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An Overview of Vibration Testing



Rotating machinery diagnostics are being conducted using a portable vibration frequency analyzer specifically designed for such field in situ testing tasks. Such machinery monitoring is important to achieve optimum machine performance over long periods of time with minimum unscheduled maintenance. (Photo courtesy of *Sound and Vibration*)

1.1 INTRODUCTION

This book is dedicated to obtaining the maximum possible benefit when applying vibration testing techniques to a wide range of practical vibration problems. Maximum benefits are obtained when appropriate instrumentation and analysis techniques are used that are consistent with the desired test objectives for a given machine and/or structure. The most sophisticated and brilliant analysis methods are easily defeated by poor, inaccurate, or inappropriate data. Thus, one needs to understand the fundamental principles that are involved in these tests so that an informed skepticism can be brought to bear on the test results. “Why is this glitch here?” is often an important starting point in understanding that there may be problems with a certain set of test data.

Vibration tests are run for a number of reasons. Among them are:

1. Engineering development testing
2. Qualification testing
3. Reliability qualification testing
4. Production screening testing.
5. Machinery condition monitoring.

The same types of instruments, frequency analyzers, and analysis methods are employed in nearly all types of tests. Different types of vibration exciters are employed in other tests. In some cases, the tests are run in the laboratory. In other cases, the only way the test can be properly conducted is in the field under actual operating conditions to determine why a particular part of the structure is either quickly deteriorating or failing to function correctly under service conditions. Because of this wide range of techniques and goals, *the intent of this book is to cover a large range of fundamental concepts that are useful in most vibration testing situations.*

The point at which I became aware of vibration testing as an engineering activity isn't important, but I do know that it was not during the laboratory exercises during my first vibrations course. However, when I worked at the Naval Ship Research Center at Carterrock, Maryland, I began to sense that getting good field vibration data was not a simple matter. At any rate, over the years a number of experiences have led me to attempt to identify what vibration testing is and how vibration testing fits into the engineering function. One thing is evident: In attempting to identify what vibration testing is, interesting facets come to light.

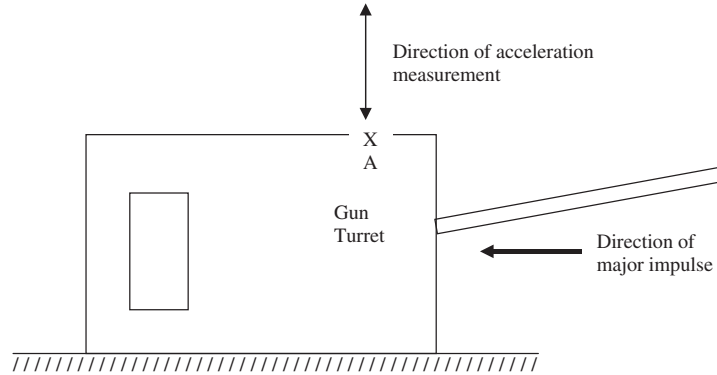


Figure 1.1.1 Schematic of a gun turret showing location of acceleration measurements.

I clearly remember an interesting event that occurred in the late 1960s at a Shock and Vibration Symposium. The essence of the story is that the U.S. Navy wanted an electronic device mounted on top of a large gun turret, as shown in Fig. 1.1.1. Apparently, navy personnel measured the vertical acceleration at point A, where the electronic device was to be mounted, while several shells were fired from the gun. These acceleration records were used to develop the device's *dynamic environment*. The electronic device was designed, tested, and passed this dynamic environment. Yet when the device was installed, it failed to function after the first firing. Obviously, there was a problem in translating the measured dynamic environment into an adequate test specification. What happened?

First, the vertical acceleration at point A is probably significantly less than the horizontal acceleration resulting from the reaction to firing the gun in a nearly horizontal direction. Second, the electronic device was mounted so that it presented a significant frontal area to the gun's air blast. It is clear that either of these two inputs could be the source of significant shock loading and large vibration levels. Obviously, the procedures employed were inadequate and caused unnecessary grief to all parties concerned.

This story illustrates that significant questions need to be answered in planning vibration tests, such as:

1. What field data should be taken?
2. Where should the transducers be placed on the test item to achieve the maximum useful information over a given frequency bandwidth?

4 AN OVERVIEW OF VIBRATION TESTING

3. How should the field data be stored for future reference and recall?
4. What is the effect of changing boundary conditions between field and test environments due to test fixtures?
5. Which testing procedures are best suited in simulating a given field environment?

