PRINCIPLES AND PRACTICES FOR SIMULATION OF

STRUCTURAL DYNAMICS OF SPACE VEHICLES

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ABSTRACT

The paper discusses the philosophy and principles for the selection
and design of dynamic models for analysis of structural dynamics of space
vehicles. Subjects treated include similitude, model scaling, applications
of modeling to launch vehicles and spacecraft, and considerations relative
to damping and model support systems. An appendix is included which sum-
marizes the various dimensionless ratios used in aerospace flight.

INTRODUCTION

From practical considerations we begin with the situation that we have a
structure which is designed to place some useful payload into space. Typical
examples include both clustered and nonclustered configurations with either

liquid- or solid-propellant systems. During the performance of this task,
the structure is subjected to an environment or combination of environments,
which induces external and/or internal responses of the structure. For ex-
ample, wind loads create external motions of these structures and induce
internal stresses in the structural elements. As engineers we have both
a professional interest and responsibility, peculiar to our own field of
endeavor, to maximize the efficiency and reliability of the structures which
we employ. Although our principal interest at this conference and the con-
tent of this paper are principally devoted to space vehicle systems, the
reader will recognize that the general philosophy and much of the basic
content are generally applicable to structures associated with other
engineering disciplines.

In order to design efficient space vehicle structures we must have
adequate means for predicting the characteristics of the structure, the
environment and loads to which it is subjected, and its response. If the
structures were simple and the environment and loads well defined in a
spatial and temporal sense, adequate solutions could be obtained by
straightforward analytical procedures. Unfortunately it is usually diff-
icult and often impossible either to define the structure or the forcing
function with necessary finesse to assure high confidence in calculated
response, and hence it becomes necessary to rely on experimental programs
to generate the information desired for solution of immediate problems and
to guide the formulation of analytical procedures for future analyses of
similar systems. Furthermore, since the principal objective of our research
programs is to continually advance the state of the art, we cannot anti-
cipate a situation where the structural systems and environments of interest
are sufficiently well defined that interesting problems can be adequately

formulated and solved solely on the basis of theoretical analysis. Consequently, our interest in and reliance on properly planned experimental programs as an adjunct to theoretical developments is more likely to wax than wane in the foreseeable future.

As outlined in figure 1, experimental programs may be conceived which employ the following: (a) full-scale structures and the actual environment; (b) modified full-scale structure and a similar environment; or (c) replica or dynamically similar model structures and simulated environments. Relative to the structural dynamics of space vehicles, the aforementioned approaches may be briefly characterized by the following considerations.

The experimental study of exact full-scale structures and their reaction to the exact environment essentially means that we employ whatever theoretical and experimental knowledge and experience we have to design and build what we think we want, fly several vehicles, and see what happens. If the vehicles perform as desired, we consider ourselves fortunate and are in business. If the performance is deficient during the flight of early vehicles, later vehicles are modified to correct these deficiencies and the program is continued to completion. For smaller, comparatively simple, inexpensive space vehicle systems, and for those which are not man rated, experience tells us that this is a good approach. Thor-Delta is a good example.

Ground vibration tests of full-scale launch vehicles or flight tests of launch vehicles with boilerplate payloads are representative of the second category. In the first case the spatial and temporal distributions of vibratory loads are simulated by acoustic pressure fields or multipoint shaker load. In the second case, internal coupling of structural elements and the coupling of the structure with the environment are somewhat compromised; however, the results of flight programs for Mercury, Gemini, and Apollo

substantiate their value. The sheer size and complexity of the systems and hardware involved postulate that such programs are both complex and expensive.

The study of replica or dynamically similar model structures and their response to simulated environments is the subject of primary concern in this paper. By a replica model, we essentially mean that we keep the same materials, the same type of construction, and essentially build a miniature of the flight article. If we have a good understanding of the structure and are primarily interested in basic phenomena and the magnitudes of events such as natural frequencies and nodal locations, it is usually possible to economize on manufacturing and test procedures and costs by use of a model which is dynamically similar. Such techniques have been successfully employed in the aircraft industry for many years and will be discussed to some extent in the present paper.

The fact that dynamic models have been used with excellent results in the study of structural dynamic problems in aircraft may, in itself, be sufficient justification for their use in space vehicles since the basic problems and structural characteristics are substantially similar. However the tremendous size, complexity, and cost of space vehicle systems indicate that construction, testing, and modification of full-scale hardware pose problems of a higher order of magnitude and further emphasize the need for effective dynamic model programs either as a sole or companion source of experimental data.

SIMILARITY AND MODEL SCALING

Fundamentals of Similarity

In general terminology, a model structure is similar to a full-scale structure in at least some respect. The extent of this similarity may vary widely. It depends on the nature of the problem under study, the types of structure involved, and to a large extent, on the feasibility of close simulation of the full-scale structure and the environment which induces some type of internal or external response of the structure.

Granting that dynamic models are of some value in the study of the structural dynamics of space vehicles, the basic question then arises: How do we design and construct the model and its environment to simulate the full-scale response of interest and obtain the needed response data?

Many technical reports and textbooks have been written with the intent of answering this question, and although the scope of this paper does not permit a detailed discussion of the answer, an attempt will be made to outline the basic principles.

To begin, we recognize that the response of any physical system is governed by a set of equations, usually differential, which are based on principles of conservation of one or more quantities. Conservation of mass, conservation of energy, and conservation of momentum are typical examples. Newton's second law, stated in the manner of d'Alembert, that $F - ma = 0$ is a very simple but typical example. Bernoulli's equation for the pressure along a streamline in an incompressible flow is another example. In some cases, where the system of structure and environment and their mutual interactions are well known, the equations which govern the response can be derived, and certain classes of these may be solved. If the governing equations can be derived and solved, the physical system is converted to a mathematical analog and the need for a dynamic model or physical analog diminishes or disappears. Thus we are primarily interested in systems for which we cannot write the governing

equations, cannot solve them, or cannot interpret the analytical solutions adequately in terms of physical responses which describe the behavior of the system.

