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SPACE VEHICLE
DESIGN CRITERIA
(STRUCTURES)

NASA SP-8030

TRANSIENT LOADS FROM THRUST EXCITATION

FEBRUARY 1969

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion.

Individual components of this work will be issued as separate monographs as soon as they are completed. A list of all previously issued monographs in this series can be found on the last page of this document.

These monographs are to be regarded as guides to design and not as NASA requirements, except as may be specified in formal project specifications. It is expected, however, that the criteria sections of these documents, revised as experience may indicate to be desirable, eventually will become uniform design requirements for NASA space vehicles.

This monograph was prepared under the cognizance of the Langley Research Center. The Task Manager was T. L. Coleman. The author was R. L. Goldman of the Research Institute for Advanced Studies of Martin Marietta Corporation, while under subcontract to Avir Associates, Incorporated. A number of other individuals assisted in developing the material and reviewing the drafts. In particular, the significant contributions made by S. A. Clevenson and V. L. Alley, Jr., of NASA Langley Research Center; A. P. Goldberg of TRW Systems; and J. I. Orlando of McDonnell Douglas Corporation are hereby acknowledged.

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TRANSIENT LOADS FROM THRUST EXCITATION

1. INTRODUCTION

Transient loads from thrust excitation are the short-duration dynamic loads or rapidly changing axial forces induced by the ignition and shutdown of solid- and liquid-propellant rocket engines. Internal stresses are produced in the space vehicle as it is forced to deform to these transient loads.

If not properly accounted for, these transient loads can damage a space vehicle by overloading the vehicle's structure. Such damage has already caused launch-vehicle failures, some of which have been traced to the incompatibility of the vehicle's structural design with its engine's ignition characteristics. As an example, a vehicle was destroyed when the thrust-transient loads overstressed the structure and caused a rupture in a propellant-tank bulkhead. Other failures may occur when the transient loads produce damaging stresses in structural and mechanical parts, and induce malfunctions in hydraulic, mechanical, and electromechanical components.

This monograph presents criteria and recommends practices for the analysis of transient loads that arise from an engine's thrust excitation during normal prelaunch, launch, and flight operations. The transient loads considered in this monograph are those induced by the ignition or shutdown of solid- and liquid-propellant rocket engines, and include the influence of effects resulting from release mechanisms, launch-stand dynamics, stored elastic energy, and staggering. Abnormal thrust conditions caused by engine malfunction, such as unanticipated ejection of an igniter in a solid-propellant engine, are beyond the scope of this monograph, although they may be critical to structural design.

Methods of analysis treated herein are appropriate for designing space vehicle basic structure. Local effects induced by sharp-edged short-duration impulses, which are important to the design of onboard equipment, require other analyses that are covered in a planned monograph on mechanical shock induced by explosives. Treatment of other thrust transient related phenomena such as vibration acoustic noise, slosh, and pogo will also be covered in later monographs in the series (e.g., ref. 1).

2. STATE OF THE ART

There are two major problems in designing a space-vehicle structure to withstand transient loads from thrust excitation. One is how to provide an adequate description of the input forces and the other is how to determine accurately the response to these forces. In practice, the first problem is resolved by using experimental data (engine test or flight data) when available, as thrust-loading inputs. The vehicle is then simulated by a dynamic model, which is translated into equation form. Finally, the equations formulated in the model are solved by one of several techniques to determine the theoretical response of the structure in terms of stresses, forces, and motions. Solution of these equations by direct extension of the classical theory of stress-wave propagation in elastic media (ref. 2) is complex. Present-day designers use approximate analytical methods that are compatible with high-speed, large-capacity digital computers.

2.1 Thrust Inputs

The thrust inputs to the vehicle structure from rocket engines during thrust buildup at engine ignition and thrust decay at engine shutdown are described by *time histories* of thrust for each engine. These time histories are represented by graphs of resultant force or pressure for a given engine versus time, and are obtained, whenever possible, from static engine firings or flight-test data. Time histories may also be used to produce *Fourier spectra* or *shock spectra.*

Static engine firings are the usual source of thrust-input data. It is often difficult to obtain acceptable readings from static engine firings because the measurements may be adversely affected by the dynamic properties of the measuring instruments or by the flexibility of the test stand. Methods of overcoming these difficulties are discussed in reference 3, which shows how accurate data can be obtained through the proper choice of instrumentation, data-reduction techniques, and test-stand design.

Thrust-input curves are usually obtained from force measurements at the engine's attachment points to the vehicle's structure. For solid-propellant engines, however, chamber-pressure measurements have been used to obtain time histories of pressure distributions.

Thrust-input curves for rocket engines have also been synthesized from flight-test data. In this procedure, the thrust input is deduced from transient pressure and acceleration measured by carefully positioned flight transducers. Various techniques for obtaining thrust-decay data from flight measurements on liquid-propellant engines are compared in reference 4. Flight data, if available, are preferred over ground-test data as a source of information on burnout transients because flight conditions cannot be accurately simulated in ground tests.

Thrust data are usually characterized by initial peaks and oscillations which converge to a steady-state value. The data must include the correct magnitude of these peaks, their decay characteristics, and frequency content. These transient characteristics will vary to some degree with each firing and with each engine, and in most instances the statistical nature of these variations has been an important design consideration.

