Around the World in 80 Courses

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This article summarizes the genesis and evolution more than 30 years of a series of short courses on analytical and experimental structural dynamics. In total, more than 120 of these courses have been presented in more than 20 countries. In the early days, the courses were specifically focussed on teaching basic techniques and applications of the then-new subject of modal testing (or experimental modal analysis). Later came the need for more advanced and complex capabilities in some of the more demanding tasks, and especially in the more challenging applications to which the modal test results were to be subjected. The major changes in information technology that have taken place in this 30-year period have resulted in some significant changes in the style and content of the courses. Most recently, the "courses" have turned more toward developing a full integration of the experimental, numerical an theoretical skills that combine to make the complete structural dynamicist – that rare individual who knows, above all, that solving problems in structural dynamics hinges on being able to ask the right questions. The answers can usually be found in textbooks and scientific papers. Not so the questions. Learning how to formulate these requires practice and experience, and this is best passed on in courses.

The "birth" of experimental modal analysis coincided with another phenomenon that has become very familiar to most engineers – that of the short course. Not surprisingly, short courses (1-5 days) on modal analysis or modal testing have become a very popular and an effective way of bridging between the classical vibrations courses taught to most undergraduates and the real world of actual engineering structures – namely, the need to measure how they vibrate and to predict and control such behavior.

The particular suite of courses that are the subject of this paper grew out of research some 50 years ago that addressed the complexities of vibration of real engineering structures. As is mostly the case, these were actually an assembly of several components, often of disparate form and composition, that constituted machines vehicles or other structures. Specifically, interest was focussed on two industrial applications where vibration represented (and still does) a major concern in regard to reliability and integrity of critical engineering products. One was machinery installed on board a ship (Figure 1), where the transmission of vibration and sound throughout the vessel and radiated into the surrounding sea was a major concern. The other was concerned with the integrity of a store mounted on the side of helicopter (Figure 2).

In both applications, some form of mathematical model was required to describe the various structural dynamic features in such a way as to be able to control and contain them within acceptable limits. In the period of those projects (the 1960s-1970s), mathematical models were hard to come by and very limited in capacity when created. As a result, it was more commonplace to rely on measured data to describe the required vibration properties even though this was inaccurate and incomplete. At least it represented how the actual structure was really behaving.

In effect, the methodology adopted in those days was to construct simple mathematical models from theory wherever possible and to formulate mathematical models from measured data where the necessary theoretical descriptions were unavailable. This approach to the engineering needs, in effect, gave birth to modal testing, or experimental modal analysis that is so widely practiced today, although it was often referred to as the "impedance" method approach rather than experimental modal analysis that has now become the norm.

First-Generation Courses on Modal Testing

There was a need for courses that could combine the classical

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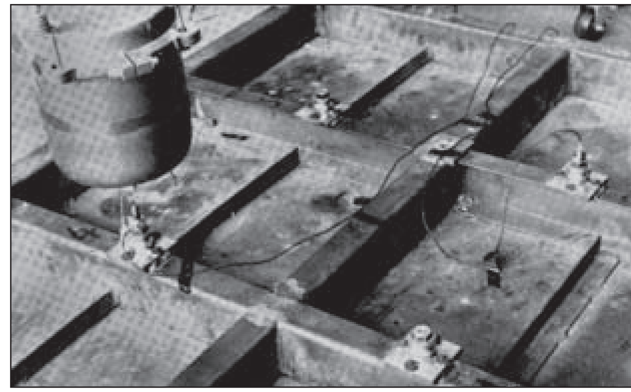

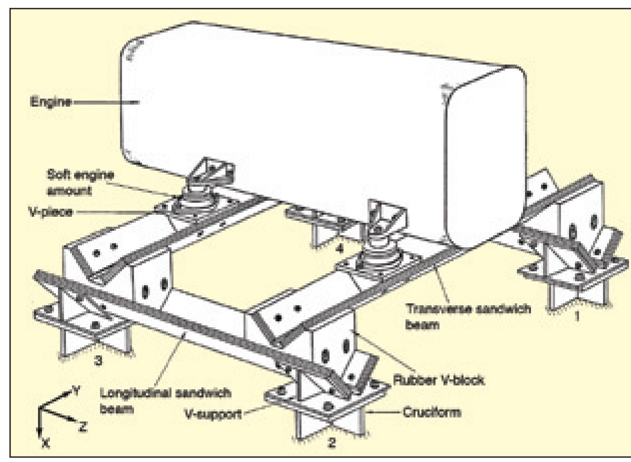

Figure 1. Early attempts to analyze the dynamics of a highly complex structural assembly of shipboard equipment.

theoretical treatment of vibration of systems and structures with the corresponding measurement techniques that were usually undertaken, since they represented the only way of gaining any useful insight into the critical characteristics of many engineering structures. The first such offering by the author was presented in Shanghai in 1982, unknowingly foretelling the international nature of the many subsequent courses that have now been visited on some 20 countries spanning six of the seven continents. The first deliberate modal testing course was given in the U.S. in 1983, followed by others the following year also in the U.S. The first course in the UK was not until 1985.