These and certainly other questions need to be answered in order to properly plan the field test as well as a corresponding laboratory simulation.

In another instance, while I was preparing to conduct vibration tests on a company's product, I found the test specifications to be quite contradictory. If I followed one set of specifications, it appeared that nothing would fail because the inputs were so low, whereas following another set of specifications could result in a premature failure because the inputs were so large. In struggling with these contradictory requirements, it became evident that the test specifications were quite arbitrary, since no one could provide me with actual field data. Thus, no clear means was available to determine what the test specifications should be, and we were left to make our own judgments. Obviously, we chose to be conservative, which in turn added unnecessary weight to the product.

I had enlightening experiences during two summers where I was involved in reviewing the shock and vibration testing procedures employed at Sandia National Laboratories. This review involved interviews with more than a dozen of Sandia's very experienced vibration test personnel. It became clearly evident that some underlying rules for conducting these tests were not being properly addressed by the test standards they were required to use. Fundamental questions about how field data is obtained, stored, and converted to useful test specifications were often discussed during these interviews. Clearly, a better framework is required by which to judge what procedures should be used. While attempting to understand and explain what these rules should be, the basic thoughts contained in Chapter 8 of this book were developed as a framework to guide the processes used in establishing a vibration testing program for a given application. This area requires considerably more thought and research to understand the implications of the many choices we can make in writing a test specification from field vibration data.

A recent experience brought to light an interesting situation where a company's product was experiencing a high rate of field failures and yet passed the *vibration test standard* that is used in the industry. The problem was a lack of understanding the type of vibration they were

trying to simulate in the laboratory. A different type of signal analysis generated a much more severe and realistic vibration test specification. Following the Sandia experience, I surveyed practitioners of vibration testing at more than a dozen sites in the United States in order to determine a broader view of the current state of events in the vibration testing industry. A striking result from this survey is that there is no general theory for vibration testing, so test specifications are often modified based on the tester's experience, much like I had to do when testing a company's product. The survey also revealed that if any model is referred to, it is most often that of a single degree of freedom (SDOF) system, a highly inappropriate model for most testing cases that involve rather complicated structural systems.

Typical comments that were returned are summarized as follows:

1. Writers of test specifications do not recognize test equipment limitations.
2. Required test spectra do not reflect actual vehicle (field) environments.
3. The relation between test level and test item endurance seems to be quite arbitrary.
4. Stress level and duration need to be sensibly related to reliability and endurance testing.
5. Test fixtures are usually much stiffer than the host vehicle.
6. Unless a person oversees instrumentation installation and subsequent data reduction, there is usually insufficient data available to separate sources of excitation.
7. When data is collected by others, sensor location is often poorly defined.
8. "Many people operate in a particular way because that is what they learned to do, without necessarily knowing why or how to predicts results."¹
9. "It takes much more competence to do it correctly than it does to do it the 'standard' way!"¹

It is hoped that this book will illuminate many of the required fundamental concepts so that test personnel will become aware of opportunities to conduct tests better—and hence obtain maximum possible benefits.

¹Personal communication from E. A. Szymkowiak, July 1990.

1.2 PRELIMINARY CONSIDERATIONS

It is hard to decide where to start this adventure, but experience has shown that an overview and precise definitions significantly improve the communication process. Figure 1.2.1 shows a general model of a structure where it is assumed that a transducer (usually an accelerometer) measures the motion X_p at location p . X_p is used to represent displacement, velocity, or acceleration. A common notation used throughout this book is that lowercase letters represent a time domain variable, so that $x = x(t)$, and capital letters represent a frequency domain variable, so that $X = X_p(\omega)$ is a frequency spectrum. This notation is most convenient, since we often have both time and frequency spectra information available from our instrumentation.

Motion X_p is caused by numerous excitation sources. These sources can be *internal forces* (such as rotating unbalances) that are represented by $S_q (= S_q(\omega))$ as well as *external forces*. The external forces are broken into two subgroups: those that are due to *external sources* and are represented by $F_q (= F_q(\omega))$ and those that are due to the presence of a *boundary* and are represented by $B_q (= B_q(\omega))$. Then, if we use the linear input-output frequency domain representation $H_{pq} (= H_{pq}(\omega))$, we can express the *frequency domain output motion* as

$$X_p = \underbrace{\sum_{q=1}^{n_1} H_{pq} S_q}_{\text{internal}} + \underbrace{\sum_{q=n_1+1}^{n_2} H_{pq} F_q}_{\text{external}} + \underbrace{\sum_{q=n_2+1}^{n_3} H_{pq} B_q}_{\text{boundary}} \quad (1.2.1)$$

