XI, 2

12/3-5/63

Section 5
APPLICATION OF DATA TO DESIGN

DESIGN OF SPACE VEHICLE STRUCTURES FOR VIBRATION AND ACOUSTIC ENVIRONMENTS*

C. E. Lifer
Marshall Space Flight Center, NASA

The advances in design state-of-the-art for space vehicle structural vibrations have not kept pace with improvements in environment definition and testing. As vehicles become larger and more expensive, this gap must be eliminated. The need for a uniform design approach throughout the aerospace industry is presented and a proposed basis derived by the MSFC is explained.

Considerable attention and effort have been devoted during the past 10 years to the definition of space vehicle vibration and acoustic environments, and to the development of better test techniques and equipment. Instrumentation of test vehicles has grown tremendously in both the number and the range of measurements, and data acquisition systems have been improved in order to make the information more accurate and useful. The introduction and refinement of random testing equipment and procedures, the development of high-force shakers, and the increased recognition and use of acoustic testing have contributed to much more reliable space vehicles. Although there is still a wide variation in the approaches to vibration and acoustic testing, the need for these tests is now accepted by all aerospace manufacturers.

For the most part, however, efforts at optimizing design procedures for vibration and acoustic environments have been unsuccessful, and comparatively little has been accomplished in this area. There is still a widespread belief among designers and manufacturers that it is not possible to design for vibration, or that the only way to consider vibration and acoustic environments is to design for the static loads with an arbitrary factor applied to these loads to cover vibration, acoustics, and other mysterious unknown loads. The component or structure is simply tested (and often redesigned and retested) to determine its adequacy under the specification environments. It is true that this procedure usually will accomplish the end result of a satisfactory component or structure, but in many cases it will result in an overdesign or in a costly test and redesign effort.

At present there is wide variation in methods and philosophies of designing for vibration and acoustics in the aerospace industry. This state of confusion is the result of the varying experiences of manufacturers with different missile and space vehicle programs, and of the absence of a centralized controlling or monitoring agency to establish a recommended procedure which has been successfully demonstrated on several design programs. The two extremes of this variation are the total disregard of vibration loads in design and the very conservative analysis using maximum environmental levels and assumed response amplifications greater than those normally encountered in practice. The first extreme invariably requires much redesign and retesting before an acceptable product is achieved, while the latter usually produces an overweight or non-optimized design. The most desirable approach is one in which a design is based on vibratory and acoustic

*Invited paper.

loads of carefully selected probability of occurrence and based on the most thorough and accurate structural analysis possible, combined with developmental testing.

The assurance of required vehicle reliability through analysis and testing has become much more important because of the manned space flight program. At the same time, we must develop more efficient space vehicles in order to increase their payload weight capability. In order to satisfy both these requirements, design for vibration must be more accurate than it has been in the past. The technology of predicting structural response must be improved, and design procedures must be developed uniformly throughout the aerospace industry.

In order to define the reliability of a space vehicle, the reliabilities of its components must be known. If various components are designed and tested to criteria which are not compatible, or even similar, the definition of reliability of the whole system becomes impossible. Design procedures for static loads, thermal stresses, pressures, and wind loads are relatively uniform throughout the industry, but vibration and acoustics design have been left open to interpretation.

As an example, let us examine a large space vehicle now under development. The engine manufacturers do not believe in vibration load design, and since their contracts do not specifically require them to design for vibration, they use the cut-and-try method of building and testing. When vibration failures occur they merely beef up the failed part and continue testing. The first stage manufacturer is at the exact opposite pole, using a large force of dynamics analysis to calculate vibratory and acoustic forces for each component and substructure, and using very conservative load prediction techniques. The second stage manufacturer is somewhere in between the two extremes, performing limited analyses in support of design within his stress analysis section, analyzing only those items which look questionable from vibration standpoint, and using a much less conservative load prediction procedure than that of the first stage producer. The third stage is designed using still another approach to vibration and acoustic loads, and finally one payload design has as yet not considered vibration in the preliminary design analysis.