The history of individual courses of is not of interest here. Rather, the structure and format is relevant; that it evolved through experience is worth noting, because it became the foundation for teaching the subject today, or three decades later. The main ingredients were:

- Theory of SDOF (single degree of freedom) and MDOF (multi degree of freedom) systems, with a strong emphasis on *both* the free vibration (modal) behavior *and* the forced vibration (FRF) characteristics.
- Measurement and testing techniques as applied to real engineering structures.
- Analysis techniques, primarily for extracting useful information about the makeup of structures based on measurements of their dynamic behavior.

These three fundamental tools were supplemented by a synthesis process that sought to combine the theoretical and experimental descriptions of a structure's dynamics into a single model for subsequent use. The applications to which the assembled model can be put to the benefit of the designer or user of the structure itself were developed.

All this information was collected for presentation first as a book whose chapters simply follow the main themes.* It was also

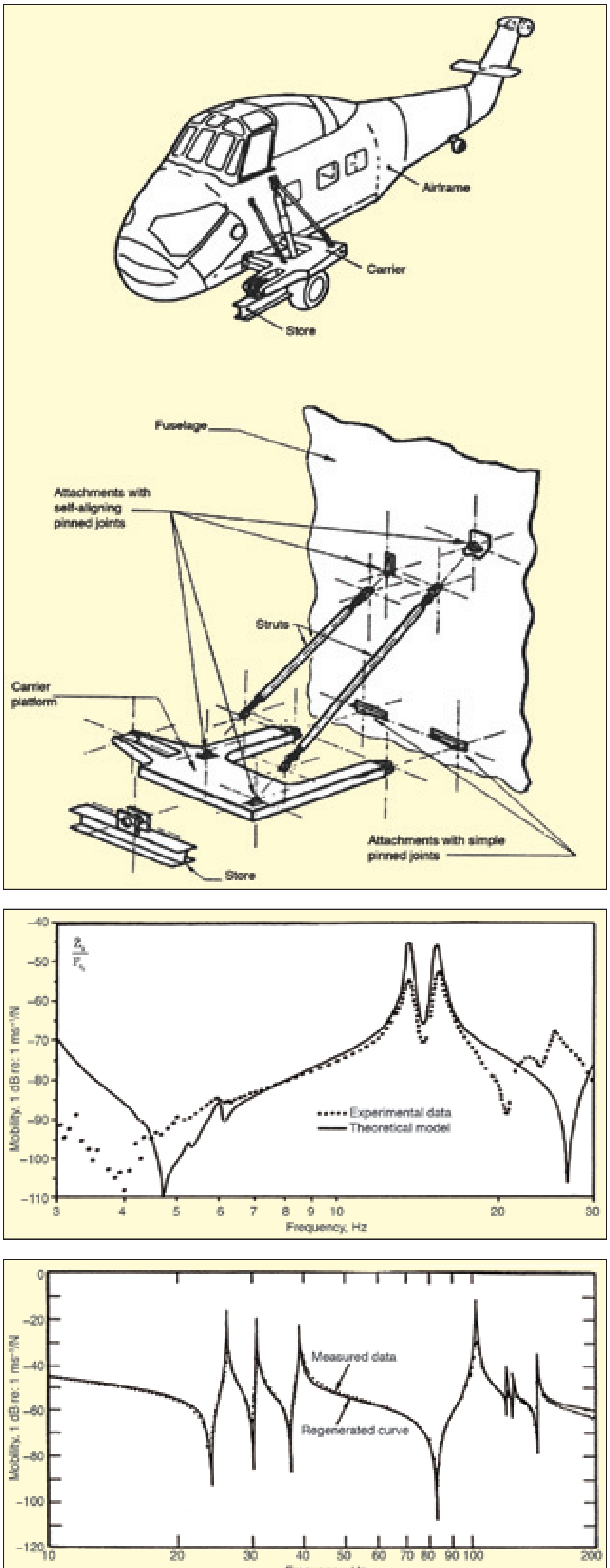

Figure 2. Combined theoretical-experimental generated model for helicopter dynamic response analysis.

formatted as a three-day course in which the subject matter is delivered piece by piece (not chapter by chapter) in such a way that the interdependence of the different parts of the process of modeling, measurement and interpretation is emphasised. Typically, the sequence would be:

- Theory 1
- Measurements 1
- Theory 2
- Measurements 2
- Analysis 1
- Theory 3
- Analysis 2
- Synthesis (modeling)
- Applications
- Advanced methods (dictated by the persistent discrepancies between theory and practice)

This is then supplemented with demonstrations and exercises to illustrate the main points through practical examples. Suddenly, three days are gone.

