Basics and state-of-the-art of modal testing

D J EWINS

Department of Mechanical Engineering, Imperial College of Science,
Technology and Medicine, London, UK
e-mail: d.ewins@ic.ac.uk

Abstract. In this paper, the current status of the technology of modal testing is reviewed with particular reference to the application of these methods to the task of ensuring the optimum design of mechanical structures. Existing methods are summarised and new techniques which are currently under development are described. Some of the current limitations and problem areas are also identified.

Keywords. Modal testing; structural dynamic design; vibration testing; modelling; laser measurement application.

1. Introduction – Theoretical and experimental contributions to structural dynamic design

The popular concept of ‘design’, and especially that of optimum design would be that of a heavily computer-based technology, with emphasis on using computer models to predict the performance of the structures in question. The idea that experimental testing could play a major role in this process is not immediately evident, and yet that is the essential message of this paper. Experimentation *can* play a vital role in design, especially when it is properly integrated with analytical processes. Experimentation serves two important functions in such design activities. The first is to obtain measured data with which to check the accuracy of theoretical predictions and the second is to check their completeness. It can be just as important to check that a theoretical model does predict *all* the phenomena which exist as well as checking that its predictions are accurate.

Figure 1a shows a schematic of the role of dynamic analysis in the overall design process while figure 1b shows the contents of the dynamic analysis process in more detail. These details comprise at least 6 distinct processes:

- modelling
- excitation
- response
- validation
- identification
- optimisation

which are usually required in order to secure an acceptable design. In several of these individual processes, both analytical and experimental activities are applicable and, as an integrated approach, are a powerful force for the task in hand.

The theoretical approach to structural dynamic design is classical and straightforward. A mathematical model is constructed to describe the dynamic properties of the structure in question, usually in the form of a spatial model comprising mass and stiffness descriptions (usually as mass and stiffness matrices) as well as some consideration of the damping effects which are likely to be present. This model is then used to predict the vibration properties of the structure in the form of its modal properties – natural frequencies, mode shapes and modal damping factors. These describe the ways in which the structure chooses to vibrate under ‘natural’ conditions, with no external excitation applied to it.

There then follows an important second phase in which an effort must be made to predict how much the structure will actually vibrate in practice (task 3 in figure 1), as this is the quantity which is required to determine the existence and extent of the potential vibration problem that has to be designed against. This second stage is only possible when an estimate has been obtained for the excitation forces to which the structure will be subjected under its design operating conditions (task 2 in figure 1). This stage can be quite difficult and often requires input from sources quite removed from the structure itself involving fluid, thermal, electromagnetic and other mechanical phenomena, which are more to do with the functioning of the structure or its neighbours than with its own structural features that determine its vibration properties. In almost all cases, the nature of these excitation forces is quite outside the control of the designer of the structural components whose vibration properties are to be optimised.

Once this calculation has been satisfactorily completed, the thus-acquired prediction capability must be used to adjust the structure so that its dynamic performance is acceptable, and this is the optimisation task (6) in the diagram of figure 1.

In support of this overall design process, it is usually necessary to conduct validations of several of the steps. Certainly, of the modelling process; often, of the derivation of excitation forces, and almost always of the performance (i.e. response levels experienced in service) of the final product. These validations can only be performed by using experimental techniques. In addition, it is often necessary to supplement the purely theoretical modelling procedures by the inclusion of certain data which have been obtained from tests. Some physical properties, such as damping and fatigue characteristics, can only be derived empirically. In the same vein, it is often only possible to validate assumed or estimated excitation levels by carefully controlled tests.

Thus it can be seen how experimental techniques play a central role in the overall design process. Without them, design predictions remain unvalidated and must be proven the hard way – by introduction to service and exposure to the risk of failure – and the structures will almost certainly be sub-optimal in their performance.

2. Vibration tests: Modal tests

The experimental tests, which can be envisaged as being appropriate to perform the functions outlined above, fall into a small number of categories. There is one type of test, widely practised, in which the finished product is subjected to a real or simulated environment which is intended to reproduce its operating conditions. The structure is thereby shown to have survived (or failed) this pass-off test as a demonstration of its fitness for purpose. These tests are often relatively crude and offer little more than a go/no-go result, with little evidence as to the proximity of the structure to its performance limits and thus as to how close it is to an optimum configuration.

Figure 1. The role of dynamic analysis in the design cycle.