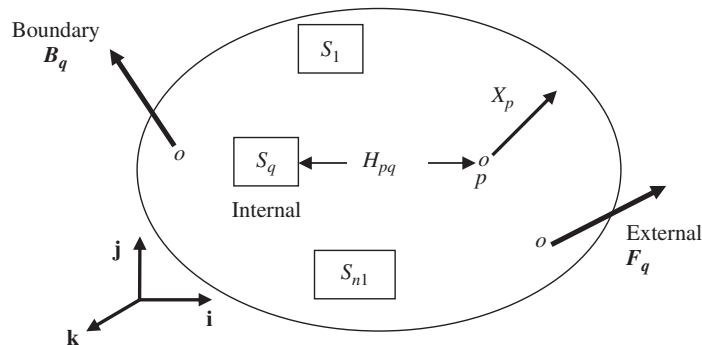


Figure 1.2.1 General structure showing internal, external, and boundary types of excitation forces.

where H_{pq} is the *frequency response function* (abbreviated as FRF) that is a function of frequency ω represents the output motion at p due the excitation forces at location q ,

n_1 is the number of internal sources,
 $(n_2 - n_1 - 1)$ is the number of external forces.
 $(n_3 - n_2 - 1)$ is the number of boundary forces.

FRF H_{pq} can represent *receptance*, *mobility*, or *accelerance* dependent on X_p being displacement, velocity, or acceleration, respectively.

The situation shown in Fig. 1.2.1 is characteristic of the general vibration testing situation where the structure (or machine) vibrations are monitored in order to determine either its dynamic characteristics or its mechanical health. The purpose of the test depends on the end use of the test data. In order to determine the structure's dynamic characteristics, we might do a modal analysis. On the other hand, we may measure the machine's dynamic characteristics in order to determine its operating condition, a process that is often called *machine monitoring*. The test structure could be either an aircraft engine or a steam turbine. Obviously, the boundary conditions, test conditions, and instrumentation requirements are strikingly different for each of these two machines.

Now suppose that a critical circuit board is used in controlling the jet engine, and this circuit board cannot fail during operation. We need to ensure that the circuit board will not only survive but continue to function properly when in this dynamic environment. The question is, how do we go about achieving this goal?

We begin by breaking the problem down as illustrated in Fig. 1.2.2, where we identify several major components that are involved in the process of gathering data, interpreting this data, communicating the results to the major participants. The components are the aircraft, which we shall call the *vehicle*, the circuit board, which we shall call the *test item*, the vibration laboratory, which we shall call the *laboratory*, and the finite element computer program or other design tool, which we shall call simply *design*, and the *process*. In the process part we need to:

1. Obtain experimental field data, which may involve installation of a prototype test item, a different test item, or no test item
2. Analyze the field data, taking field test conditions into account
3. Communicate the field data in the proper form to the designer for use during the design stage

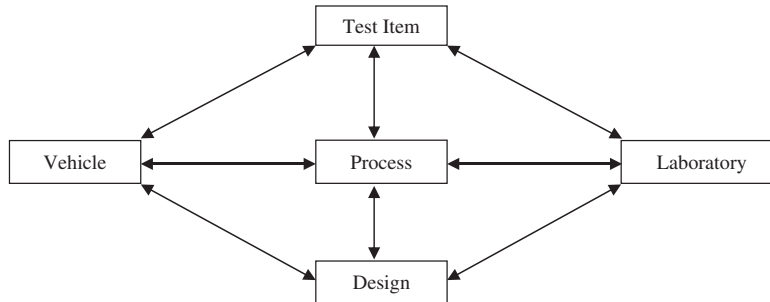


Figure 1.2.2 Definition of major elements and data flow under various test configurations.

4. Provide vibration test personnel with realistic data so that adequate laboratory testing is performed to achieve a realistic dynamic environment

This process often requires communications between persons from different government and/or industrial organizations, and these people may have their own vested interests that are not completely compatible with each other. Consequently, interesting personal relationship situations often occur in large projects, and the importance of skills for working together becomes evident. However, if everyone can keep their eye on the target and cooperate for the common good of the project, the result will be a successful product that is reliable, cost effective, and performs as expected. The full implications of Fig. 1.2.2 will be evident as the reader proceeds through the book.

