Abstract

Teaching complex concepts related to modal analysis (both analytical and experimental topics) to undergraduate students can be quite difficult. The student must be familiar with a wide range of different subjects - some of which he has forgotten and others he may have never taken. In addition to traditional topics, the student must become familiar with vastly new and diverse subject matter.

In order to expose undergraduate students to experimental modal analysis to support capstone design projects and other related projects, a simplified approach is necessary. Complex mathematical concepts can be easily illustrated using detailed pictures where color becomes an extremely important contribution. These concepts can be further explained through the use of multimedia format presentations. Multimedia provides a mechanism for students to review material as often as needed to fully understand complex concepts. This paper addresses some of these issues through the use of some typical teaching examples used.

I. Introduction

Teaching experimental modal analysis involves a very wide assortment of different disciplines. The student must be familiar with basic dynamics and vibrations with exposure to a variety of different mathematical tools such as Fourier series and Laplace transforms. Beyond these traditional disciplines, the student must become familiar with digital signal processing concepts, instrumentation, testing techniques and modal parameter estimation techniques involving numerical estimation.

To address all of this material, in detail, requires several graduate level courses. However, many times undergraduates need to be exposed to the basic techniques and concepts of experimental
modal analysis in order to solve some basic dynamic/vibration design problem for a capstone design project or other similar project.

In order to allow undergraduates to get exposed to experimental modal analysis in the support of design projects without learning all the detailed aspects of experimental modal analysis, a simplified approach is necessary. Using simple graphics in conjunction with mathematical expressions often helps to break this difficult barrier. The use of color is a significant contributor to the explanation of these difficult theoretical topics. Often it allows for much clearer presentation of these topics. Through the use of multimedia, the student can be exposed to the development of these theoretical concepts in a very natural progression of pieces used to describe a certain topic. The multimedia approach allows the student to progress through all the detailed steps of the development as often as necessary until he fully understands the basic concepts.

This paper presents some of the approaches that have been used to clarify some of the important concepts in modal analysis that often cause student difficulty. Several examples are presented in this paper. The pictures used in this paper are presented in color to illustrate its importance. Obviously, the multimedia presentations cannot be provided in this paper; excerpts of the multimedia material presented can be obtained upon request.

II Examples of Pictures and Multimedia to Explain Difficult Topics

Several examples are illustrated below to show the use of graphics and multimedia to explain some of the more difficult topics for the undergraduate engineer. Some of this material can be found on the UML-MACL web page cited in Reference [1]. Some of this material has been extracted from the series of articles entitled "Modal Space - In Our Own Little World" that is currently under continued development. These articles are also published in Experimental Techniques magazine (by the Society for Experimental Mechanics) entitled "Modal Space - Back to Basics" [2-10].

These articles were originally developed to address the practicing engineer who may not have had formal training delving into modal analysis. These engineers need to become better versed in some of the rudimentary concepts in analytical and experimental modal analysis. The articles are all intended to be a very short, brief treatment of a particular topic that often is a common stumbling point for practicing engineers. Each article is started by a simple question, asked by a young engineer, of an experienced engineer as seen in Figure II-1. These articles have been well received and are often used as handouts to undergraduate engineers taking vibration and modal courses at several different universities across the country.
II.1 How Do Structures Vibrate?

The undergraduate students are often involved with laboratory experiments that may involve vibrations. One such instance involves the balancing of some rotors. One of the rotor assemblies is on an unusually long base. The base is made of what appears to be a relatively thick aluminum plate which to most novices implies that the base is stiff. But unfortunately, the balancing is to be performed at a frequency which happens to coincide with the first bending mode of the rotor assembly base plate. Of course, the students are quite baffled by this since the other rotor assemblies are shorter and have different natural frequencies. Somehow, this very complicated phenomena must be explained in such a way that the students can understand the basic problem that all structures vibrate.