Thrust-input data can be obtained from engine manufacturers who normally maintain engine-performance records of firings. A critical evaluation of the measuring technique is usually made to ensure that the instrumentation used in collecting the data is appropriate. For example, instruments with unrealistically slow rise times will not provide correct data for transient-response purposes.

2.1.1 Thrust Buildup or Ignition

With the development of newer ballistic missiles and larger rocket engines, sufficient knowledge has been accumulated so that realistic thrust buildup of both liquid- and solid-propellant engines can be predicted from ground-test data. Examples of typical thrust-buildup curves from static firings of liquid-propellant and solid-propellant engines are shown in figures 1 and 2. These figures demonstrate that different propulsion systems have different thrust-buildup curves. Single engines or different engines of the same design also exhibit variations of thrust input, and consequently have significant differences in thrust-buildup curves. As discussed in Section 2.1.4, the usual procedure is to conduct many static firings to establish the statistical nature of the ignition-thrust input.

2.1.2 Thrust Decay or Shutdown

The abrupt decay of thrust, or thrust "tail-off," at engine shutdown produces transient responses that are influenced by the sudden release of the strain energy stored in the structure. In effect, the structure is strained by the steady-state flight loads into a static equilibrium shape. At thrust decay, the structure adjusts rapidly to a new equilibrium position. In the process of adjusting, high tension or compression stresses may be produced in such structural elements as propellant tanks and external shell walls. These stresses may be critical if, for example, a joint designed for high compressive stresses is too weak to sustain the transient tension stresses.