Even if the governing equations cannot be written conceptually, they still exist and we know from the principles of dimensional homogeneity that the dimensions of every term of any given governing equation must necessarily be the same. For example, every term of a force equation is a force and every term of a moment equation is a moment, etc.

Since the dimension of each term of a governing equation is identical, the ratio of any two terms is dimensionless. Thus, conceptually, all governing equations for any physical system may be made dimensionless, and every term then becomes a dimensionless ratio. The solutions of the governing equations are then independent of the dimensions of the system. Complete similarity is then achieved if all significant dimensionless ratios (a complete set) are included and corresponding dimensionless ratios pertinent to the problem have the same value for both the model and full-scale systems where the system includes both the structure and the environment.

The next task for achieving similarity is the determination of the dimensionless ratios which are pertinent to the problem at hand. During the decades which have followed since Professor Osborne Reynolds critical analysis of the importance of simulating significant dimensionless ratios in experimental research, many such ratios (frequently referred to as parameters or numbers) have been derived which pertain to one or more regimes of aerospace flight. The more important of these have been assembled by Norman Land of the Langley Research Center and are compiled in the appendix for reference. Four possible ways of obtaining these ratios are outlined in figure 2 and briefly described as follows:

(1) Select the parameters which are significant on the basis of past experience. For example, past experience indicates that the forces and moments on a rigid wing at subsonic speeds are dependent on the Reynolds number and if model and full-scale tests are run at the same Reynolds number, full-scale forces and moments may be determined from model test results.

(2) Write the governing equations of motion and nondimensionalize them. As illustrated in figure 3, the dimensionless parameters are readily obtained if the governing equations can be written, but for most of the problems of real interest, this may not be possible.

(3) Form ratios of dimensionally similar quantities which govern the system response. Reynolds number is obtained and defined, for example, as the ratio of the fluid inertia forces to the fluid viscous forces.

(4) Derive the dimensionless parameters by application of the principles of dimensional analysis. Since the techniques involved here are widely known and published, further discussion of dimensional analysis is not believed to be necessary.

The reader will recognize from the foregoing discussion that the successful application of dynamic model techniques to the study of any class of problems requires a substantial knowledge of the structure, the environment, and a fair assessment of what the response will be. We must know what variables, forces, moments, etc., are important, and we must have some recognition of why and how a given variable influences the response. If insignificant variables are introduced, they complicate the problem, and if important variables are omitted, the results may be completely erroneous and useless. Consequently, dynamic model design and testing are perhaps as much an art as a science and the scaling of dynamic models usually involves selection of the important dimensionless ratios by application of several or all of the four aforementioned techniques, as will be borne out by specific examples given in subsequent sections of the paper.

The dimensionless ratios or dimensionless products of interest are independent of each other in the sense that no one of the ratios is a product of powers of the others. A sufficient condition that each ratio be

independent is the condition that each ratio contain at least one variable
which is contained in no other ratio. The set of all possible independent
dimensionless ratios which can occur for a given problem is then complete.
As an example, figure 4 shows the complete set of independent dimensionless
ratios for the force on a body in a fluid under the assumption that the
force is dependent on the length of the body, gravity, and the velocity,
density, viscosity, speed of sound, and surface tension of the fluid.

Finally the question arises as to the number of dimensionless ratios
which occur in the study of a given problem. To answer this question, we
must first define the nature of the physical quantities which we use for our
standard of measurement and thus designate as fundamental, i.e., will we use
mass, length, and time or force, length, and time. Mass, length, and time
are dimensionally independent in the sense that their magnitude can be de-
termined by only one specific type of measurement. On the other hand, force
is not dimensionally independent because it can be determined by measuring
mass, length, and time, or mass and acceleration. If the fundamental
physical quantities are dimensionally independent and r in number, and if
the problem involves a total of n physical quantities, then, as shown in
reference 1, the number of independent dimensionless ratios will be n - r.
In any event the number of independent dimensionless ratios in the complete
set will be equal to the number of variables minus the rank of their dimen-
sional matrix.

Let us consider two examples involving the forces on a body in an in-
viscid, compressible flow where, in the first case, the fundamental quantities
are dimensionally independent and, in the second case, they are dimension-
ally dependent.

Case I

	$\tilde{F}$	V	l	ρ	c	g
M	1	0	0	1	0	0
L	1	1	1	-3	1	1
T	-2	-1	0	0	-1	-2

Since there are 6 variables involved and the rank of the matrix is 3, there will be three dimensionless products in the complete set. These will be the Force coefficient, Mach number, and Froude number.

Case II

	$\tilde{F}$	V	l	ρ	c	g
F	1	0	0	1	0	0
L	0	1	1	-4	1	1
T	0	-1	0	2	-1	-2

Though the matrix is different, the rank is still 3 and the comments pertaining to case I are pertinent.

Types of Similarity

With respect to structural dynamics of space vehicles, the types of similarity of primary interest are geometric similarity, kinematic similarity, and dynamic similarity. The definition of each of these types of similarity is given in figure 5 and the relationships which exist between the independent quantities (length, mass, and time) are given in figure 6 where the subscripts f and m are used to denote corresponding full-scale and model quantities, respectively.

In addition to geometric, kinematic, and dynamic similatiry, in some instances there is a need for thermal similarity. However, the introduction of thermal effects may be treated as a separate problem, and is not of prime importance to the discussion on structural dynamics presented herein. The subject of thermal similarity is discussed in some detail in references 2, 3, and 4.

