system undergoing vibration or shock motions. It is conceivable that the dynamic characteristics of the body must be taken into account in determining the response of the system. The dynamic characteristics of the human body as well as the body's response to dynamic environment should be studied.

VEHICLE ROTATION

There are two prime sources for rotational structural dynamics problems in space vehicles. These sources are either a spin, de-spin, or similar type of attitude control maneuver, or a more gradual rotation to produce an "artificial gravity." Spin-up for attitude stabilization is not uncommon, and in many cases a de-spin maneuver is required. Some of the de-spin maneuvers (such as the "yo-yo" de-spin device) can be fairly violent and produce appreciable impact-type loadings on the spacecraft. A rotation to produce a gravitational type field in the vehicle will probably not be so violent, but shifts of mass within the vehicle will produce dynamics problems. For instance, crew members may move around, fuel will be expended, or for other reasons the center of mass may change, resulting in a wobble or vibration of the vehicle. Thin-walled or flimsy structures could respond in various modes of vibration. In addition, all rotating space vehicles will experience a cyclic stress due to local changes in temperature as exposure to solar radiation varies. For very flimsy structures which may have a period of vibration close to the period of rotation, severe resonance problems may result.

APPENDIX L

ENVIRONMENTAL OCCURRENCES OF PROBLEMS

The previous appendixes contain discussions of the missile and spacecraft structural dynamics problems classified by the principal specializations or disciplines used in their solution. It is also significant, however, in understanding the broad scope of these problems and their effects on all phases of a vehicle's life, to identify the various environmental conditions to which the vehicle is subjected in which the problems occur. It will be noted that many of the problems appear, in one form or another, in several environments (shock, for instance), lending emphasis to the need for considering the cumulative effects of all environments in evaluating the relative importance of any type of excitation on a structure.

I. Prelaunch

   A. System and Component Testing

      1. Realistic specification of test requirements

      2. Establishment of test techniques such as consideration of sinusoidal equivalents of random vibration

      3. Effects of testing on structure degradation

   B. Transportation Handling, Erection and Placement

      1. Measurement and specification of meaningful shock and vibration loadings

      2. Determination of response of structure

      3. Establishment of allowable structural loads and stresses

      4. Investigation of isolation devices

   C. Fueling

      1. Thermal shock effects of cold fluids in warm tanks

      2. Dynamic effect of boiling liquids

   D. Protection of Missile or Spacecraft at Launch Site

      1. Specification of air blast or ground motions due to accidental detonation or offensive attack

2. Isolation of missile from blast effects

3. Dynamic effects of thermal radiation

E. Weather

1. Dynamic response of missile due to ground winds and vortex shedding

2. Differential heating effects

F. Taxiing

1. Effects of motion on ground for long slender configurations with and without full fuel loads

II. Launch

A. Engine Start Transient

1. Measurement of engine start characteristics and determination of response of structure

B. Release Shocks

1. Response of structure caused by sudden release

C. Pressure Pulses

1. Shock wave effects on structure from engine start or in-silo environment

2. Determination of structure buckling in transient pressure fields

3. Coupling of acoustic energy to structure; structural and component responses and fatigue damage

4. Response of nonlinear elements to random pressure loadings

D. Engine Combustion Instabilities

1. Determination of engine input characteristics

2. Response of structure to random vibration

3. Effects of damping and nonlinearity

4. Interaction of engine thrust characteristics and structural motions

E. Launch From Water

1. Determination of forces acting on missile

2. Hydroelastic interactions

3. Interface, air-to-water dynamics

F. System Interactions A620

1. Determination of responses during the simultaneous effects of release conditions, control forces, engine motions and thrust, propellant sloshing and ground winds

G. Take-Off Ground Run

1. Effects on long slender configurations

III. Flight in Atmosphere

Various processes occur during the boost phase of the flight in addition to the aerodynamic forces which may be critical.

A. System Interactions - Determination of the over-all responses of the flexible structure under the simultaneous interactions of:

1. Aerodynamic forces including buffeting and flutter

2. Control system characteristics and engine gimbaling dynamics

3. Engine thrust variations and random excitations

4. Motion of propellant sloshing and vortexing

5. Mass flow effects of center of gravity change, moments of inertia and damping

B. Internal Pressure Variations

1. Effects of pressure change in propellant tanks or interstages

C. Staging Transients - Transient forces and responses to staging procedures such as:

1. Separation forces caused by sudden release

2. Thrust build up and decay

3. Gas impingements between stages

4. Control motions and forces

D. Aerodynamic Heating

IV. Space Flight

Many of the same problems occur in the space flight phase as in the atmospheric flight except for the effects of aerodynamic forces. In addition there are:

A. Attitude and Altitude Control - Measurement and specification of:

1. Drag effects

2. Magnetic field

3. Radiation pressures

4. Internal forces such as rotating machinery, fluid motions or biological experiments

B. Attitude Response - Responses to the above environment with concern for such factors as:

1. Structures with very low natural frequencies

2. Active and passive control dampers

3. Motion and stability of fluids in low g environment

C. Heating

1. Internal or external heating such as solar heating or thermal control

D. Propellant Utilization

1. Dynamic effect of systems for utilization of propellants at low g

E. Rotation for Artificial Gravity

F. Rendezvous

   1. Transportation, handling and fabrication of structures in space

G. Spin and De-spin

   1. Effects of impulses, yo-yo devices, etc.

H. Crews

   1. Human reactions to attitude changes

I. Meteoroid Impacts

   1. Conditions for crack propagation

   2. Design of protection devices

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V. Entry

Many of the problems encountered in entry are similar to the atmospheric boost flight problems. In addition:

A. Thermal Shock and Heating

   1. Effect of intense thermal environment

   2. System interaction of aerothermal elasticity

B. Aerodynamic Noise

   1. Fatigue of structures with high intensity acoustic energy

C. Flutter and Buffeting

   1. Panel and control surface aerothermal elasticity

D. Control

   1. Maneuver of winged and unwinged vehicles

E. Planet Atmosphere

   1. Determination of characteristics of extra terrestrial atmosphere and environment

VI. Landing

There are special problems concerned with landing depending on the requirements for a hard or soft landing, the nature of the terrain, and unknown conditions.

A. Attitude and Altitude Control

1. Dynamics associated with control by aerodynamic surfaces or thrust devices

B. Landing Shock Control - Active or passive devices to limit landing impact, such as:

1. Crushable structures

2. Hydraulic pneumatic systems

3. Retrorockets

C. Surface Condition

1. Measurement and specification of surface conditions on extra terrestrial bodies

D. Air Snatch

1. Forces, maneuvers and conditions for air recovery

E. Water Landing

1. Hydrodynamic effects of water impact

F. Ground Roll

1. Directional control, stability and dynamic response

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An attempt is made to indicate the research studies which should be vigorously supported in order to provide necessary information for the solution of structural dynamic problems of missile and space vehicles. The problem areas are discussed in terms of the disciplines or functions required in their solution. Among the latter are: (1) interactions of the complete system and the environment, (2) criteria for design conditions and performance, (3) interactions of aerodynamic forces with flexible structures, (4) motion of liquids, (5) vibration, (6) impulsive loading and transient responses, (7) guidance and control, (8) testing, and (9) materials considerations. In addition, some (over)

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