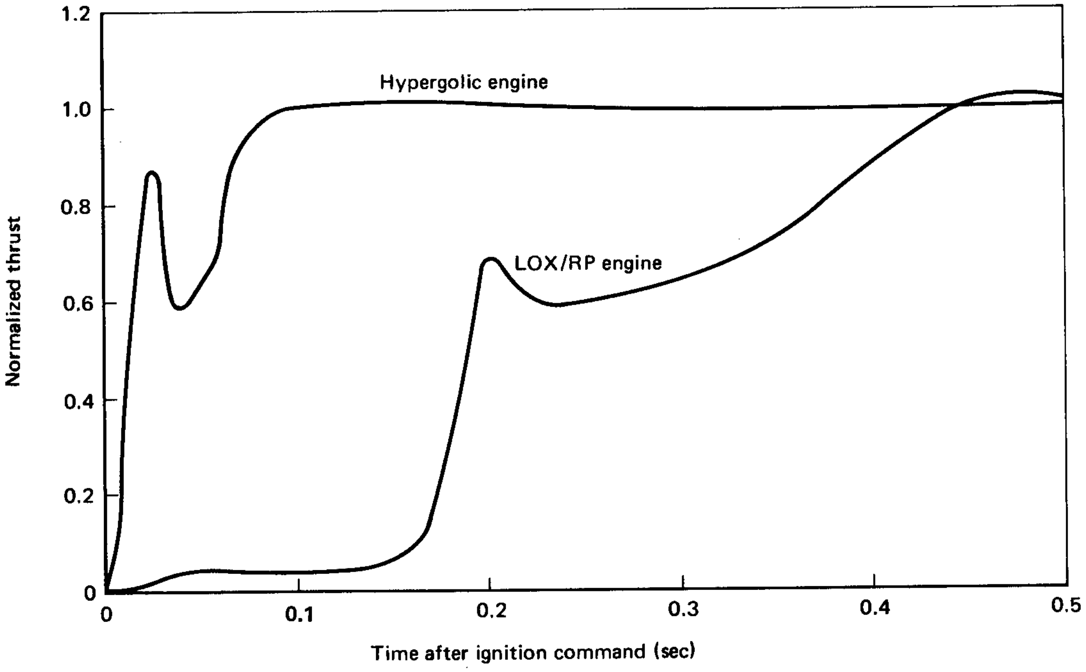

Figure 1
Sample thrust-buildup curves for liquid-propellant engines

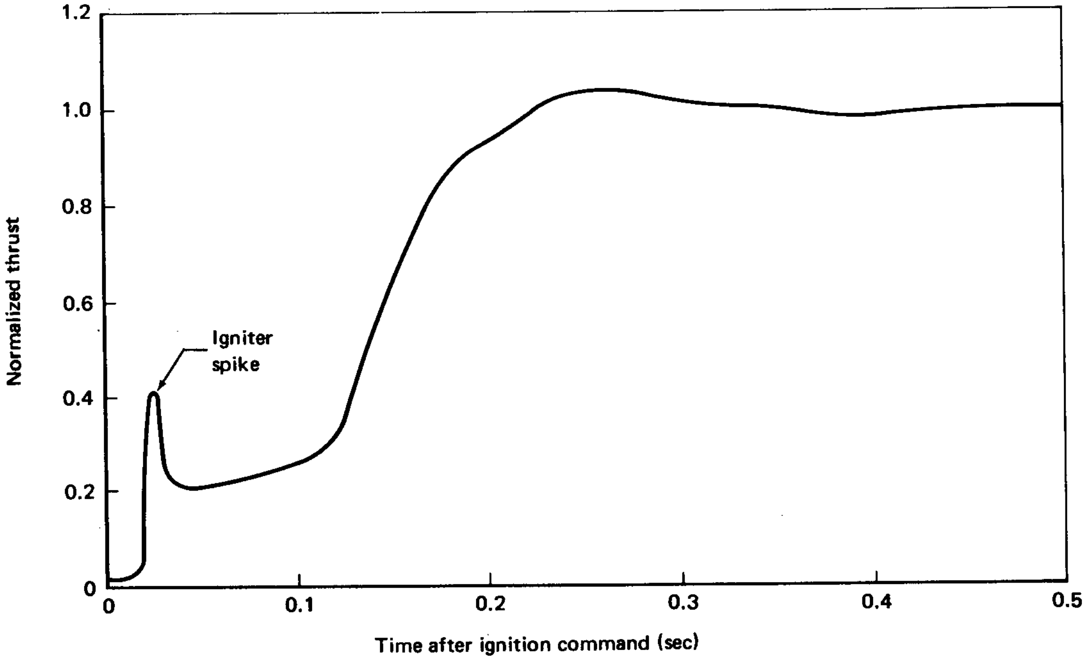

Figure 2
Sample thrust-buildup curve for solid-propellant engine

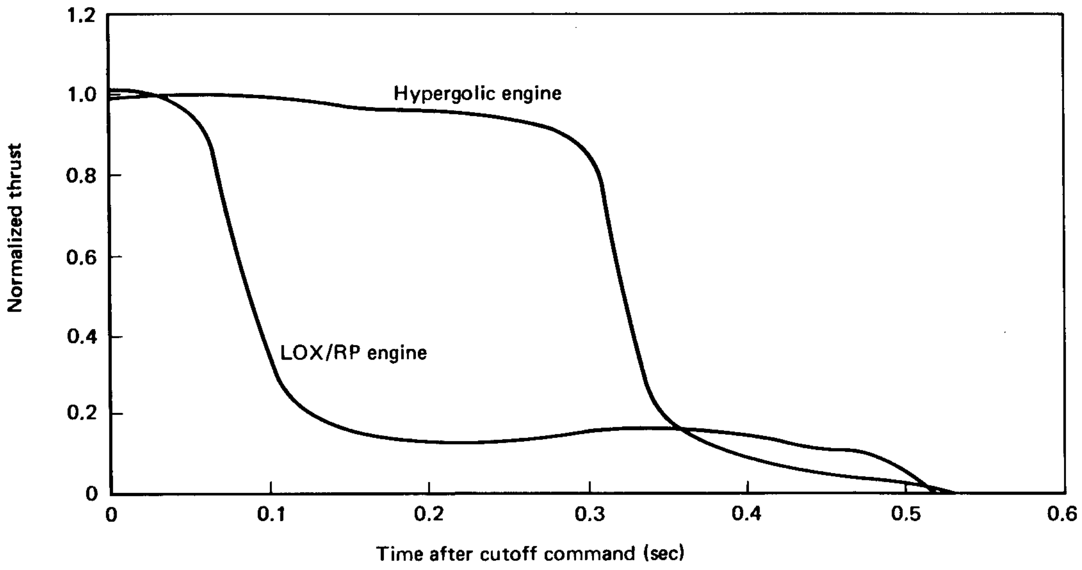

Figure 3
Sample thrust-decay curves for liquid-propellant engines

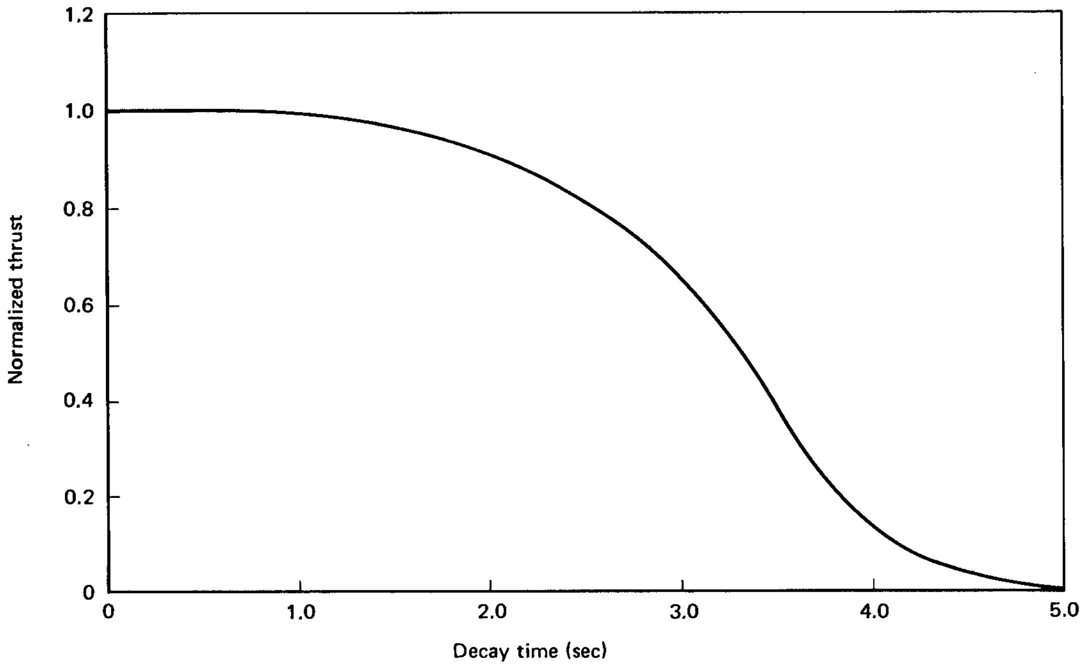

Figure 4
Sample thrust-decay curve for solid-propellant engine (no termination device)