DERIVATION OF SCALE FACTORS FOR STRUCTURAL
DYNAMICS MODELS
Launch-Vehicle Structures

In the scaling of launch-vehicle structures for lateral or longitudinal structural dynamics, only dynamic similarity is of principal concern. Kinematic similarity is automatically assured if dynamic similarity is achieved. Since the tests of such models do not, in general, involve aerodynamic flows, geometric similarity enters only in a gross sense.

Lateral dynamics. The lateral dynamics of a liquid-propellant launch vehicle involve the longitudinal distributions of four principal types of forces; namely:

Structural stiffness

$$\frac{\partial^2}{\partial z^2}\left(EI \; \frac{\partial^2 u}{\partial z^2}\right)$$

Structural inertia

$$m \frac{\partial^2 u}{\partial t^2}$$

Fluid stiffness

$$\bar{m} \, a$$

Fluid inertia

$$\bar{m} \frac{\partial^2 u}{\partial t^2}$$

where

EI flexural rigidity of structure

u structural bending displacements, or lateral fluid displacements

m mass per unit length of vehicle (includes structural mass plus pro-
pellant mass which moves with the structure)

$\bar{m}$ mass of propellant per unit length of vehicle which moves as a sep-
arate degree of freedom and participates in fuel sloshing

a absolute acceleration of vehicle (includes acceleration of gravity
plus acceleration of vehicle relative to a fixed coordinate system)

 If the distributed values of the ratios of these forces are the same on
the model and full-scale vehicles, dynamic and kinematic similarity are assured.

 If the fluid stiffness forces are neglected, and l is a characteristic
length, the fluid mass may be considered as additive to the structural mass-
es, and

$$\left[\frac{EI/l^3}{\frac{(m + \bar{m}) l}{t^2}} \right]_f = \left[\frac{EI/l^3}{\frac{(m + \bar{m}) l}{t^2}} \right]_m \tag{1}$$

or

$$\omega_m^2 = \omega_f^2 \frac{\left[\frac{EI}{(m + \bar{m}) l^4} \right]_m}{\left[\frac{EI}{(m + \bar{m}) l^4} \right]_f}$$

 On the other hand, if the fluid stiffness is felt to be important from
the standpoint of the coupling of fluid and structural masses, then the
structural and fluid frequencies are related as follows:

$$\omega_{m,s}^2 = \omega_{f,s}^2 \frac{(EI)_m}{(EI)_f} \frac{m_f}{m_m} \frac{\ell_f^4}{\ell_m^4} \tag{3}$$

$$\omega_{m,p}^2 = \omega_{f,p}^2 \frac{a_m}{a_f} \frac{\ell_f}{\ell_m} \tag{4}$$

and since the structural and fluid frequencies should bear the same ratios on model and full-scale vehicles,

$$\frac{(EI)_m}{(EI)_f} \frac{m_f}{m_m} \frac{\ell_f^3}{\ell_m^3} = \frac{a_m}{a_f} \tag{5}$$

For a replica model, the quantity on the left is equal to $\overline{\lambda}$ and the conditions for similarity are satisfied only if the acceleration field for the model tests is increased by a factor of $\overline{\lambda}$. However, similarity can also be achieved by any combination of reduction in stiffness or increase in mass of the model such that the product reduces the left-hand side of equation (5) by $\overline{\lambda}$.

Longitudinal dynamics. The procedure here is the same as for lateral dynamics. The forces are:

Structural stiffness

$$\frac{\partial}{\partial z} \left(EA \frac{\partial w}{\partial z} \right) \tag{6}$$

Structural inertia

$$m \frac{\partial^2 w}{\partial t^2} \tag{7}$$

Fluid stiffness $\overline{m} \, a$ (8)

Fluid inertia $\qquad \bar{m}\,\dfrac{\partial^2 w}{\partial t^2}$ $\qquad\qquad$ (9)

where

EA $\quad$ extensional rigidity of structure

w $\quad$ structural extensional displacements, or longitudinal fluid displacements

Again if the distributed values of the ratios of these forces are the same for the model and full-scale structures, the conditions for dynamic similarity are satisfied. The scale factors which evolve are the same as those for lateral dynamics.

Tank pressures. In the case of liquid-propellant launch vehicles, a condition for similarity is that the stresses induced by internal ullage pressure bear the same ratio to the dynamic stresses for the model and prototype. It can be readily shown that this condition is satisfied if the model and full-scale ullage pressures are equal either for a replica model or for a model designed to maintain full-scale ratios of structural frequencies to fluid frequencies.

Spacecraft Structures

In the design of orbiting spacecraft structures, it is only necessary to maintain the full-scale distributions of mass and stiffness throughout. This condition assures proper simulation of mode shapes and the model to full-scale frequency ratio is readily calculated from simple beam, plate, or mass-spring considerations.

However, if the spacecraft is to land, its toppling stability during

landing is dependent on the gravitational field. The condition for simulation then requires that the ratio of the inertia forces to the gravity forces be invariant or that

$$\frac{\omega_m^2 l_m}{\omega_f^2 l_f} = \frac{g_m}{g_f} \tag{10}$$

where g is the acceleration due to gravity.

If the model is a replica model, $(\omega_m^2/\omega_f^2) = \bar{\lambda}^2$ and since $(l_m/l_f) = \bar{\lambda}^{-1}$, simulation of the dynamics during landing requires that $(g_m/g_f) = \bar{\lambda}$. Thus, to model a lunar landing spacecraft for tests on earth, $(g_m/g_f) = \bar{\lambda} = 6$. If the scale is larger, the model must be distorted or the gravitational field has to be reduced by testing in a simulator.

APPLICATIONS OF DYNAMIC MODELS

General Remarks

For practical reasons, dynamic model studies of space vehicles seldom involve a complete simulation of the composite environment-structure system. Instead, such studies are usually problem oriented in that one or more dynamic models is designed to study a specific or limited group of related problems. The logic of this approach has several justifications among which are those discussed in the following sections.