1.3 GENERAL INPUT-OUTPUT RELATIONSHIPS IN THE FREQUENCY DOMAIN

The input-output *frequency response function* (FRF) plays an important role in experimental vibration testing in general and modal analysis in particular. Generally, standard testing arrangements employ either one or more electrodynamic vibration exciters or an impulse hammer as excitation sources. These excitation sources usually have minimum bending moments if properly implemented. However, in general, boundary forces actually consist of both a resultant force (a vector) and a resultant moment (a vector). Each of these vectors has three orthogonal components in unit vector directions of \mathbf{i} , \mathbf{j} , and \mathbf{k} as shown in Fig. 1.2.1. Similarly, the resultant motion at any point can have three orthogonal

linear motions: and three orthogonal angular motions; one motion for each ($\mathbf{i}, \mathbf{j}, \mathbf{k}$) direction.

The frequency-domain input-output relationship between the measured output motion at location p due to an input excitation applied at location q as shown in Fig. 1.2.1, can be stated as

$$\{U\}_p = [H]_{pq} \{P\}_q \quad (1.3.1)$$

where $\{U\}_p = \{U(\omega)\}_p$ is the frequency-domain motion output vector composed of six entries, three linear motions and three angular motions, that are associated with location p .

$\{P\}_q = \{P(\omega)\}_q$ is the frequency-domain input vector that is applied at location q and is composed of six load components, three forces, and three moments.

$[H]_{pq} = [H(\omega)]_{pq}$ is the 6×6 input-output FRF matrix relating these input and output quantities, and thus contains 36 FRFs for a single pair of measurement points on the SUT! An expanded form of Eq. (1.3.1) is given by

$$\begin{Bmatrix} \{X\} \\ \{\Theta\} \end{Bmatrix}_p = \begin{bmatrix} [H]_{xF} & [H]_{xM} \\ [H]_{\theta F} & [H]_{\theta M} \end{bmatrix}_{pq} \begin{Bmatrix} \{F\} \\ \{M\} \end{Bmatrix}_q \quad (1.3.2)$$

In Eq. (1.3.2), $\{X\} = \{X(\omega)\}$ and $\{\Theta\} = \{\Theta(\omega)\}$ are each 1×3 vectors containing the linear and angular output motions, respectively, and $\{F\} = \{F(\omega)\}$ and $\{M\} = \{M(\omega)\}$ are each 1×3 vectors containing the force and moment input components. As can be seen from Eq. (1.3.2), the full FRF matrix $[H(\omega)]$ is partitioned into four submatrices where three of these submatrices contain information about rotational DOFs. The 3×3 $[H]_{xF}$ matrix relates linear motions to the forces and corresponds to the data obtained in most standard testing procedures. The $[H]_{xM}$ and $[H]_{\theta F}$ matrices contain the FRFs relating either output linear motions due to moment inputs or angular motions due to force inputs. The $[H]_{\theta M}$ matrix relates the angular output motions due to moment inputs.

The importance of rotational degrees of freedom becomes clear when an element of the linear motion vector is obtained from Eq. (1.3.2) such as

$$\begin{aligned} X_{1p} = & H_{11pq} F_{1q} + H_{12pq} F_{2q} + H_{13pq} F_{3q} + \tilde{H}_{11pq} M_{1q} \\ & + \tilde{H}_{12pq} M_{2q} + \tilde{H}_{13pq} M_{3q} \end{aligned} \quad (1.3.3)$$

where subscripts 1, 2, and 3 refer to directions parallel to orthogonal Cartesian x , y , and z directions and \tilde{H}_{rcpq} are the linear output/moment input-output FRFs. Thus, Eq. (1.3.3) shows that six terms are required to fully characterize the relationship between structure's linear motion X_{1p} and its force/moment inputs.

If a single axis accelerometer is attached at the p th location with its primary sensitivity axis oriented in the 1-direction, and only a single input force F_{1q} is measured, then Eq. (1.3.3) reduces to

$$X_{1p} \cong H_{11pq} F_{1q} \quad (1.3.4)$$

which is only approximately true unless care is taken to reduce the unmeasured inputs to being negligible, since the remaining five terms from Eq. (1.3.3) are not accounted for in the measurements described by Eq. (1.3.3). This situation becomes more troublesome when the test structure is attached to another structure at several points. Generally, the test fixture will not simulate the actual field structure, so that the test item's dynamic performance may be significantly different in the laboratory compared to the field conditions. These issues are discussed in Chapter 8.

1.4 OVERVIEW OF EQUIPMENT EMPLOYED

There are many different types of vibration tests. Some involve field measurements while the structure is in its normal operational state; others involve situations where the structure is excited by some external means, either in place in the field or in a laboratory setting. The purpose of these tests can cover a wide range of reasons, such as vibration monitoring in order to determine a machine's suitability for operation, a general vibration survey to find out what is happening, a complete modal analysis to determine the structure's dynamic characteristics, and so on. However, in each instance, commonly used concepts and equipment are involved.