A second type of test is that which is conducted to determine the levels of vibration response, or of vibration excitation forces which are experienced in service. In these tests the objective is to determine these parameters quantitatively, either to verify some predictions or to obtain raw data of parameters which cannot be predicted. These are tests of observation: they furnish information on certain features but provide little insight to the underlying behaviour which they are observing.

The third type of test is the group which includes modal tests. These are tests in which measurements are made that allow us not only to measure the vibration behaviour but also to characterise it and thereby to understand and explain it and, ultimately, to change it. Essentially, the first and second types of test are concerned with measuring only one feature – usually the vibration response levels. The modal test measures not only response but also the excitation that causes that response and does so in such a way that the two quantities can be related to each other – cause and effect – thereby permitting a relationship to be defined between them. This relationship is, in effect, a mathematical model of the structure under test, in just the same way that a theoretical analysis produces such a model, although the actual form of the model produced from a test may well be different from that created by direct analysis. Indeed, while theoretical analysis generally leads to a spatial model, the experimental approach directly yields a response model. A third type of model – the modal model, which is much used in this whole process – can be derived from both of these two original forms, as illustrated in figure 2.

3. Phases of a modal test

We have now established the role and essential features of a modal test and may conclude that introduction with a definition:

A modal test is one which is conducted in order to construct a mathematical model of the structure based entirely on measured vibration data.

A key term in this definition is ‘mathematical model’ and this implies a degree of completeness to the measurements which is not automatically required in other types of test. In this context, it is necessary that all the relevant modes of the structure are included in the modelling process and not just those which are ‘visible’ from an arbitrarily-chosen measurement point. This demands a degree of rigour in the testing procedure, in addition to the obvious demands of accuracy and precision which are normal for quantitative tests of most types. It is thus appropriate to review the essential steps or phases in a modal test in a systematic way.

3.1 *Test planning phase*

In modal testing, as in every type of test, it is important to ensure that the correct equipment is used for the various transduction, signal processing and analysis tasks and we shall be reviewing these different stages in this paper. However, because of the mathematical model feature just mentioned, another very important requirement of a modal test is to ensure that *all* the necessary parameters are measured. This means ensuring that all those quantities which are required for the eventual application are included in the list of quantities to be measured and, likewise, that unnecessary data are excluded from the list. It is inappropriate to spend valuable testing time measuring data which serve no useful purpose and do not add significantly to the information which is acquired as a result of the

Figure 2. Dynamic analysis models.

test. (We shall discuss later on the difference between ‘data’ and ‘information’, as they are not synonymous.)

Essentially, a modal test comprises the measurement of a set of response functions. These are usually measured as time-history records of various responses and excitation signals but are most often processed at source to reveal individual Frequency Response Functions (FRFs) or Impulse Response Functions (IRFs). Whether output as FRFs or IRFs, we usually describe the model from which they are derived as the FRF response model and this is fully defined by the FRF matrix, $[H(\omega)]$. This model is related to the modal and spatial models by the following two relationships (subject to various conditions, which should be consulted prior to application (Ewins 1984).

$$[H(\omega)] = ([K] + i\omega[C] - \omega^2[M])^{-1},$$

$$[H(\omega)] = [\Phi][(\omega^2 - \omega_r^2 + 2i\omega_r\zeta_r)]^{-1}[\Phi]^T.$$

In these expressions, $[M]$, $[C]$ and $[K]$ constitute the spatial model of mass, damping and stiffness properties, while ω_r , $\{\phi\}_r$ and ζ_r represent the modal properties of representative mode r , the complete set of which for all m modes constitute the modal model. Based on these expressions it can be shown (DTA 1996) that a single row or column of the FRF matrix, $[H(\omega)]$, is capable of containing all the information which is present in the modal model and thus that such a set of FRFs is all that needs to be measured in a test designed to elicit the modal properties from measurements of responses. There are caveats, however, and the question of which row or column of the FRF matrix should be taken as the optimum choice is often difficult to resolve. The degree of freedom (DOF) which relates to the row/column selected is called the ‘reference DOF’ and there are several features which can apply to any given case that result in some FRF data omitting important information on certain modes. Symmetry of a structure can mean that the choice of reference DOF is very important and so it is necessary that the test be carefully planned before the measurement set up is committed. What has to be done is the following.

- A convenient excitation point should be selected and a point FRF measured.
- A second excitation point should then be selected and a new point FRF measured.
- The resonance frequencies evident on the two plots must then be compared to establish whether there are any present in one plot and absent from the other.
- The process of selecting and checking further excitation points for the discovery of additional resonances should continue until the user is satisfied that all modes have been identified.