Multiplicity of Environmental Conditions

From a dynamics viewpoint, the environment of space vehicles may be defined as the composite of conditions which induce, or limit dynamic motions of the structure. Those conditions which induce motions, commonly referred

to as the sources of excitation, are of fundamental importance and will be discussed first.

Figure 7 lists the primary sources of excitation of space vehicle structures. Even a percursory glance at the figure will indicate to the reader the difficulty of a realistic simulation of these sources of excitation on any given dynamic model in a realistic test setup. Yet, each of the inputs has posed severe problems for one or more vehicles, and most vehicles are encumbered by the majority of the inputs. As indicated by the figure, induced responses of the structure become of concern during the manufacturing and shipping stage, persist through ignition, lift-off, flight, stage separation, and in the case of the Apollo vehicle, pose a significant problem during landing.

During flight through the atmosphere, the sources of excitation are highly transient due to the structure of the atmospheric wind profiles, the dissipation of launch-vehicle fuel, the changes in characteristic flows about the vehicle from subsonic to transonic to supersonic, and the changes in vehicle structure due to separation of spent stages. As a consequence of these highly transient and variable conditions, the spatial and temporal distributions of the sources of excitation are only approximately known and hence any one of the environmental effects can only be approximately simulated. Of significance also is the fact that, during the flight phase, nearly all of the inputs are superimposed, leading to a condition commonly referred to as "combined environments."

The principal phenomenon of importance relative to the limiting of dynamic motions is damping, and from a structural dynamics veiwpoint, the principal concern relative to environmental effects is that the thermal and vacuum environments of space, acting separately or collectively, may

tend to reduce the damping of composite structures to the very low levels
associated with the hysteretic dissipation of energy in the structural
materials themselves. Some comments pertinent to this problem are presented
in a separate section on damping.

Various Types of Dynamic Models

In view of the difficulty of subjecting a single dynamic model to the
space vehicle environment and interpreting the full-scale response by scal-
ing up the dynamic model results, the general approach at present is to use
a combination of models to generate structural, aerodynamic, and propellant
inputs which are integrated into analytical programs for prediction of over-
all vehicle responses. The types of models used to accomplish these object-
ions, and the nature of the data obtained are given in figure 8. In some
instances, such as for aeroelastic and landing dynamics studies the model
results may be scaled to directly indicate full-scale vehicle responses.
In addition, special purpose models for studying various phenomena and
problem areas are widely used as in the case of aircraft. Models to study
control-surface loads, propellant baffle dampers, and the response of
panels to acoustic pressures are typical of these.

To date, the application of models to the study of space vehicle
dynamics has been primarily focused on the launch-vehicle characteristics
with the spacecraft represented as a concentrated mass, or appropriate
aerodynamic shape. Figure 9 shows some such models utilized in various
studies, current or in the past, by the Langley Research Center. Details
of the model design characteristics, research objectives, and test results
are presented in comparison papers at this symposium by Reed and Runyan.
As shown by the figure, the models represent both monocoque and cluster

launch-vehicle configurations, and are used to study problems involving
structural dynamics, ground winds, and buffeting.

Typical Examples of the Use of Structural Dynamics Models

Launch vehicles - Titan III. Typical samples of the data obtained from
tests of structural dynamics models of launch vehicles are shown in figure 10
and 11. These data were derived from early tests of a 1/5-scale model of
Titan III, the vehicle shown in figure 12.

Figure 10 shows the acceleration of a simulated 45,000-pound payload in
the yaw direction (the longitudinal plane containing the solids) for a
simulated flight condition wherein one-half of the mass of the strapped-on
solids is spent. Resonance conditions, exemplified by peak response levels,
are shown and the first three natural modes are identified. Although the
exact structural deformations involved have not yet been clearly identified
the figure also shows the existence of strong resonances at higher fre-
quencies.

An interesting observation from figure 10 is the fact that the re-
sponse levels at resonance increase with frequency which indicates that,
since the magnitudes of the force inputs are held essentially constant, the
damping of the structure-fuel system decreases with frequency. This trend
is substantiated by the logarithmic decay presented in figure 11 which
show that the damping of the third natural mode is only 60 percent as high
as for the first natural mode and about 80 percent as high as for the second
natural mode.

The data presented in figures 10 and 11 represent only a small sample
of the data being generated on this model. The Langley Research Center, is
working in cooperation with the Air Force and Martin-Denver (who designed,

built, and is jointly testing the model) to measure the structural dynamics characteristics for the full range of payloads, inputs, and propellant loadings. The test program involves the use of multiple shakers and includes analysis of both the core and core-plus-solids configurations. It is hoped that the model test results will provide the necessary checks and modifications to the theory so that the full-scale responses can be analyzed with confidence without the need for extensive dynamic testing of the full-scale hardware.

Orbiting spacecraft - Nimbus. As previously mentioned, the use of dynamic models to study the experimental aspects of the structural dynamics of space vehicles has been focused on launch vehicles. The reason for this is that the great majority of spacecraft in the past have been small enough to permit a full-scale dynamic mockup to be readily constructed and tested, or they have been sufficiently compact that the structure could be adequately restrained from highly undesirable dynamic responses. Ranger and Tiros, respectively, are good examples.

As spacecraft become larger, more flexible, and more expensive, an increased need for dynamic model tests will no doubt arise. As an example the Nimbus spacecraft, a future polar orbiting weather satellite shown in figure 13, exhibited complex high-amplitude dynamic responses during early qualification tests wherein the solar panels were folded to simulate the launch configuration. A review of the early test results suggested the need for a simple, inexpensive, dynamic model program to establish:

(1) The characteristic motions of the vehicle as a function of frequency including natural frequencies, mode shapes, and forced response;

(2) The relative merits of hard vs. soft mounting systems for attaching the spacecraft to the launch vehicle; and

(3) The effectiveness of localized and distributed damping on the frequency response.