From the above information, how does one attempt to define system reliability from the vibration and acoustic aspect? The answer is that one cannot readily predict the reliability of this system design until extensive ground and flight tests have been completed. Furthermore, if the ground test specifications and procedures are not uniform and compatible, their results will be difficult to use in establishing reliability. Since design of new vehicles and their components for vibration and acoustics are based primarily on the environmental specifications, a uniform system design requires uniform specifications for all portions of that system. To further point out this problem, components and stages are often used on more than one vehicle system, and uniform design and test specifications and procedures for all systems would facilitate the selection and evaluation of these components for use on new vehicles.

The need for vibration testing of space vehicle structures and components prior to flight testing the system assembly became obvious as these vehicles grew more complex and costly, and extensive development and qualification tests are now accepted as integral parts of vehicle programs. In a similar manner, increasing complexity and cost of structural components and of test programs require good assurance before designs are released for manufacture that they will withstand their environmental vibration and acoustic conditions. This assurance can come from a proper consideration of these environments in the structural design, through analysis and development testing.

The vibration and acoustic environment conditions which are significant in design usually result from engine or stage static firings or system flight tests. The energy sources are: combustion and exhaust flow noise; turbopump vibrations; ignition, release, and cutoff dynamics; and, aerodynamic and buffeting pressures resulting from high-speed flight through the atmosphere. In addition to the conditions of static and flight tests, ground handling and transportation conditions should be covered in the environmental specifications. The sources of vibration energy are generally random in nature, but their mean level variation with frequency and time can be predicted with fairly good confidence.[1,2] The transfer characteristics of the vehicle structure modify the statistical nature of the environment in such a way that, at a typical structural section, the response

[1] R. H. Lyon and P. A. Francken, "A New Approach to The Estimation of Space Vehicle Vibration," Bolt, Beranek, and Newman, Inc., Report No. 815 (May 1962).

[2] I. Dyer, "Response of Structures to Rocket Noise," Chap. 7 of Random Vibration, Vol. 2, Edited by S. H. Crandall (The M. I. T. Press, Cambridge, Mass., 1963).

usually resembles several superposed sinusoids which have randomly varying amplitudes.

The dynamics analysts and the designers rely on the specification writers to describe the vibration and acoustics environment accurately and in sufficient detail to permit prediction of vibration loads. Some of the requirements of a good specification from the design viewpoint are described below:

1. The specification must be based on well defined and meaningful reliability values. These should be established considering vehicle or system mission, criticality of individual structures, and cost.

2. The specification must be in sufficient detail to cover the wide variation of environments which occurs between structures of different mass and geometry. It should also be specific as to whether the values listed are to be regarded as inputs or responses.

3. The definition of time or condition for which the environment applies should be included wherever possible, since vibration loads must be added to other time varying loads. Figure 1 illustrates this need.

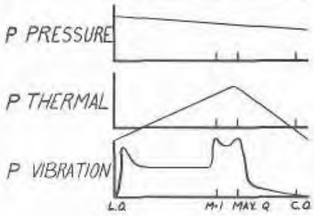

Fig. 1 - Flight time vs loads

4. The specification should be kept current so that it includes any effects of design changes, results of analyses and tests, etc. It should become increasingly accurate and detailed as more knowledge is obtained.

The effects of the vibration and acoustic environments which are important to a structural designer are the loads or stresses induced in materials and connections, and the displacements which result from these loads. The loads are response inertial loads which cannot be considered as static loads except at the point or section for which they are calculated. Similarly, the displacements must be defined with respect to points on a structure. Since the environment is basically random, the loads and displacements must be described in terms of probability of occurrence, and in terms of the contributing modal frequencies.

Assuming that the specifications have been perfected to the level or state described above, it remains for the designer and the dynamics analyst to achieve a structural design which is best suited to withstand the environments of that specification in conjunction with other conditions. The basic intent of this paper is to prescribe an organizational arrangement, and a functional procedure which will make the achievement of this end more probable and less costly in time and effort. An outline of this procedure is shown in Fig. 2.