When this process has been completed, the test engineer should have a clear picture of how many modes there are to be identified and which excitation point(s) should be used. At this stage, there is a decision to be made as to whether an excitation point is chosen such that all modes are excited or whether it is preferable to excite some modes with one excitation and others from other points. Although this latter course results in more measurements being made, the resulting FRFs (or IRFs, if this is the format chosen) are simpler in form as they contain fewer active modes and are therefore easier to analyse at the parameter extraction phase. This is a choice which the experienced test engineer will be able to make.

However, the situation outlined above illustrates the need for a test planning phase to precede the acquisition of the volume of data which is gathered in the course of a full modal test. Attention and thought before the main measurement phase will be repaid in the quality and completeness of the data and the model which result.

Another aspect of test planning which will be discussed elsewhere concerns the choice of response measurement locations. This choice is governed by the eventual application and it should be noted that the set of DOFs required for a clear visual interpretation of animated mode shape displays is not necessarily the optimum set for a more quantitative application such as model validation, updating or modification. There are procedures available nowadays to guide the selection of measurement points and these should be used so that the actual testing time is used to greatest effect. The (usually limited) time and resources available can best be used measuring only those data which are valuable, and these to the highest accuracy possible in the timescale.

3.2 Measurement phase

Following planning, the next phase is that concerned with the preparation of the structure for test and the acquisition of the raw data that will be used to construct the model of the structure's dynamics. It must be emphasised here that the second most important feature of these measured data (after ensuring their completeness, i.e. that the correct ones are measured) is their accuracy. The main concern in this respect is to guard against the incursion of systematic errors, such as those caused by incorrect use of the equipment or installation of the transducers. These errors are much more difficult to detect and to eradicate than are those of a more random nature, such as arise due to noise, and once embedded in the data will seriously degrade the effectiveness of the model constructed.

The essential feature of the measurement phase in a modal test is that a controlled excitation forcing must be applied and measured together with the resulting responses at as many 'points' as are necessary. The ensuing measured data will be presented in the form of response functions which are a series of ratios between responses and excitations, either characterised by functions which describe the responses to an arbitrary harmonic excitation (FRFs) or to an impulsive excitation (IRFs). In fact, the actual excitations can take any of a wide variety of signal forms – not just harmonic or impulsive, but almost any type of time-varying form – random, transient or periodic (figure 3). The properties of the Fourier transform enable us to convert raw data from any of these excitation patterns into the required format of FRF or IRF by suitable signal processing. Of course, care must be taken in this process if a true estimate of the response functions is to be obtained and it is worth noting that whereas excellent results can be obtained by proper use of the techniques involved it is also true that extremely poor results will ensue from improper use of the same equipment.

3.3 Analysis phase

Immediately following the data acquisition and processing phase comes the interpretation or analysis-of-response-functions task. Here, the measured data are subjected to a process which seeks to determine the specific parameters of a generic mathematical model which makes this particular model exhibit the same dynamic behaviour as that measured in the test. The model in question is usually a modal model so that the analysis task is one of determining the modal properties of the system which most closely described the dynamic behaviour observed in the tests. This analysis is often achieved using a curve-fitting approach in which the coefficients in a specified polynomial function are established by requiring a minimum difference between the measured curve(s) and the curve(s)

Figure 3. Excitation signals.

regenerated using the polynomial expression (see figure 4). This is not the only means of deriving the modal model but is by far the most common.

There are many different algorithms available for performing this task. Their basic classification is noted here as the choice of analysis procedure is influenced by the quality of the FRF data which are available. The most powerful analysis methods are those which are performed on all the FRF curves in a single computation, and spanning a relatively wide frequency range in one run. While the numerical algorithms for such an approach to the modal analysis task are well established, their performance on the type of data obtained from a typical modal test is strongly dependent upon the quality of that data. In particular, these methods demand a level of consistency and uniformity across the complete set of data used that is difficult to achieve in conventional modal testing methodology.

3.4 Modelling phase

The final phase in the modal testing process is referred to as 'modelling'. Sometimes, most of this step is taken together with the previous one and, in such cases, the user is largely unaware that it constitutes a separate step. However, there is an important aspect of the modelling phase which should be retained as it serves to provide some insight into the validity and quality of the model which has been constructed. In processes such as we have

Figure 4. Curve-fit FRFs.

just described for the modal analysis phase, it is generally the case that a ‘result’ is always obtained: it is always possible to define a curve which has a minimum distance from a set of measured data points. That line can be a “least-squares best-fit” result but there is no guarantee, nor even likelihood, that such a ‘best-fit’ result is a ‘good’ result. Only if the distance between the original data and the curve-fit is small can we claim that we have a sensible model of the measured behaviour.