Sketches of the model and two samples of the test results, selected from reference 5, are shown in figures 14 and 15. The scale chosen was 1/2, and as shown in figure 14, the model afforded a reasonable simulation of the dynamics of the full-scale structure over the lower frequency range as desired. The model was constructed of standard tubing and plates with mixed welded and riveted construction. In lieu of honeycomb sandwich solar panels, the model panels were constructed by laminating two thin sheets of aluminum to a sheet of balsa. Two sets of panels were constructed. In one set the bonding agent used to laminate the panels was an epoxy resin (a hard-setting glue) and in the other set the bonding agent was a visco-elastic damping adhesive. Figure 15 shows that the use of the damping adhesive effectively reduced the amplification factor (the ratio of output to input accelerations) by nearly an order of magnitude over the frequency range of primary interest. Other tests also demonstrated the effectiveness of isolation techniques, and all test results were of substantial aid in the definition of the contributions of the various components of the structure to the overall vehicle motions.

Landing spacecraft - Apollo LEM. A substantial research effort is currently directed to the analysis of the landing dynamics of space vehicles designed to land on extraterrestial surfaces such as the moon. This research includes both theoretical and experimental studies, and is oriented to establish both the tipover stability during the landing process and the loads and motions generated in the landing gear during the impact process.

Among the more important variables for such problems is the gravitational constant. As shown in a previous section of the paper, free-fall

drop tests of a vehicle on the earth's surface will not simulate landing of the same vehicle on the moon even though the velocity conditions and the surface materials at the point of touchdown are the same. The necessary experimental test results can be obtained by testing full-scale structures or large dynamic models in some type of lunar gravitational simulators, or by testing 1/6-scale dynamic models.

Gravitational simulators may be of several types such as the inclined plane, a counter force system which supports 5/6 of the weight of the vehicle, or a simulator which permits impacts for the velocity and surface conditions desired onto a surface which is accelerating downward relative to the earth. A simulator of the latter type is discussed in reference 6 and shown in figure 16. For simulation of full-scale lunar landing vehicles, the impact surface would accelerate downward relative to earth at 5/6g and the ratio of the counter mass M_2 to the simulator mass M_1 would be such that $M_1 \approx 11M_2$.

An example of a 1/6-scale dynamic model for simulating lunar landing dynamics is shown in figure 17. The basic structure of the model is designed to readily permit variations in spacecraft mass and moments of inertia by appropriate distribution of added masses to the basic structure. Landing-gear configurations can also be varied in number and structural details. The configuration shown has four tripod gears with each member of the tripod having honeycomb shock absorbers to permit dissipation of the impact energy with minimum rebound. Other gear configurations are also under study. In addition to generating basic information on landing dynamics of lunar spacecraft, the model parameters are selected so as to include values pertinent to the Apollo LEM vehicle.

DAMPING

General Remarks

The damping of launch-vehicle and spacecraft structures is among the more critical factors in the control of their response to the many types of inputs. Since the peak amplitudes of forced responses are essentially inversely proportional to damping, and since the rate of exponential decay of free oscillations is directly proportional to damping, it is necessary to know the inherent damping of the structure in all cases to predict its response. As a general rule, the higher the inherent damping the better, and a great deal of effort has been expended in recent years on the development of viscoelastic films, tapes, sandwiches, etc., to achieve higher damping.

From the viewpoint of simulation, damping is among the more difficult quantities to scale. Several types of damping are of concern including aerodynamic damping and structural damping. Some discussion of each of these as they pertain to dynamic modeling is presented in the following paragraphs.

Aerodynamic Damping

Since the primary vibrations of launch vehicles and spacecraft occur during flight, the density of the air which surrounds the structural components of the vehicles during conditions of peak response is usually lower than ambient conditions at the earth's surface. Yet for convenience, it is highly desirable to be able to conduct tests of structural dynamic models under atmospheric conditions. Thus the question of the effect of air density on the aerodynamic damping of the vibrations of space vehicles and

their components arises. In addition to the density effect, the question
of size or area of the components also exists. In an effort to determine
the effects of these and other variables on the damping of structures for
space vehicle applications, a study of the damping of typical components
was recently conducted at the Langley Research Center. The study consisted
of measuring the damping of various sizes of circular and rectangular panels,
spheres, and cylinders at air pressures ranging from atmospheric down to
4×10^{-2} torr. The test components were mounted on the ends of cantilever
beams of different frequencies and the damping was determined by measuring
the logarithmic decay of the free vibrations of the beam-component systems.
Typical samples of the results are shown in figure 18, where the ratio of
the damping to the critical damping is plotted as a function of the press-
ure of the surrounding air medium for a panel and sphere for two amplitudes
of oscillation. For the case shown, the cross-sectional area was 30 square
inches and the frequency of oscillation was 3.8 cycles per second. The
results show that the aerodynamic contribution to the damping of the panel,
obtained by subtracting out the damping at 4×10^{-2} torr, is proportional
to the amplitude of oscillation and the density of the test medium. The
results also show that the damping of the sphere is essentially proportional
to density, but independent of amplitude. Other tests involving cylinders
showed the same characteristic variations as for spheres. In summary the
results of the studies to data show that the damping for panels varies as
follows:

$$\delta = 22 \frac{\rho X A^{4/3}}{m}$$

where

δ damping coefficient, $2\pi c/c_{cr}$

ρ density of the test medium, slugs/ft^3

X   amplitude of oscillation, ft

A   area of the panel, ft^2

m   effective mass of the panel-beam system, slugs

Thus it appears that the increase in damping due to testing panel-
type structures in atmosphere as opposed to the low-pressure space en-
vironment is directly proportional to the pressure ratios and can be
readily accounted for. The same is true for spheres and cylinders. On
the other hand, the results show that the damping ratio for a model of
a panel structure tested in atmosphere is substantially less because of
the smaller area then it would be for a full-scale structure tested under
similar conditions. The damping factor for spheres and cylinders, how-
ever, are independent of size and the scaling problem is rather straight-
forward. The essence of these remarks also points up the fact that the
low-amplification factors measured for tests of spacecraft having large
solar panel arrays may be due to high aerodynamic damping – a condition
that will not exist during flight in low-density regimes.