Typical thrust-decay curves from static firings of liquid- and solid-propellant engines are shown in figures 3 and 4. Thrust-decay curves of liquid-propellant engines similar to those shown in figure 3 have also been derived from flight data. It should be noted that in liquid systems thrust decays rapidly because the propellant flow is closed by quick-acting shutdown valves. Solid systems either burn to complete fuel exhaustion with a gradual reduction in the burning area or are terminated by auxiliary devices, such as blowout ports or nozzle ejection. The relatively long tail-off of solid-propellant engines that burn to complete fuel exhaustion makes them less likely to induce high transient stresses.

2.1.3 Multiengine Systems

More than one thrust input must be considered for multiengine systems, and unusually high transient stresses can result if all the thrust inputs are applied simultaneously. The most direct method used to reduce these stresses is to separate or stagger the timing of each engine's ignition or shutdown. The time separation or interval is selected so as to minimize the dynamic response of the vehicle. This is accomplished by avoiding simultaneous inputs, inputs that reinforce each other, or inputs that cause large structural resonances. A typical example of ignition staggering for an eight-engine liquid-propellant system is shown in figure 5.

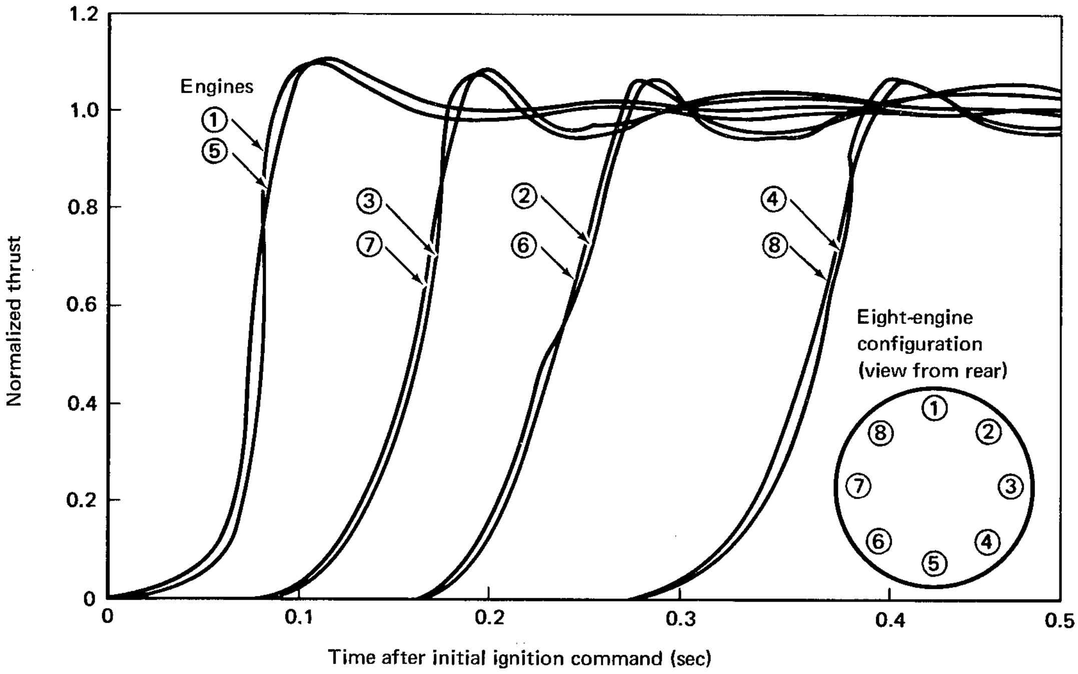

Figure 5
Sample eight-engine thrust-buildup curves (liquid-propellant engines ignited in diagonal pairs)

The sequence of staggering is also selected so as to avoid the application of large unsymmetrical loads, usually by igniting and shutting down engines in diagonal pairs. The selection of a favorable stagger sequence and timing is discussed in reference 5. Some small deviations in the actual ignition and shutdown times between these pairs will, however, always occur so that lateral and torsional responses can be anticipated from multiengine systems.

2.1.4 Statistical Nature of the Thrust Input

Supposedly identical engines will produce variations in thrust inputs on different vehicles or at different static firings. This is due to such factors as the interaction between the engine's propulsion system and its supporting structure, or to slight differences in ambient conditions and engine construction.

Two main approaches have been used to examine the statistical nature of these variations. In the first approach, the vehicle's responses are computed for a family of thrust inputs obtained from many static firings or from many flight measurements on similar vehicles. The maximum stresses from each application of thrust input are then treated as one element in a sample collection of stresses. The stresses obtained from the entire collection of thrust inputs are then used to derive mean and standard deviation of stresses in structural members of the vehicle. This is done for each critical structural member to determine the probability of exceeding allowable stresses.

In the second approach, a thrust-input curve is synthesized. The curve incorporates the statistical features of a large number of representative test firings. When data are available from only a few test firings, the thrust-input curve is based on an extrapolation of the statistical characteristics of similar types of engines.