Underlying Philosophy

As mentioned previously, the destination of most of these studies was almost always the construction of some form of mathematical model that would allow users to extend their knowledge of how the structure would vibrate under different circumstances – both under different loading (excitation) conditions and/or when selected physical changes had been made to the original structure by adding mass, stiffness or damping.

Now I want to describe what is meant by "mathematical" model, and in particular from the perspective of an instructor who wants to instil in the pupil the necessary understanding and philosophy of the concepts involved – or understanding the physics as well as the math.

In general, a mathematical model is defined by a set of equations that describe the dynamic behaviour of the subject structure. Not surprisingly, there is more than one type of model, and three different versions are in regular use in structural dynamics:

- A *spatial model* is one that describes the structure's relevant properties in terms of their distribution in space; that is, the geographic distribution of mass, stiffness and damping and the interconnections of these elements at and between junctions. It is what the structure looks like. We can influence this directly by changing individual element thicknesses, etc.
- A *response model* is one that describes the structure's dynamic properties in terms of set of response characteristics – most commonly, the FRF properties, but any other formal response characteristic will suffice. The response model describes how the structure behaves in a response sense and is a direct measure of the performance of the structure from a vibration perspective. The response is what we want to be able to predict and to control, but cannot adjust this quantity directly; we can only change the spatial model elements. So, the relationship between the spatial and the response models is what most structural dynamics analysis is all about.
- The third type of model is the *modal model*, or a virtual model that is an intermediate form sitting between the spatial and the response models and providing a very convenient means of communication between these two real models.

The three models are illustrated in Figure 3. The usual analysis activity in structural dynamics seeks to predict the response behavior of the subject structure by defining its spatial model and solving the equations of motion to a given input excitation loading. The usual test activity consists of measuring some of the response characteristics of a test structure and seeking to infer from these measurements the underlying spatial model properties with a view to changing these to bring about an improvement in the response behavior. The modal model provides a very efficient way of communicating between these two primary models.

A full grasp of this underlying philosophy is essential to the student of structural dynamics who seeks to design and maintain machines, vehicles and structures that are subjected to dynamic loads.

Future Needs and Trends

The preceding paragraphs describe the aims and the form of a suite of courses that have been delivered for more than 20 years.

*Ewins, D. J., *Modal Testing: Theory, Practice and Application*, Research Studies Press, 2000.

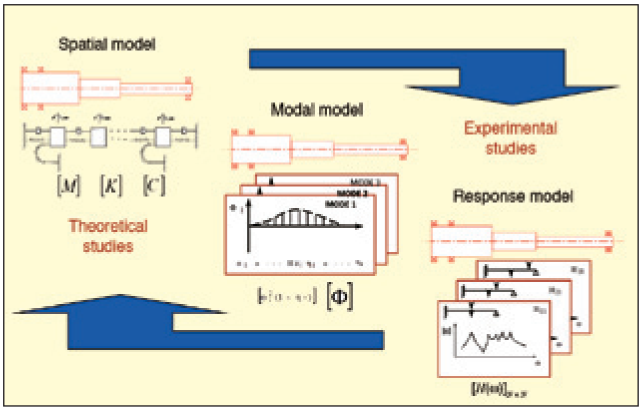

Figure 3. Types of model used for structural dynamic studies.

What's next? The underlying subject matter that needs to be taught and, more importantly, learned has not changed much. There are some more advanced topics but, essentially, the basics are still the same. Perhaps what is changing is the context in which the material needs to be taught and learned. In fact, what started out as a course for modal testing or EMA (experimental modal analysis) has now evolved into the broader and more complete subject of structural dynamics.

The conventional wisdom is that what is needed is an improved modeling capability. We need better (more reliable and cheaper) models with which to design and to maintain – through monitoring and diagnostics – our engineering products with greater reliability and resilience to the dynamic loads that are incurred from all machines ad vehicles.

At first glance, this approach suggests that the future is in analysis, with less emphasis on testing. However, it is not that simple. There are three primary tools are distinct but mutually interdependent:

- Theoretical modelling
- Numerical analysis
- Experimental measurement

Modern structural dynamics requires an integration of all three. Figure 4a shows the trio of basic skills; Figure 4b shows how the three basic skills are used in combination to provide the procedures (or technologies) of simulation, identification and validation, which together provide the capabilities required to address and resolve most structural dynamics problems encountered today. This construction is more complex than the simpler test vs. analysis scenarios that are often cited and is thought to be more realistic of the real situation. It is important here to note the central role played by experimental measurement activities.