In order to be most efficient, the consideration of vibration and acoustics must be included in the preliminary design or concept phase of structural development. The reason for this is quite well known to dynamics analysts who have had to recommend that a design be changed extensively in order to have better dynamic characteristics. Once a design concept has been studied from the normal aspects of weight, static strength, producibility, and the like, it is very difficult and costly to convince the designer, as well as management, of the necessity for changing the design, thus requiring restudy and reevaluation. During the preliminary phase, the configuration and material selection are most readily influenced, and parameter studies can yield valuable results. An illustration of this is shown in Fig. 3.

The preliminary design phase is an appropriate time to consider the use of materials and fabrication techniques which will improve the vibration and acoustic response characteristics of a structure. These practices and materials have been in existence for several years, yet their use is still resorted to only in problem areas where standard techniques have proved unsatisfactory. The usual practice is still to modify the equipment to take the structural response environment rather than design the structure to have a minimum environment. I submit that we are reaching the limits of the use of such a philosophy. This subject has been

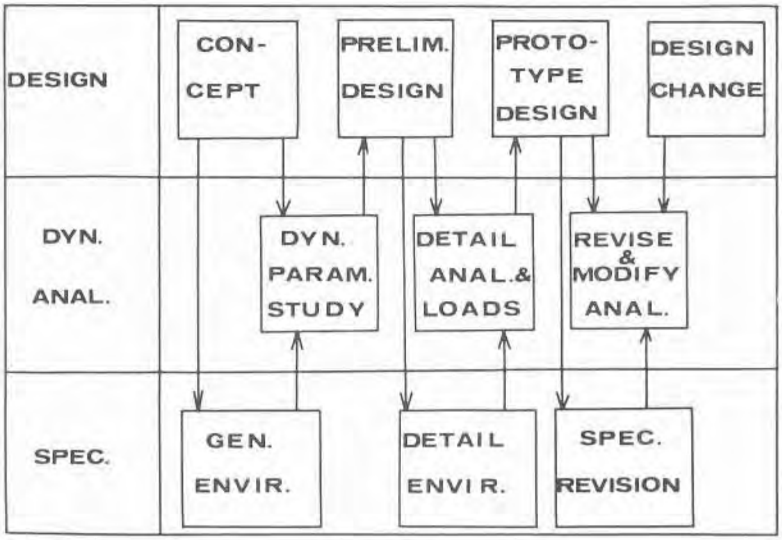

Fig. 2 - Dynamics support of design

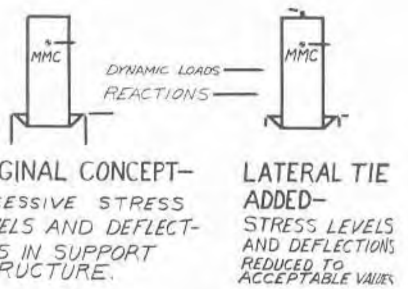

Fig. 3 - Concept analysis

treated extensively in Refs. 3 through 5, and the details will not be repeated here.

As an example of the applications of dynamics analysis to the preliminary design phase, let us take an imaginary payload structure and assume the mission of this payload, its maximum structural weight, exterior shell configuration, and vehicle location and interface definition are the only fixed or predetermined characteristics. It is known that certain components and equipment must be included in this payload, but their exact location and method of support are left to the designers. Working with the designer, the dynamics analyst can study possible configurations to compare their response to the vibration and acoustic excitations of the launch vehicle. If a particular internal component is sensitive to acoustic energy, methods of acoustic isolation such as those employed in submarines and oceanographic research vessels[6] may be employed in structural configuration. Arrangements of structure to de-tune or de-couple resonances can be studied analytically by making use of analog computers and small-scale dynamic model tests. Mountings of components which are sensitive to vibration may be studied to determine if grouped "cannister" mounting is superior to a dispersed mounting arrangement. In these studies, simple mathematical models are utilized in analysis, such as in Fig. 4.

Once the payload configuration and component locations have been established, the dynamics analyst can provide the designer with approximate vibration loads for components and structures for use in his preliminary design, and can tell him which components require vibration isolation mountings. An iterative process is then conducted, as the designer derives

[3] M. A. Hechl, R. H. Lyon, G. Maidanik, and E. E. Ungar, "New Methods of Understanding and Controlling Vibrations of Complex Structures," ASD-TN-61-122 (June 1963).