2.2 Mathematical Models of Dynamic Systems

The mathematical model is an idealized representation of the space-vehicle structure that is used to investigate the structure's response to a thrust excitation. For most thrust-excitation problems studied to date, a longitudinal dynamic mathematical model that does not include the effects of lateral and torsional dynamics has been sufficient. Coupling of longitudinal, lateral, and torsional dynamics can, under certain circumstances such as thrust misalignment and differential-thrust inputs, lead to large lateral or torsional responses. In these cases, consideration of the stresses resulting from lateral and torsional responses may be necessary in design (ref. 6).

A general description of mathematical modeling methods for both longitudinal and lateral analyses may be found in reference 7. Additional longitudinal models of space-vehicle systems and methods used to determine the dynamic characteristics needed for analysis of the vehicle's response are discussed in references 8 to 11, and are treated in NASA SP–8012, "Natural Vibration Modal Analysis" (ref. 1).

The derivation of the mathematical model is dependent upon the formulation of equations that accurately represent the structure's inertia and stiffness properties. The *lumped-parameter* method of references 8 and 9 is one approach that has been used to obtain the desired representation. Another method, described in reference 10, uses axisymmetric shell equations to derive a *finite-element* model. The successful application of this finite-element method is discussed in reference 11. *Continuous-model* methods have been used, in some instances, for structures having well defined, continuously distributed properties. Although *wave-propagation* methods are being studied, they have not been sufficiently developed to be considered useful.

The models must also account for launch-stand flexibility and damping effects. The analyses of dynamic systems of liquid- and solid-propellant vehicles are treated separately, since each has different modeling problems.

2.2.1 Liquid-Propellant Vehicles

For liquid-propellant vehicles with thin-skinned cylindrical tanks, the *lumped-parameter* models are usually adequate to determine system response to thrust excitation. The problem in liquid-propellant vehicles is how to represent the longitudinal dynamics of the propellant tanks. Mathematical models of elastic tanks containing liquids have been reviewed in detail in references 12 and 13. Some of the tank problems which have been studied are initial stresses in tanks, sloshing, unsymmetric surface motions, compressibility of ullage gas, elasticity of bulkheads, and tank construction.

Figure 6 shows a highly simplified schematic of a lumped-parameter model of a liquid-propellant vehicle. In actuality, most lumped-parameter models are considerably more complex than the model illustrated. The tanks containing propellants are represented in figure 6 by a basic single mass with springs to account for tank flexibility. Structural elements not containing liquids are modeled by lumped masses interconnected by springs with stiffnesses equivalent to the effective longitudinal stiffness between the masses. Viscous-damping effects are illustrated in the figure by dashpots. However, the methods of including damping effects in the analysis are not well understood and care must be taken in including damping in a lumped-parameter approach (Sec. 2.2.4).

2.2.2 Solid-Propellant Vehicles

Solid-propellant vehicles have a compact structural design and have been modeled by both the lumped-parameter and *continuous-model* methods. In solid-propellant vehicles, the propellant is usually bonded to the case wall. Simulation of the