In order to illustrate this new phenomena to the students, a very simple flat plate, excited with a sinusoidally varying constant amplitude force, is used. First, the time response at one point is shown to illustrate how the amplitude varies depending on the frequency of oscillation (Figure II.1-1). This time response is then transformed to the frequency domain using the FFT. The peaks of the frequency response (Figure II.1-2) are noted to coincide with the rate of oscillation corresponding to the peak amplitude in the time domain.
Obviously, using only one measurement point is not sufficient to show how the structure behaves. If many measurement points are included then as the frequency of oscillation is allowed to dwell at each of the natural frequencies, then the response of all the accelerometers can be measured. The resulting deformation is approximately the mode shape (Figure II.1-3). The students often are in complete disbelief that the deformation patterns are completely different at each of the different natural frequencies of the system.

A picture is worth a thousand words but the ability to animate the deformation patterns allows the students to see the actual phenomena much more clearly. When possible, a laboratory demonstration using this flat plate allows the students to see the actual vibration using a strobe light. In order to further illustrate this phenomena, time data is digitally collected for the plate structure and a sweep performed. This data is then used in a multimedia presentation to show the time sweep and plate deformations.

The discussion of this material is the subject of Reference [2]. (The multimedia presentation will be given at the live paper presentation.)

II.2 How Do You Get Shapes From FRFs?

The next example helps to easily illustrate how shapes come from FRFs. The same plate structure is used so that the simple plate mode shapes are already known from the previous example. Six measurements are collected from the plate structure as shown in Figures II.2-1 and II.2-2 for the first and second modes, respectively. Each individual measurement is then studied and the student is asked to jot down the amplitudes for mode 1 and mode 2 at each of the points. This data is then used to sketch the mode shapes as shown in the figures. The students are then required to test a simple plate to determine what mode shapes they get for the first two modes of the system.
Using a single picture, all of the points that need to be made, can be quickly seen. However, stepping through the collection of each of the measurements separately offers a more realistic summary of the actual measurement process. Using a multimedia approach, each measurement can be viewed separately as what might likely occur in an actual measurement process. Then, at each point, the student can review the peak amplitudes that occur for each mode. This way all the pieces of the puzzle are obtained at a slower pace and the student has time to absorb the material incrementally, rather than having the results laid out in one complete picture. Not only is this more realistic and easier to absorb, the material is more likely to be retained and better understood since it is developed incrementally. The multimedia approach allows the student to step through all the pieces at his own rate of absorption of the material, thereby allowing better retention of the material. The discussion of this material is the subject of Reference [9]. (The multimedia presentation will be given at the live paper presentation.)

II.3  How Do I Measure Terms of the FRF Matrix?

While the FRF matrix equation contains all the information to describe the system, from a student's perspective, it may not be very clear as to what each of the terms of the matrix represents. Often students seem to comprehend the measurement process better if individual input-output measurements are described and discussed individually.

Two different testing scenarios, impact and shaker excitation, are described in Figures II.3-1 and II.3-2, respectively. Each picture is very clear in terms of what data is collected. But again, all this information is clear, providing that the concepts are already understood.

By using the multimedia approach, the material can be presented in a more natural form. Each measurement can be viewed and discussed separately in a manner that is more like the actual
collection of data in the lab. The individual measurements can be discussed as to their specific characteristics. Measurements can be acquired incrementally and discussed and understood before proceeding to the next measurement. In addition, the differences between the data acquired in an impact test vs. a shaker test can be developed and discussed more slowly so the student can absorb the material.

The discussion of this material is the subject of Reference [4]. (The multimedia presentation will be given at the live paper presentation.)

II.4 FRF, Residue and Shape Equations

The frequency response equation written in partial fraction form is a fairly harmless equation. At least if you understand the basic theory. However, many times this simple equation is very overpowering to many students. And often the students get the general idea of the equation but the use of color in the formulation of the FRF helps to vividly identify the pieces of the equation in much greater clarity.