Structural Damping

In addition to the aerodynamic damping which may dissipate the motion
of a structure, all structures possess an internal dissipation mechanism
usually referred to as structural damping. For purposes of this paper,
structural damping is defined as the composite of those effects which in-
volve hysteretic dissipation within the crystals of the structural mater-
ials and the damping associated with the deformation of the structure at
its joints.

It has long been expected that the damping of small composite struc-
tures representative of aerospace usage would have higher structural damping
than larger structures constructed of the same materials by the same tech-
niques. In other words, is the structural damping coefficient of a replica
dynamic model inherently higher than that for the full-scale structure? In
an attempt to answer this question, the Langley Research Center constructed
four aluminum beams with cantilever supports and tested them. The beams
had a rectangular cross section with a width-to-thickness ratio of 6 to 1,
and a length-to-width ratio of 10. The largest beam was 5 feet long. The
cantilever support for each beam consisted of two machined angle blocks de-
signed so that the stresses in the support were consistent with the stresses
in the beam. The relative scale of the models and the results of the damping
tests are shown in figure 19. The beams were mounted to a massive steel
and concrete backstop and every precaution was taken to assure that the
mounting and test conditions were consistent.

During the tests, the clamping pressure of the beam supports was con-
trolled by varying the torque applied to the bolts and for a comparative
test condition, the clamping pressure for all beams was the same. The
damping was measured for both a low torque condition (representative of
a semitight fit) and a design torque condition. For each torque condition,
the damping was also measured for a range of amplitudes.

The results of the tests show that the damping coefficient decreases
as the clamping pressure, joint tightness, or torque is increased, and in-
creases as the amplitude of the vibration is increased. But perhaps of
greater importance from the standpoint of dynamic modeling of structures is
the fact that the structural damping increased by a factor of 2 as the scale
was reduced by a factor of about 18 for design torque conditions and by a

factor of 4 for low torque conditions. Yet every attempt was made to assure

that each beam was a replica model of the other three. On the basis of

these results, it would appear highly likely that the structural damping

of a realistically sized dynamic model of a launch vehicle might differ

substantially from that of the full-scale structure. Furthermore, the

results also emphasize the importance of maintaining close control over

joint tightness and integrity during model construction.

Another factor of concern relative to the structural damping of space-

craft is the probability that long exposure to space vacuum conditions may

outgas the adsorbed gases from the mating surfaces at structural joints and

permit them to vacuum weld. In this event the structural damping of the

assembled structure would approach the inherent damping of the materials -

a reduction of one or more orders of magnitude. A conservative approach

in this case would be to use welded joints in the construction of dynamic

models to assure that the amplification factors for the full-scale structure

do not exceed those of the model insofar as structural damping is concerned.

MODEL SUPPORT SYSTEMS

Launch Vehicles

In essentially all cases of interest, the boundary conditions for launch

vehicles are essentially free-free, and an equivalent support system must be

used during dynamic model tests to assure that the natural frequencies, mode

shapes, structural damping, and dynamic response of the model represent those

which occur on the full-scale vehicle under flight conditions. The fundam-

ental criteria is one of frequency separation. If the frequency of the

support system can be made sufficiently low compared to the natural frequency

of the lowest frequency natural mode of interest, say by a factor of 3 octaves, the effect of the support system on the structural characteristics of the model can usually be neglected.

If the structure of the vehicle is such that it may be handled as a unit and can be oriented horizontally, the better approach is usually to support it as shown in figure 20. In this type of support system, the effect of the support is secondary, and if, in the excitation of the natural modes of the structure, the supports are located at the nodal points, their effect on the structure is negligible. It is usually desirable to mount the exciter near an anti-node to maximize the response of the structure in the mode of interest. However, if the response of the vehicle indicates coupling of other modes, such coupling can be minimized by mounting the exciter at a node point of the mode producing the undesired coupling effect.

In general, the support cables should be made of elastic shock cord but the results of many tests of small solid-propellant rocket vehicles at the Langley Research Center indicate that steel cables can be used successfully if properly adjusted. In most cases, a two-point support is adequate for such vehicles, the location of these supports being adjusted to coincide with nodal points of the mode being excited.

In some cases, particularly those involving vehicles containing liquid propellants and thin pressurized shells, it is necessary to orient the vehicle vertically to properly simulate the effects of the earth's gravitational field on the dynamics of the vehicle-propellant system. Robert W. Herr of the Langley Research Center has studied this problem, reference 7, and has developed two unique and very effective support systems which are shown in figure 21. Both of these systems closely duplicate the

free-free boundary conditions for such vehicles.

The first of these vertical support systems is referred to as a high-bay harness. The weight of the vehicle is carried by two support cables which are attached to the bottom of the vehicle and to the overhead support structure. Stability is achieved by two horizontal restraining cables tied between the support cables and the periphery of the vehicle at some point, e.g., above the vehicle's center of gravity. This support system has essentially two degrees of freedom in the plane normal to the cables - translation as a pendulum and pitching. In terms of the dimensions shown on the figure, the stiffness, and thus the frequency, of the pitching mode can be controlled by separation of the points where the support cables fasten to the rigid support structure. The vehicle will stand erect if

$$a > f \left(\frac{b}{e_1} - \frac{c}{e} \right) + b$$

and the frequency of the pitching mode will approach zero as

$$a \rightarrow f \left(\frac{b}{e_1} - \frac{c}{e} \right) + b$$

This support system was used successfully on the 1/5-scale SA1-Block I, and the 1/40-scale SATURN V dynamic models studied at the Langley Research Center.