[4] E. G. Fischer and H. M. Forkois, "Theory of Equipment Design," Chap. 42, and "Practice of Equipment Design," Chap. 43 of Shock and Vibration Handbook, Vol. 3 (McGraw-Hill Book Co. Inc., New York, 1961).

[5] C. M. Harris, Editor, Handbook of Noise Control (McGraw-Hill Book Co. Inc., New York, 1957).

[6] I. P. Vatz and R. F. Williams, Jr., "Development of Noise Control Specifications for the Woods Hole Oceanographic Research Vessel," Edited by H. C. Herreshoff, New England Section, SNAME, Bethlehem Steel Co. (Oct. 1962).

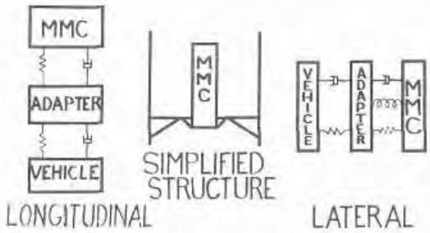

Fig. 4 - Preliminary dynamic model

structural details such as member sizes and materials and the dynamics analyst incorporates these in his study to provide more accurate loads and recommends changes. It follows naturally that as the stage of design progresses the analysis should become more and more detailed, i.e., the mathematical model of a structural system should include more mass-spring-damper elements, and sub-system studies should be made in order to provide detailed design information. Figure 5 illustrates a detailed analysis model.

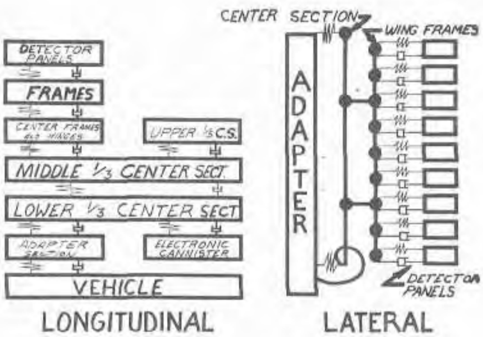

Fig. 5 - Detail dynamic models

Development tests provide valuable support to design and should be considered in any large structural development program. These tests may range from small scale model tests and tests of individual structural components through an exact replica of the system. Their purpose may be merely to provide response information (damping, and the like) about structural elements, or they may be used to select a design concept for the system. When used to supplement a thorough analysis, they permit accurate prediction of environmental response and more efficient structural design.

As was indicated previously, the support of final design is an extension and refinement of the preliminary design analysis work, making use of the results of development tests and, when possible, qualification and static firing tests. In the case of long-duration programs, designs may be improved as the result of static firing tests and flight tests. The environments, or the structural response, may be shown to be less severe than that predicted, and the need for weight savings may justify redesign for the actual environment.

One principle which should be kept in mind is that the accuracy of prediction techniques for environments and of the load calculation procedures does not warrant carrying the resulting accelerations, loads, or pressures to more than two or three decimal places. Admittedly, it is much more impressive (on the surface) to tell the designer to include an acoustic response stress of 11,976 psi in his design that it is to quote a figure of 12,000 psi, but a predicted acoustic level of 155 ± 2 db does not warrant such accuracy.

In order to accomplish the close and strong support of the designer, as was described above, it is necessary to have a strong dynamics analysis group consisting of engineers familiar with design as well as with vibrations and acoustics. The theory and methods of analysis are well established and are described quite adequately in the literature,[7-10] and can be learned by engineers with the above experience in a short while, so that with a small nucleus of dynamicists one can develop an effective analysis group in a matter of a few months. Figure 6 illustrates methods of analysis which are commonly used.

The possible organizations which may be used are diverse, but for most effective coordination one where dynamics analysis, stress analysis, and design are together under one organizational head is recommended. The most desirable are those arrangements which provide close teamwork with minimum organizational bottlenecks. When such organizational

[7] J. P. Den Hartog, Mechanical Vibrations, Fourth Edition (McGraw-Hill Book Co. Inc., New York, 1956).