In the modelling phase a number of steps are taken. First, when the modal analysis has been carried out in a one-function-at-a-time way, we are confronted with a set of modal parameters which will most likely contain some inconsistencies. These inconsistencies will be manifest by the fact that there are many duplicate estimates for the natural frequency and damping factor for most of the modes – a different value for each from each individual FRF – and these multiple values are not compatible with the type of MDOF linear system which forms the basis of our modal model. Thus, it is necessary to extract from these multiple estimates a single value for the natural frequency and damping factor for each mode. Such a process is done ‘automatically’ in the course of the global type of modal analysis (in which all FRFs are analysed in a single step, rather than individually, as is the case with other analysis strategies). While it is a simple matter to compute an average value from several different estimates, this should only be accepted as a reasonable value if the variance of the individual estimates is small and their differences are random in nature. Otherwise, the significance of the variation should not be ignored. It probably indicates a non-trivial error or problem with the original data set or with their modal analyses.

There are other checks which must be undertaken on the resulting model, such as verification that the modes are suitably real, and not complex, except in the specific conditions where modal complexity can be justified. There are a number of checks that can be applied to the measured data and to their extracted models to test the statistical and physical reliability of the final results and these checks should be routinely applied to ensure that the appropriate quality is maintained throughout all the stages of the test.

4. State-of-the-art of modal testing

4.1 Standard technology

These, then, are the stages in a standard modal test and satisfactory results can be obtained in most practical situations where appropriate care is taken to ensure that the best practice is followed for each of them. Recent documentation published by the DTA (Dynamic Testing Agency) has greatly enhanced the provision of suitable guidance to ensure that such best practice can be applied by all (DTA 1996).

As with all advanced technologies, certain cases and situations are found in modal testing which take the methods to and beyond their limit of reliable applicability. One of the important reasons for performing the checks referred to in the preceding paragraph is to make sure that such excursions are recognised and alternative measures taken, or at least that the results are treated with due caution. In this section, we shall review some of the more advanced methods available for modal testing, and some of the problem areas which constitute the state-of-the-art of the subject, and the areas of current research and further development.

4.2 *Advanced methods*

4.2a *Multi-point excitation:* Traditionally, the test structure was excited by a single exciter, be that an attached shaker, an instrumented hammer or a non-contacting magnetic exciter. This form of testing has the advantage that the measured responses can be related directly to the sole excitation force and the classical FRFs (or IRFs) derived directly. This configuration, however, has the disadvantage, which is especially applicable for large structures, that it is difficult to supply sufficient power to the vibrating structure to attain vibration levels which are typical of in-service conditions and also that such excitation is quite unrepresentative of the excitation experienced in service. In cases where a slightly non-conventional characteristic is expected, such as slight nonlinearity, these effects can become problematic and restrict the validity of the test data obtained.

In order to overcome some of these concerns, it has long been the case that specialised test methods in which several exciters are used simultaneously have been available. Originally, these were the so-called “appropriation” tests in which the excitation is ‘tuned’ so as to generate a response which is dominated by the contribution of a single mode. When such a condition is attained, the measured response pattern across the structure yields the shape of the mode in question with no further analysis (e.g. curve-fitting) necessary. This type of test still exists, but is often expensive to carry out because the time required is nearly all on-structure time, requiring the test structure to be available as well as the test facility, for relatively long periods of time.

Alternative multi-excitation procedures are now widely used, based on a series of algorithms which are less demanding of measurement time than the appropriation method and which provide the additional effort in the immediately post-measurement phase, where the FRFs are computed from a complex extraction procedure that relies on one of several criteria which essentially require the different exciters to be driving with excitation forces which are uncorrelated with their neighbours. One of the very important advantages of these methods is that the resulting FRF data are almost guaranteed to be free of any kind of inconsistency errors, such as those which can seriously degrade the global modal analysis algorithms mentioned in the previous section.

4.2b *Laser measurements:* For many years, the transducers which have been used for modal tests have been predominantly of the piezoelectric type – accelerometers and force transducers. More recently, there has been a growth in the availability and use of laser-based response measurement techniques, including holography, ESPI and laser-Doppler velocimetry. These methods offer major advantages over the conventional transducer, partly because of the non-intrusive nature of their operation (they are all non-contact transducers) and partly because they offer the prospect of what is called full-field measurements – coverage over the surface of the structure with a mesh density that is orders of magnitude greater than could be achieved with individual discrete transducers. This feature opens up applications that are simply inapplicable with the typical point-by-point measurement options available using conventional means. A new family of modal testing methods using the scanning laser Doppler velocimeter has been introduced and described by Ewins (1997).