In some instances involving the tests of very large dynamic models or full-scale launch-vehicle structures, it may be difficult to provide an overhead rigid support structure as necessary for the high-bay harness. In such cases, the low-bay harness, though slightly more complicated is

preferable and is being used for the structural dynamics studies of the
full-scale Thor-Agena launch vehicle to be conducted at Langley in the
near future. As was the case for the high-bay harness, the weight of the
vehicle is carried by two support cables. However, in this case the
support cables may be much shorter than the length of the vehicle. The
vehicle is held erect by controlling the tensions in the restraining
cables by means of turnbuckles, and the condition for neutral stability,
and hence, zero frequency in pitch, is

$$T = \frac{Wb}{8(\frac{L^2}{d} - S)}$$

Although it is still necessary to have some support structure near the top
of the vehicle, this structure can be relatively light since it need sup-
port only a small fraction of the weight of the vehicle.

Spacecraft

Since the majority of spacecraft are small relative to the size of
launch vehicles, the support of spacecraft models for dynamic studies can
be accomplished with comparative ease. Since spacecraft are usually mount-
ed to the launch vehicles in semirigid fashion, the in-flight support system
is closely representative of fixed-free boundary conditions. Hence the
general procedure is to rigidly fasten the spacecraft to the exciter for
tests along the longitudinal or flight axis, and to attach the spacecraft
to a slippery table for excitation of lateral modes and frequencies. It
is important to recognize, however, that the impedance of the support system,
whether it be the exciter or slippery table, will differ from that of the
launch vehicle, and proper consideration of this fact should be exercised

during interpretation of the response data obtained during vibration tests of spacecraft or spacecraft models.

CONCLUDING REMARKS

During recent years, dynamic models have been used to good advantage for solution of some of the problems related to structural dynamics of space vehicles. Because of the size, complexity, and cost of the structures and the variable environments which constitute the structural loads, it appears that current trends which involve the construction and testing of specialized models for analysis of structural characteristics, and responses to ground winds, wind shear, buffeting, and fuel sloshing loads will continue in the foreseeable future. Much additional work is necessary to understand the effects of the highly transient nature of structural properties and loading conditions, and to establish appropriate modeling techniques for their simulation and analysis. Particular attention is needed in the areas of simulation of the coupling of propellant systems with the structure to avoid instabilities such as the POGO oscillations.

As pointed out in the paper, careful attention must be given to proper simulation of both aerodynamic and structural damping in model design and testing.

Proper support of launch-vehicle models to simulate free-flight conditions during tests is important, and methods are presented in the paper which have proven to be adequate and simple.

In several areas of concern such as fuel sloshing and lunar landing, gravity is an important variable. Some of the techniques which may be employed to simulate gravity effects are discussed.

APPENDIX

DIMENSIONLESS RATIOS

The dimensionless ratios which pertain to fluid and flight dynamics are summarized in the following table. The variables which are combined to form the various ratios are defined in the symbols, which are presented at the end of this appendix. Insofar as possible, pertinent references are given which relate to their derivation and use.

SYMBOLS FOR DIMENSIONLESS RATIOS

Symbols and definition	$\left(\begin{matrix} l,\ m,\ t, \\ T,\ Q \end{matrix}\right)$ dimension	Frequently used dimension
a sonic speed	l/t	ft/sec
B magnetic induction field	m/Qt	
b semichord	l	ft
c_p specific heat at constant pressure . . .	l^2/t^2T	Btu/lb-°R
c_v specific heat at constant volume	l^2/t^2T	Btu/lb-°R
D coefficient of self-diffusivity	l^2/t	
E_1 energy	ml^2/t^2	ft-lb
E_2 modulus of elasticity in tension	m/lt^2	lb/in.^{2}
F force	ml/t^2	lb
G_1 modulus of elasticity in torsion	m/lt^2	lb/in.^{2}
g gravitational acceleration	l/t^2	ft/sec^2
h heat transfer/area/time/temperature . .	m/t^3T	Btu/ft^2/sec/°R
k Thermal conductivity	ml/t^3T	Btu/hr-ft-°R
l reference length	l	ft
L length of mean free path, $\dfrac{16}{5}\dfrac{\mu_1}{\rho\sqrt{2\pi RT}}$ . .	l	ft
m unit of mass	m	lb-sec^2/ft
$\dot{m}$ mass flow rate	m/t	slugs/sec
m_1 mass flow rate	m/t	lb-sec/ft
p local static pressure	m/lt^2	lb/ft^2
p_c critical or vapor pressure	m/lt^2	lb/ft^2
Q unit of electric charge of flux	Q	coulombs
Q_1 heat added at constant pressure	ml^2/t^2	Btu

Symbol and definition	$\left(\begin{array}{c} l,\ m,\ t, \\ T,\ Q \end{array}\right)$ dimension	Frequently used dimension
q dynamic pressure	m/lt^2	lb/ft^2
R universal gas constant	l^2/t^2T	
r radius	l	ft
T temperature	T	°R
t time . . . . , . . .	t	sec
V speed	l/t	ft/sec
V_a Alfven wave speed, $\sqrt{\dfrac{B^2}{\mu_2\rho}}$	l/t	ft/sec
β coefficient of thermal expansion	$1/T$	in./in.-°R
μ_1 coefficient of viscosity, abs	m/lt	$lb\text{-}sec/ft^2$
μ_2 magnetic permeability	Q^2/ml	
ρ mass density	m/l^3	$lb\text{-}sec^2/ft^4$
σ_1 coefficient of surface tension	m/t^2	dynes/cm
σ_2 electrical conductivity	Q^2t/ml^3	ft^3/ohm
σ_3 structural density	m/l^3	$lb\text{-}sec^2/ft^4$
ω frequency	$1/t$	rad/sec
ω_α torsional frequency	$1/t$	rad/sec