The magnitude and phase and real and imaginary parts of the frequency response function are shown in Figures II.4-1 to II.4-4 along with the equation for the residues and modes shapes in Figure II.4-5 and II.4-6. The figure helps to explain the relationship between the contribution of each of the modes to the frequency response function through the use of colors to show mode 1 in blue, mode 2 in red and mode 3 in green. In each of the figures, the upper trace is the resulting summation effects of the modes of the system - this is the frequency response function that we are trying to measure. However, it is critical for the student to realize that each of the modes of the system contribute to the overall measured response. The use of color here is a significant benefit to the student.
To further explain the contribution of each of the modes of the frequency response function, multimedia can greatly accentuate the key points. Each of the pieces of the frequency response function can be added individually as each of the modes are used to form the entire frequency response function. In this way each piece of the equation can be built up along with the corresponding part of the frequency response function in a logical fashion to clearly show the contribution by mode for each part of the frequency response function - namely the real, imaginary, magnitude and phase. (The multimedia presentation will be given at the live paper presentation.)
II.5 Just What Are Complex Numbers?

Of course, the students often get thrown for a loop when we start talking about the real and imaginary parts of the frequency response equation. Their eyes get glassy when we talk in these terms. This is likely due to the fact that most of their nomenclature has been obtained from a system dynamics, controls or other class where they were exposed to magnitude and phase as the quantities of interest. A quick picture showing the very simple relations of real, imaginary, magnitude and phase allows them to better understand the material. The color in this picture helps the student clarify this information.

One very good example illustrating these relationships is available from a Mathcad movie clip (AVI file). The animation is simple but it helps the student to put things in proper perspective and grasp material that otherwise might slip by him.

II.6 Time/Frequency/Modal Domains

The illustration of the differences and similarities of the time, frequency and modal domains is best described through the use of the picture below (Figure II.6-1). Often, a good part of a hour lecture can be given just in describing this picture. It is an excellent example of the relationships between all the different forms of the system that we might use. The students can quickly see the relationship between the single degree of freedom time and frequency domains. They can also see the fact that the physical mode shape and modal space SDOF system are related. As different modes are considered, the summation of all the effects gives the total response of the system.

The multimedia format presentation allows for the individual concepts to be fully explained and exploited in careful steps. The discussion of this material is the subject of Reference [3]. (Currently, a multimedia version of this material is under development.)
II.7 Overview of Experimental Modal Analysis

This diagram happens to be my all time favorite. This particular graphic has been used for over ten years now. It is an excellent example of how a picture is worth a thousand words. The explanation of the similarities of the finite element model and the Laplace domain formulation of the poles and residues (frequencies and mode shapes) helps to show that both techniques are different formulations that are trying to approximate the dynamic characteristics of the system.

Of course, once the transfer function matrix is developed then any one of the individual frequency response functions can be determined from the matrix. It stands to reason that if the poles and residues (frequencies and mode shapes) are used to generate the FRF, then it should be possible to extract those parameters from the FRF. This process is commonly called curvefitting or modal parameter estimation. But in going through that path, the same assumptions used to develop the finite element equations are the same assumptions used to form the Laplace equations. If there was some way to measure the FRF rather than computing the FRF then possibly the parameters could be extracted from the measurement.
Actually this is what is done in an experimental modal survey - FRFs are acquired by measuring time data which is digitized and transformed to the frequency domain using the FFT. Basically, a ratio of output to input is computed to form an estimate of the FRF and then modal parameters are extracted from the measurement.

This graphic is always good to have handy to keep everything in perspective when covering detailed areas of the theory of experimental modal analysis. I refer to this figure as the big picture of experimental modal analysis (Figure II.7-1).

In reading the discussion above, it is difficult to explain all the pieces of the picture in text. It is relatively easy to get lost as to what part of the picture I am describing - especially if you don’t fully understand modal analysis. However, using a multimedia format presentation allows for the slow, methodical presentation of each of the individual concepts. Each concept can be fully
explained and explored before proceeding on to other concepts in the graphic. Use of a multimedia approach allows for a much more natural way to present and explain this material such that the most can be extracted from the information presented. The multimedia format presentation should be viewed more like a classroom presentation where all aspects of the topic can be explored in greater detail. (The multimedia presentation will be given at the live paper presentation.)