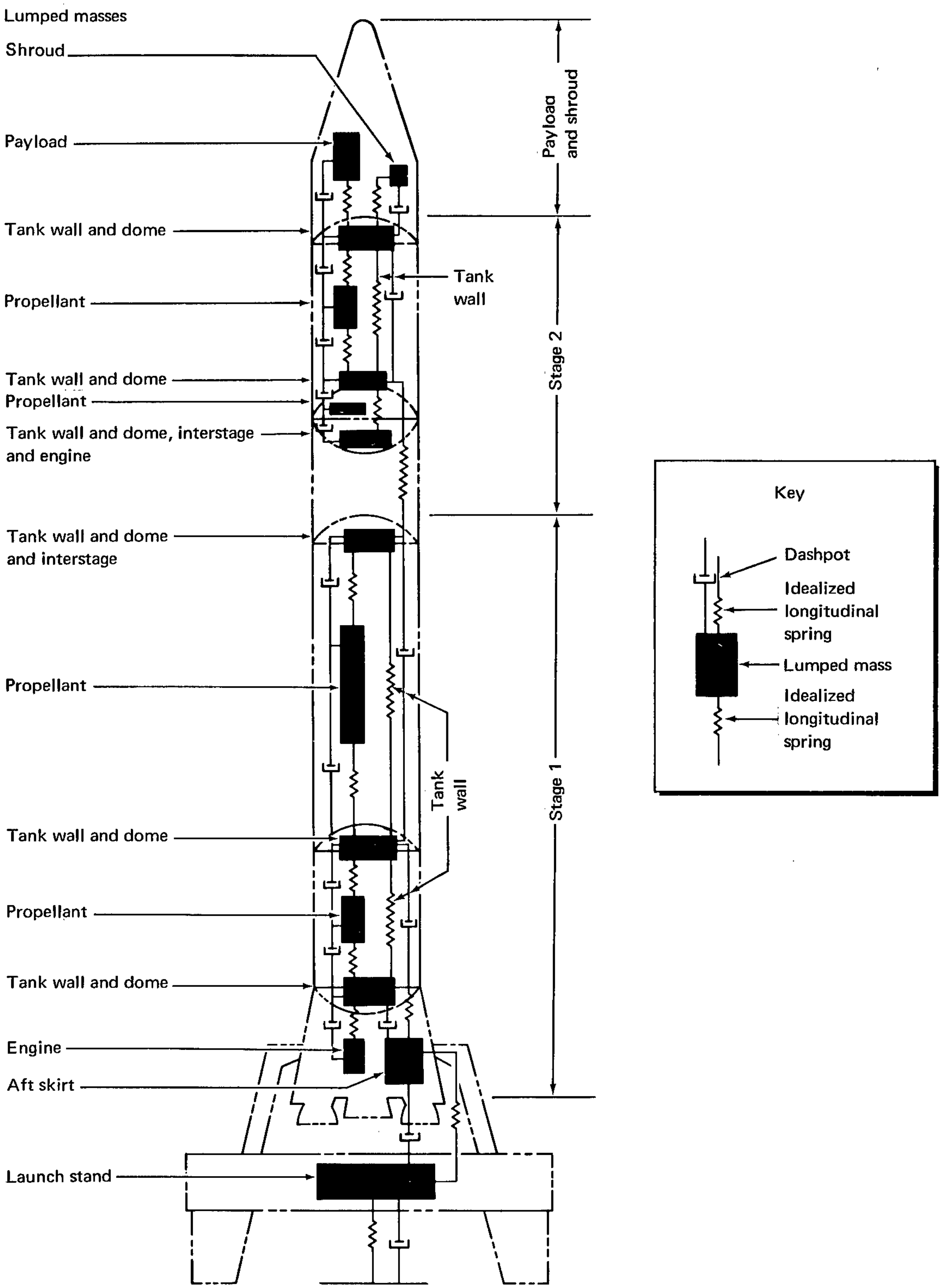

Figure 6
Simplified longitudinal dynamic model of space vehicle held to launch stand

longitudinal elastic properties of this composite structure is difficult, in part because of the effects of dynamic interaction between the propellant and the case wall. Because of its structural properties, the propellant contributes little to the stiffness of the composite structure. However, because of its viscoelasticity, the propellant does provide considerable damping.

Lumped-parameter models with spring-mass analogies of solid propellants require special treatment to account for the effective mass and shear stiffness of the solid-propellant core and the stiff outer casing. For example, reference 14 discusses a model in which springs, masses, and dampers of the propellant segments were chosen so that they would have the same frequency and damping as the computed first shear mode of the propellant grain. This approach not only requires separate calculations of the dynamic behavior of the propellant, but also careful integration of the propellant mass into the model. Calculated responses using this approach have compared closely with experimental data, and as a result this technique is often used for analyzing solid-propellant vehicles.

The continuous-model approach is based on the assumption that the solid-propellant segments can be represented by a continuous-beam model with mass, stiffness, and viscoelastic properties uniformly distributed along its length. The dynamic characteristics of such a model, including the stress-strain relationships for solid-propellant materials, are discussed in reference 15. Once a continuous model of the solid-propellant segments has been obtained, the remainder of the vehicle structure, modeled by a lumped-parameter analogy, can be interconnected with the solid propellant by the technique described in reference 16. This combination of approaches is straightforward and poses no difficulty in synthesizing a model.

2.2.3 Launch and Test Stands

The launch vehicle is attached to a stand during static test or prior to launch. The vehicle's response to thrust excitation at these times depends on the inertial and stiffness properties of the stand; the analysis is performed with some representation of the stand and the vehicle's restraining mechanisms. The simpler, flexible stand structures have generally been represented by a lumped parameter model in which the stand is considered to be composed of springs, masses, and dampers. Large, complex stands, such as the one used for the Saturn V, have more appropriately been modeled by the finite-element method (ref. 17). The mathematical representation of the interconnection between the vehicle and its stand depends on whether the stand is of the hold-down or of the free type. Hold-down launch stands restrain the vehicle until the vehicle is released (all engines having attained a preselected thrust level). Free launch stands present no restriction to the vehicle's vertical movement and the vehicle is free to rise when thrust exceeds weight.

Devices for releasing a vehicle from a hold-down launch stand include explosive bolts and retracting pins. A slow-release mechanism, developed specifically to reduce transient stresses resulting from abrupt disengagement of a vehicle from its launch stand, is described in reference 5.

2.2.4 Damping

Energy dissipates in a vibrating launch-vehicle structure as a result of nonlinear material and system damping. Material damping, which includes internal hysteretic damping and friction forces, is small in metal structures but is large in such viscoelastic materials as solid propellants. System damping, which includes energy dissipation at joints, interfaces, and fasteners, and fluid damping due to propellant motion can also be quite large. This nonlinear damping effect, as discussed in reference 18, does not readily lend itself to a simple linear mathematical model. Generally, an equivalent linear viscous-damping model is devised which has the same energy dissipation per cycle as the actual damping.

Two basic modeling methods have been used for damping. The first method (ref. 19) is a lumped-parameter spring-mass analogy, and concentrates the equivalent viscous-damping properties of each space-vehicle structural element into a dashpot, shown in figure 6. This permits distribution and variation of damping with vehicle geometry. A second method, reviewed in reference 7, has been used principally with response solutions of the normal-mode type (Sec. 2.3.1). In this approach, a modal viscous-damping factor is selected to represent the equivalent energy dissipation in each mode of vibration. This procedure and its limitations are discussed in detail in reference 18. Either approach has been found to be adequate for lightly damped systems. For systems with significant damping, however, errors are introduced by using the modal approach, and the lumped-parameter analogy is preferred.