[8] C. T. Morrow, Shock and Vibration Engineering, Vol. I (John Wiley and Sons, New York, 1963).

[9] H. H. Hubbard and J. C. Houbolt, "Vibration Induced by Acoustic Waves," Chap. 48 of Shock and Vibration Handbook, Vol. 3 (McGraw-Hill Book Co. Inc., New York, 1961).

[10] C. E. Crede, "Failure Resulting from Vibration," Chap. 5 of Random Vibration, Vol. 2, Edited by S. H. Crandall (The M. I. T. Press, Cambridge, Mass., 1963).

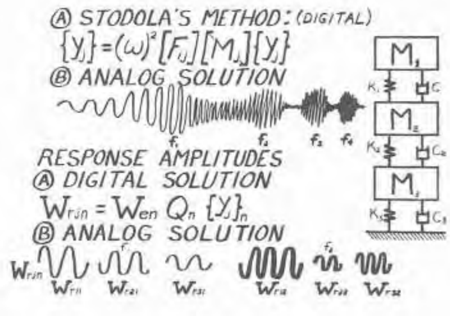

Fig. 6 - Analysis procedure

alignments as described above are not possible, an alternate arrangement would be for the dynamics analysis group to have drawing signoff responsibility, just as the stress analysis group normally has. This does not insure the close support during the early design stage described previously, and must be supplemented by liaison activity. The effective utilization of development testing indicates the similar need for close organizational ties with a testing facility whose services would be available quickly to the analysis personnel. For a majority of these tests, a small facility would be sufficient, and large tests could be performed by other laboratories.

One of the major problems in designing for vibrations and acoustics is the selection of a "sigma level" for design, or a design factor for the levels given in the environmental specifications. Ideally, one would determine the expected number of cycles of each level of vibration and do detailed fatigue damage study to arrive at a design. This is not feasible economically, nor is it warranted by the accuracy of the specifications and load calculation procedures. It remains for the dynamics analyst, therefore, to select an optimum procedure for deriving design loads, pressure, and so on, from the specifications. This must be done considering the probability and confidence level of the specification environment, the required confidence in the vehicle design, and the manner in which the designer uses or treats the loads which are given him.

The environmental specifications derived by the Propulsion and Vehicle Engineering Laboratory at the Marshall Space Flight Center consist of acoustic specifications and random, sinusoidal sweep, and sinusoidal resonance dwell vibration specifications. In addition, shock test specifications are included. The sinusoidal resonance dwell levels have been determined to represent the optimum design vibration environment level, considering the confidence level requirements of man-rated vehicles and the design practices of contractors (as required by design criteria). The resulting design if felt to be near optimum, with an effective confidence level of 97.5 percent and a probability of 2.8 sigma for the predicted environments.

The procedure described above is not being specified as the optimum procedure, for use by all agencies because it has been shown to be perfect. Rather, it is being recommended in order to achieve some degree of compatibility in design in at least a segment of the industry. If all contractors on even one vehicle program utilize this procedure and experience similar results (hopefully they would be successful results), this could be used as a basis for deriving an improved procedure. It could be pointed to as an example of a complete system design with compatible, uniform consideration of vibration and acoustic environments.

I would like to recommend to the leaders in this field, both in government and industry, the formation of a representative working group to study the serious problem of structural design for vibration and acoustic environment. The specific areas of study would include the following:

1. What are the design practices which have been most successful in producing structures to withstand their environments?

2. In those successful practices, what was the relationship of design to specifications?

3. What was the statistical confidence in the specification environment?

4. What was the target confidence level in the successful design procedure?

5. Is the concept of uniform and compatible specifications feasible?

6. If compatible specifications is a possibility, what steps are needed to achieve this goal?

7. What research has been done, and what must be done in order to better define the optimum design procedure?

It is suggested that this working group consist of personnel from government agencies, universities, or independent laboratories. Representatives of industry and government could be requested to assist in exploring the problem areas. Should this working group derive positive results, it should make them widely known over the entire engineering field.

With the application of the principles I have described above, and with careful study by a conscientious engineering working group, the art of designing structures for vibrations and acoustics can become a science.

* * *