III Observations

Classroom lectures are used to further explain difficult concepts that may be presented in a standard textbook. If the textbook was sufficient to describe the material at hand, then there would be no need for classroom lectures. However, we often learn through reading material as well as through listening to the presentation of that same material by an educated individual who can further explain and describe the material in more detail. Unfortunately, the live classroom presentation is only given once. If the concepts have not been adequately absorbed and understood, then there is no chance to re-visit the live presentation again.

The use of pictures and graphics helps the transfer of information and is another mechanism to explain the specific information. The use of color in pictures and graphics just amplifies the transfer of that same information. However, color can be used to make distinctions between different pieces of information which otherwise are difficult to distinguish in black and white.

Multimedia offers one additional step in the transfer of that material. The multimedia approach allows for the student to re-visit the material as often as necessary until the concepts are more fully understood. Multimedia allows the student learn the material at his own pace - not at the pace of the instructor in the live classroom presentation. Students extract the most information when they are allowed to progress at their own pace.

IV Summary

Some very simple examples were presented to show how pictures can be used to explain very complex theoretical concepts and equations found in modal analysis. The use of color in the pictures helps to reinforce certain concepts. Color also aids in the distinction between different pieces of different information.

The use of multimedia further enhances the learning experience. The multimedia approach allows for the student to re-visit the material as often as necessary until the concepts are more fully understood.
IV References

1) Peter Avitabile's Homepage at the University of Massachusetts Lowell's Modal Analysis and Controls Laboratory - http://www.eng.uml.edu/Macl/macl-pa/pete1.htm


3) Avitabile, P., "Could you explain the difference between the time domain, frequency domain and modal space?", Modal Analysis - Back to Basics, Experimental Techniques published by Society for Experimental Mechanics, April 1998

4) Avitabile, P., "Is there any difference between a modal test with a shaker excitation or impact excitation?", Modal Analysis - Back to Basics, Experimental Techniques published by Society for Experimental Mechanics, June 1998


8) Avitabile, P., "Curvefitting is so confusing to me - what do all the different techniques mean?", Modal Analysis - Back to Basics, Experimental Techniques published by Society for Experimental Mechanics, February 1999

9) Avitabile, P., "I still don't understand curvefitting - how do you get shapes from FRFs?", Modal Analysis - Back to Basics, Experimental Techniques published by Society for Experimental Mechanics, April 1999 (to be published)

10) Avitabile, P., "What's the difference between mode shapes and operating data - they look the same to me?", Modal Analysis - Back to Basics, Experimental Techniques published by Society for Experimental Mechanics, June 1999 (to be published)


Peter Avitabile is the Manager of the Modal Analysis and Controls Laboratory at the University of Massachusetts Lowell supporting testing and research contracts; he also teaches for the Mechanical Engineering Modal Analysis Graduate Program.

He has over 25 years experience in design, analysis, finite element modeling and experimental modal testing. His main area of research is structural dynamics specializing in the areas of modeling, testing and correlation of analytical and experimental models. He has written over 50 technical papers and has given numerous seminars in the areas of experimental modal analysis, structural dynamics, vibration fixture design, and modeling and correlation.

In 1996, he was awarded the Dr. Irwin Vigness Memorial Award at the 42nd Institute of Environmental Sciences' National Conference; the award was presented in recognition of his outstanding technical guidance in the development of the IES Boston Chapter's Vibration Fixture Seminar Training Program.

He was instrumental in the development of the first multimedia format Modal Handbook on CD. The Modal Handbook is a computer based training and reference guide which addresses the practical aspects of experimental modal testing. He is a Registered Professional Engineer with a BS, MS and Doctorate in Mechanical Engineering. He is also a member of ASME, IES and SEM.