In the identification process, experiments are the basis for observing, understanding and thereby modelling the increasingly complex physics that we need to describe in our models. At the other end of the design process, tests are the means of checking or validating the predictions that are the result of simulations (modeling plus computation). Even later in the life cycle of these products, measurements are the basis for the monitoring and diagnostics that will keep the products in effective service throughout their life. A full set of experimental procedures is shown in Table 1. Clearly experimental methods will continue to play an essential role in structural dynamics and need to be embedded in modern courses on the subject – not added on as an afterthought.

Table 1. Experimental procedures.

Measurements	Quantification of physical parameters
Experiments	Use of measurements to observe (then to understand and explain) physical phenomena
Tests	Use of measurements to prove or "test" a theory (validation)
Trials	Use of measurements to demonstrate overall performance of a machine or structure (certification)
Monitoring/ Diagnostics	Repeated measurement of selected parameters to detect changes in structural condition or differences between nominally identical structures

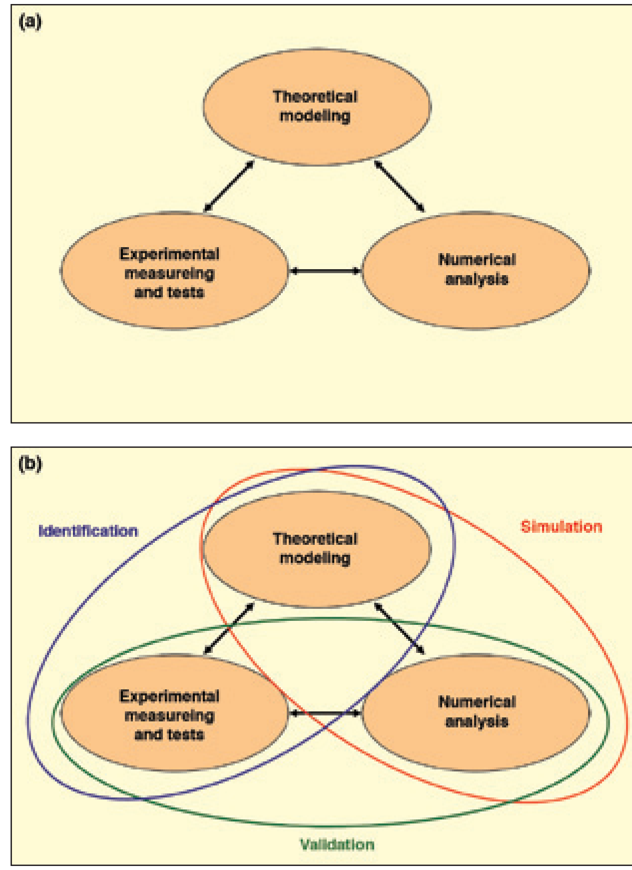

Figure 4 (a) Three basic skills required for structural dynamics studies and (b) three main procedures carried out.

Subtleties and Questions

The future need is for *valid* models. Valid means good enough – not perfect, not too good, but good enough. This requires a definition of what is good enough followed by methods to test if a model is good enough and, if not, then to improve or update it so that it is good enough, or to *validate* it.

At this stage, it is important to consider more thoroughly the different types and sources of deficiency that determine whether a model is valid or not. There are essentially two types of deficiencies to be considered. The first arises from the use of inaccurate data in the modeling procedure: incorrect values of the various parameters that comprise the model, perhaps resulting from errors in measured data or assumed data. The second and more serious deficiency is the omission of parameters that are relevant but may be assumed to be unimportant or ignored. Such omissions can be of physical elements themselves, or the degree of complexity with which individual elements are described.

A classic example of this latter situation is the oversimplification of a non-linear characteristic by a simple linear representation. A model that is deficient in this way, by incompleteness of the parameter set, is more seriously limited in its usefulness and cannot generally be validated. Both of these limitations – often referred to as variability and uncertainty – must be addressed and corrected.

These issues may seem to be subtleties, but they can differentiate between models that are fit for purpose – good enough – for the increasingly stringent demands placed on structural dynamics analysis today, and those that are not good enough. The means to answer these questions are to be found in the theoretical and experimental tools mentioned above.

The ability to ask the right questions comes from experience and effective teaching of the subject. Verified? Validated? Uncertainty? Variability? Linear or nonlinear? S&V

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