2.3 Structural-Response Methods

Once the mathematical model is defined, the stresses, forces, and moments may be determined by computing the response of the model to the thrust inputs. Essentially, the solution desired is the response of a multidegree-of-freedom, linear, dynamic system (the space vehicle) to prescribed time-dependent external forces (thrust inputs). Although many techniques have been used to solve this type of problem, and even more are presented in the literature, the various techniques can be grouped into three basic approaches: the *direct* method, *normal-mode* method, and *shock-spectra* method. The response calculations, however, require some further definition of the boundary conditions (e.g., the vehicle held down to the test stand during static firing) and of the change in boundary conditions with time (e.g., release of the vehicle from its launch stand). These boundary-condition problems are discussed in the following sections.

Experimental verification of structural response to transient loads is not normally performed. However, there have been instances where both full-scale and model test programs have been run to investigate structural failures that occurred during flight.

2.3.1 Methods of Analysis

In the *direct* method, solutions are obtained in the coordinate system of the original mathematical model. The direct method can be applied to analyze systems with nonlinearities and nonproportional damping, as well as systems with time-varying coefficients, such as mass variations or changes in boundary conditions.

The *normal-mode* method differs from the direct method in that the coordinate system of the original mathematical model (which is coupled) is mathematically transformed to an uncoupled (orthogonal) set of coordinates (normal vibration-mode coordinates). The method is generally restricted to the study of linear systems. Either method may be used with thrust inputs in the form of time histories or Fourier spectra. Numerical techniques for the solution of differential equations developed in the direct method are contained in reference 20. A good treatment of the normal-mode method is presented in reference 18.

In the normal-mode approach, there are two widely used superposition methods for calculating transient stresses, the mode-displacement method, and the mode-acceleration method. These methods are discussed in references 16 and 21. Both methods give equivalent results if a sufficient number of normal modes are considered. As noted in reference 21, however, only a few modes can usually be taken. It has therefore been found desirable to use the method giving the more rapid convergence whenever possible. The mode-acceleration method usually offers the quickest solution for thrust-excitation problems.

In conjunction with the normal mode method, the *shock-spectra* method as discussed in references 22 and 23 is used to calculate the absolute response maxima of the normal modes to a thrust input. The method always leads to an upper bound of response and is particularly useful in assessing the relative severity of different types of thrust inputs and in estimating internal stresses. Some limitations on the use of shock spectra in structural design are given in reference 24, while a concise discussion of shock spectra is presented in reference 25.

2.3.2 Boundary Conditions

Space-vehicle transient stresses from thrust excitation are usually determined under three different system boundary conditions: (1) the vehicle held down to the test stand during static firing or to the launch stand prior to release; (2) the completely free vehicle unencumbered by external constraints; and (3) the constrained release of the launch vehicle from its launch stand.

For the vehicle held down to its test or launch stand, the mathematical model encompasses a combined vehicle-and-stand system which is fixed to the ground. The attachment between the vehicle and its stand is usually treated as a set of prescribed elastic constraints at the hold-down points. The usual assumption in this case is that there is no relative motion between points on the structure prior to the application of a thrust input.

For the completely free vehicle, the mathematical model represents an unconstrained or free-free space-vehicle structure with dynamic properties and static deformation compatible with flight conditions at launch or stage burnout. Again, it is usually assumed that there is no relative motion between points on the structure prior to ignition or shutdown of an engine.

The constrained release of the launch vehicle from its launch stand involves two physical considerations which must be mathematically simulated: (1) the change in boundary conditions at the instant the vehicle is released from its stand, and (2) any subsequent restraining force of the actual release mechanism.

In many cases, the release mechanism offers no restraining force and the vehicle disengages the instant it is released. This usually causes large transient motions throughout the structure as the vehicle adjusts to the sudden change in boundary conditions. This adjustment can be treated analytically as an initial value problem by assuming that the calculated motions of points on the held-down vehicle structure immediately before release are the initial conditions for the completely free vehicle just after release.

To reduce the large transient motions at release, a number of mechanisms have been developed which provide a restraining force from the instant the hold-down devices are released until the vehicle is completely disengaged from the launch stand. A technique for simulating controlled release is described in reference 5. The response equations in this reference are those of a completely free structure with initial conditions set at the instant the hold-down device is released. The controlled-release mechanism is simulated by an external force applied to the vehicle structure at the mechanism's attachment point. The magnitude of this force is related in a prescribed manner to the distance between the launch vehicle and its launch stand.

For response calculations of liquid-propellant vehicles, the thrust inputs are applied to the vehicle structure solely at the engine attachment points. Although this approach is sometimes used for solid-propellant vehicles, it is customary to apply the thrust inputs to the forward and aft domes of the propellant case, as well as to the rocket nozzle.

3. CRITERIA

3.1 General

The structural design of a space vehicle shall adequately account for the combined effects of transient loads from thrust excitation and all other concurrent natural and induced loads. In no case shall the stresses, forces, or motions calculated to result from the above transient loads exceed specified allowable values.