Figure 1.4.1 shows a generic test item with its motion is measured by one transducer system (usually an accelerometer) and the input force is measured by a second transducer system (usually a force transducer). In either case, these transducers often employ either the piezoelectric or the strain gage type of sensing element. The electronic signals from these transducers are amplified electronically and analyzed. The frequency analyzer is commonly employed for analysis purposes. It then becomes the engineers' job to interpret the resulting frequency spectra and to store

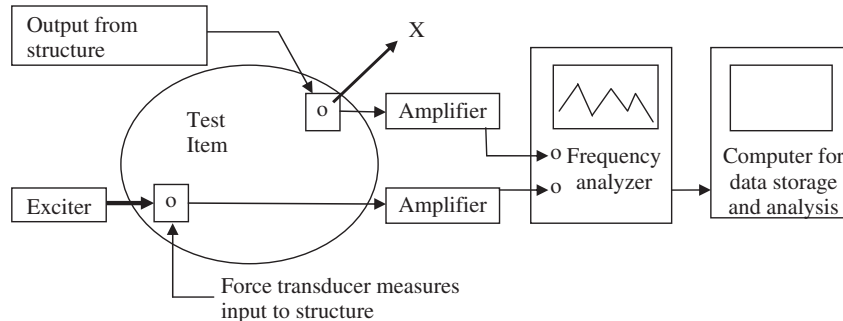


Figure 1.4.1 Generic test items showing force and motion transducers, amplifiers, frequency analyzer, and computer data storage and analysis.

the data in a suitable form. A computer is often used for this purpose.

As one thinks about the processes shown in Fig. 1.4.1, it becomes evident that certain common concepts and physical laws are employed. The task is then to organize these concepts and laws in an orderly fashion so that we can explore their importance. This information is organized into seven additional chapters as follows.

Chapter 2, “Dynamic Signal Analysis,” is devoted to the basic concepts involved in dynamic signal analysis, since these concepts underlie much of what we do in later chapters. Periodic, transient, and random signals are considered on a theoretical basis.

Chapter 3, “Vibration Concepts,” is a review of basic vibration concepts. While we could cite this material from other texts, we have included it here because a certain set of fundamental ideas and view points are required in order to understand what is happening in vibration testing and why procedures should be done in a certain way.

Chapter 4, “Transducer Measurement Considerations,” is concerned with how transducers behave. Models are developed for the mechanical and electrical characteristics of common transducers. Experience indicates that transducers can do interesting and unpredictable things that are caused by the environment that we put them into. Often, the user can dramatically change the transducer’s behavior, so an informed user is required to obtain reliable data.

Chapter 5, “The Digital Frequency Analyzer,” carefully examines the characteristics of the digital analyzer. The rules by which a digital analyzer works are important to understanding what the measured frequency spectrum means. If the analyzer is improperly set, the calculated results may contain grossly distorted information.

Chapter 6, “Vibration Excitation Mechanisms,” concerned with the dynamic characteristics of vibration exciters. These excitations include static release, mechanical, and electromagnetic-type devices. The interaction of these exciters with their test environment is also explored.

Chapter 7, “The Application of Basic Concepts to Vibration Testing,” looks at what happens when we put everything together while attempting to conduct an actual test. Several simple examples are used to illustrate significant factors that must be considered and how these factors can influence the experimental results.

Chapter 8, “General Vibration Testing Model: From the Field to the Laboratory,” explores the framework for conducting field tests and converting the results into a meaningful laboratory test specification.

1.5 SUMMARY

This introduction suggests that a broad range of physical laws and mathematical concepts are involved in the practical execution of a successful vibration test. This book is dedicated to exploring these laws and concepts so that practicing test engineers as well as graduate students will be able to understand some of the subtleties that can occur. No results can be better than the instruments employed to derive them. As will be seen, recent research shows that instruments as well as frequency analyzer use can be the Achilles’ heel to the entire process.

In closing this first chapter, we offer the following definition:

Vibration testing. The art and science of measuring and understanding a structure’s response while exposed to a specific dynamic environment; and if necessary, simulating this environment in a satisfactory manner to ensure that the structure will either survive or function properly when exposed to this dynamic environment under field conditions.

As with all definitions, this one has its limitations. If any reader can find a more inclusive statement, we would appreciate your sharing it with us.