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DIMENSIONLESS RATIOS

Name	Symbol	Associated variables	Meaning	Application or comments	Reference
Biot	B_i	hl/k_b	Heat transferred to fluid / Heat transferred through body	Compares external thermal resistance to internal	13
Bond		$\rho l^2 g/\sigma_l$	Gravity/Surface tension	Capillary flow, sloshing equals $1/F \times W$	17
Cauchy	C	v^2/a^2	Inertia/Fluid elastic	Compressible flow equals M^2	8
Cavitation	σ	$(p - p_c)/q$	A pressure coefficient	Hydrofoils, liquid nozzles, and pumps	8
Dam Kohler's 1st	Dam 1	l/Vt_{chem} or $t_{transl.}/t_{chem}$	Transit time / (Relaxation time, Reaction)	Real-gas effects	9
Dam Kohler's 2nd	Dam 2	$q_L/c_p T_o m$	Heat content after reaction / Heat content before reaction	Real-gas effects	9
Structural damping coefficient	$\bar{g}$		A measure of energy dissipated during vibration due to structural friction	Free, forced, and self-excited vibrations of structures	14
Euler	E	$p/\rho v^2$	Pressure/Inertia	Pressure distributions	8
Force coefficient	C_F or C_R	$2F/\rho v^2 l^2$	Fluid force/Dynamic pressure × Area	Immersed moving bodies	8
Fourier	F_o	$kt/\rho g c_v l^2$	Heat conducted/Heat capacity	Temperature-time problems	13
Froude	F_r	v^2/gl	Inertia/Gravity	Surface ships, airplane flight path, structural sag	10, 8
Graetz		$\dot{m} c_p/kl$	Heat transported by fluid motion / Heat transported by molecular motion	Laminar convective heat transfer in pipe equals Constant × P_e	11
Grashof	G	$\beta(\Delta T)g l^3 \rho^2/\mu_l^2$	Inertia × Buoyant/(Viscous)^2	Free thermal convection equals $\beta(\Delta T) \times R_e^2/F_r$	11, 2
Hartmann	H	$Bl\sigma_2^{1/2}/\mu_l^{1/2}$	Magnetic/Viscous	Flow of viscous magnetic fluid	8
Knudsen	K	l/L	Reference length/Mean free path	Free molecule flow equals $1.28\sqrt{\gamma}\, M/R$	8
Lewis	L_e	$Dc_p\rho/k$	A fluid property	Equals P_r/S_c	9

DIMENSIONLESS RATIOS - Concluded

Name	Symbol	Associated variables	Meaning	Application or comments	Reference
Mach	M	V/a	Inertia/Fluid elastic	Compressible flows	8
Magnetic Mach	Mn	V/V_a	Flow speed/Alfven wave speed	Magnetic compressibility	8
Magnetic Reynolds	Rm	$Vl\sigma_2/\mu_2$	Motion induced field/Applied field	Fluid field interaction	8
Nusselt	Nu	hl/k	$\dfrac{\text{Heat transferred to fluid}}{\text{Heat transferred through fluid}}$	Convective heat transfer	11, 2
Peclét	Pe	$c_p Vl/k$	$\dfrac{\text{Heat transported by fluid flow}}{\text{Heat transported by molecular motion}}$	Compressible flow equals R × Pr	11
Poisson	μ	$\left(E_2/2\sigma_1\right) - 1$	$\dfrac{\text{Lateral contraction}}{\text{Longitudinal extension}}$	Elasticity	15
Prandtl	Pr	$c_p\mu_1/k$	A fluid property	Equals 2/3 monatomic, 3/4 diatomic, $\frac{2}{5}$ ~1.0 polyatomic	2
Regier	R_r	$b\omega/\sqrt{\mu_3/s}$	Measure of torsional stiffness required for neutral flutter stability	Flutter index for subsonic speeds	18, 19
Reynolds	R_e	$\rho Vl/\mu_1$	Inertia/Viscous	Skin friction, boundary layers, sedimentation	8
Schmidt	S_c	$\mu_1/D\rho$	A fluid property	Equals 0.7 to 0.74 real gases	10
Sherwood		S_cN_u/Pr	Mass transfer by diffusion	Mass transfer in gases	13
Specific-heat ratio	γ	c_p/c_v	A gas property	Ideal isentropic gas flow equals 1.67 monatomic, 1.4 diatomic	8
Stanton		$h/c_p\rho V$	$\dfrac{\text{Heat transferred to fluid}}{\text{Heat transported by fluid flow}}$	Conductive heat transfer	11
Strouhal		$l\omega/V$	$\left(\begin{smallmatrix}\text{Vibration}\\\text{Shed vortex}\end{smallmatrix}\right)$ speed/Transl. speed	Flutter, wind-induced oscillation	16
Viscoelastic		$\sigma_1/\omega\mu_1$	Elastic shear/Viscous shear	Dynamics of plastics and "thick" liquids	12
Weber	W	$\rho V^2l/\sigma_1$	Inertia/Surface tension	Ripple surface waves, capillary flow	11
Nuclear explosion	λ	$r/\left(\left(\frac{E_1}{\rho}\right)^{1/5} t^{2/5}\right)$	Growth parameter	Spherical wave instant energy added at center	8
Magnetic-dynamic	N	$\sigma_2 H^2l/\rho V^2$	Magnetic/Dynamic pressures	Magnetic fluid flow	8
Mass ratio	μ_3	σ_3/ρ or $m/\frac{\pi}{4}\rho l^3$	Structural mass/Fluid mass	Flutter, airplane stability	4
		$E_2/\rho V^2$	Structural stiffness/Aero. force	Aero. deflections	4
		$\sigma_3 gl/E_2$	Structural weight/Stiffness	Sag due to weight	4