3.2 Guides for Compliance

3.2.1 Analysis

An analysis of transient loads from engine ignition and shutdown shall be performed. This analysis shall use proven methods.

3.2.1.1 Thrust Inputs

Thrust inputs for the analysis shall account for:

- Dynamic inputs from thrust excitation during thrust buildup and decay and under anticipated flight conditions (Section 3.2.2).
- Statistical nature of the thrust buildup and decay under anticipated flight conditions.

3.2.1.2 Mathematical Model of the Dynamic System

The mathematical model of the dynamic system used in the analysis shall adequately simulate the inertias, stiffnesses, and damping properties of the space vehicle.

3.2.1.3 Structural-Response

When appropriate, the method for calculating structural response to thrust inputs shall adequately account for:

- Launch-stand dynamics and launch-stand release mechanisms.

- Changes in space-vehicle boundary conditions and stored elastic energy.
- Staggered engine ignition or shutdown.

3.2.2 Tests

The dynamic inputs from thrust excitation at thrust buildup and decay shall be derived from experimental data obtained from the rocket engine under consideration or from similar rocket engines. When applicable data are not directly available, these dynamic inputs shall be derived from a logical extrapolation of related experimental data.

4. RECOMMENDED PRACTICES

Major tasks in the design process are as follows:

1. Experimental determination of the thrust input from engine test.
2. Analytical determination of the space vehicle's vibratory responses by devising a multidegree-of-freedom mathematical model representing the dynamics of the space-vehicle structure.

Analyses of these vehicle responses are used in several ways. They must clearly demonstrate that the structure of an existing vehicle is compatible with the transient characteristics of its propulsion system. For a new vehicle, the analyses offer a means of optimizing the design of the structure by investigating tradeoffs between thrust-excitation characteristics and the vehicle's dynamic properties. In all cases, experience with similar vehicles should be applied in selecting an appropriate method of analysis.

4.1 Thrust Inputs

Dynamic inputs from thrust excitation should be defined by time histories. Data for obtaining dynamic input curves of thrust buildup and thrust decay should be obtained directly from static firings of the actual engines, with care taken to correct the data for test-stand motion (ref. 3). Flight-test data, when available, should be used to supplement test-stand measurements of rocket dynamic input data (ref. 4).

When data are not readily available, as in the preliminary design of a new rocket engine, then thrust-input curves should be taken from engines whose operating characteristics are judged to be similar to the new engine. These estimates must be reviewed and updated as static-firing and flight-test data become available.

The varied nature of the thrust input requires a statistical description that can best be derived from a collection of engine-test data. It is recommended that this statistical information be used in the design analysis. Twenty to thirty thrust-input curves from a single type of engine are desired, although initial design often proceeds with fewer.

4.2 Mathematical Models of Dynamic Systems

The lumped-parameter and finite-element methods described in references 8 to 11 are suggested for use in analysis. The possibility of coupling of longitudinal with lateral and torsional motion should be considered. Either method may be used to model solid-propellant or liquid-propellant launch vehicles. The finite-element method should be used to model large, complex launch and test stands (ref. 17). If possible, these models should be linear; however, for systems with significant response of nonlinear elements, a nonlinear lumped-parameter model should be derived.

Damping should be included in the model, either in the lumped-parameter form suggested by reference 19, or as a modal viscous-damping factor. Care should be taken in selecting an appropriate damping value, since the results will not be conservative if the value selected is too high. It is recommended that actual measured values of damping be used, when available, in a final analysis.

4.3 Structural-Response

The normal-mode and shock-spectra methods (refs. 18 and 25) represent the simplest approaches to solving for structural response and should be used in the qualitative assessment of transient stresses in a system. Since the shock-spectra method is conservative, it is a means of eliminating from further consideration those transient loads that are clearly not a problem. When stresses obtained by the normal-mode and shock-spectra methods are found to be excessive, a more comprehensive analysis should be performed.

The comprehensive analysis should be based on either the direct method (ref. 20) or the normal-mode method. Both methods will yield precise response solutions for external forces applied as thrust inputs in the form of time histories or Fourier spectra. The type of computer facilities and computer programs available should determine which method to select.

The statistical nature of an engine's thrust input should be considered in these analyses of the vehicle's responses. The vehicle's responses and stresses in a structural member should be computed for a collection of thrust-input curves. If such a collection is not available, then a single synthesized thrust-input curve obtained from available data should be used.

For multiengine systems, the sequence and timing of engine ignition and shutdown should be considered in response analyses, along with the anticipated deviations in timing. The objective of these analyses should be to select timing intervals which minimize stresses.

For the vehicle held down to a test stand or a launch stand, the transient stresses should be determined by applying the thrust inputs, each at its appropriate input point, to a model of the cantilevered space vehicle and stand combination. For the completely free vehicle, the transient stresses should be determined by applying the thrust inputs to a model of a free-free space-vehicle structure. For the constrained release of the vehicle from its launch stand, the transient stresses should be determined by applying the thrust inputs to a model of a free-free structure whose initial conditions of velocity and displacement are identical to those of the held-down cantilevered model at the instant of release. Time-varying forces resulting from release mechanisms may be simulated in the manner presented in reference 5.

4.4 Tests

Experimental verification of structural response to thrust transient loads is not recommended unless special circumstances indicate a need for precise information on local stresses and motions.

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