4.2c *Test planning:* As we seek to use the results of our modal tests for more and more ambitious applications, the quality of the measured data and the model they produce become ever more critical. It is thus more and more important to ensure that these

measurements are exactly what are required. One of the relatively new features in modal testing that have been developed with these demands in mind is that of test planning. In the formal sense, this involves performing a sort of rehearsal of the eventual application using data which are simulated measured data, as opposed to actually measured data. By this means, the relative importance of the various parameters to be measured can be tested, and the choice of data to be measured can be determined systematically, instead of by the application of experience and judgement of the operator, as was the case in the past.

There are several applications which involve both the test-derived and analytically-derived models. It is these applications, in particular, which can benefit considerably from a formal test-planning activity. A pre-existing finite element model of a structure which is to be tested, often for the purpose of validating that very model, can be used to determine the optimum selection of the following features.

- Location of excitation position(s).
- Location of suspension and boundary conditions.
- Set of response DOFs to be measured.

These, and other aspects of test planning, are discussed in more detail elsewhere (Stanbridge & Ewins 1995; DTA 1996).

4.2d Rotating machines: The obvious problems associated with testing components in rotating machines has inhibited the application of modal testing to this important class of mechanical structure, widely known for its susceptibility to vibration problems. Specifically, the difficulty of exciting moving components, and then of measuring their response while in motion, makes the task a formidable one. Early attempts were made to use conventional equipment on rotating structures, with encouraging results obtained which suggested that if these practical problems could be overcome, then the standard toolkit of modal analysis methods could be readily applied to these structures (Rogers & Ewins 1989).

Theoretical analysis of such structures reveals that they possess more complicated vibration properties than their non-rotating counterparts. The modes of vibration are frequently very complex and the principles of reciprocity, widely used in conventional modal testing as a means of checking data quality, are not generally applicable. Nevertheless, the underlying expressions used to describe FRF quantities share some common foundations.

Recent developments in two important areas have led to renewed attempts to apply modal testing to rotating structures. These two topics are –

- the scanning laser Doppler velocimeter (SLDV), and
- the active magnetic bearing (AMB).

The former has been mentioned earlier but its particular significance, and attribute, is the programmable capability of its measurement site. The point whose velocity is measured by the LDV can be programmed externally to be targeted on any point of interest, including a point which is fixed to a rotating disc, even if that rotation is at variable speed. Measurements using this device have been successfully made on a range of rotating components, paving the way for routine modal investigations to be possible.

The second requirement for modal testing is the excitation and, although the early efforts found a solution to the problem of exciting a rotating shaft via an extra bearing, these were not ideal. With the growing development of the magnetic bearings, these devices offer a

possibility to input controlled excitation forces to a spinning rotor free of the usual difficulties which attend a direct physical connection, as was done in the tests reported by Rogers & Ewins (1989). Recent developments have demonstrated the possibility of performing modal tests on rotating machinery structures with considerable encouragement from the first generation of results. This is certainly an area which will expand in the near future.

4.3 *Limitations of modal tests*

At the same time as we summarise some of the current developments and advances in the subject, so too is it appropriate to review some of the outstanding difficulties, and areas in which there remain problems, including those which resist attempts to find a straightforward solution. Amongst these problem areas, nonlinearities and the modelling of damping in real structures are two of the most common. These are discussed in the following sections. Also described below are some recent developments in the area of modal testing for rotating machinery. This important area of mechanical engineering has long been bypassed by developments in modal testing, largely because of the practical difficulties of conducting tests on rotating components. However, in recent years, there have been developments in both excitation and response measurement techniques which have permitted the application of modal testing to these structures. These developments are summarised below as well.

4.3a *Nonlinearities:* Most structures are nonlinear to some degree. In general, that degree is relatively small and, as a result, the effects of the nonlinearity are barely perceptible against the other measurement uncertainties in most vibration tests. However, against that, it must be noted that the marked increase in accuracy which has accompanied recent developments in modal testing technology has resulted in a much higher incidence of nonlinearity observations than in previous years. It is ironic that an improvement in a technique should lead to an increase in difficulties rather than a reduction. Not only is nonlinearity visible in the measured data as slight distortions in the usual plots of FRF, but it is also responsible for sometimes significant discrepancies in the modal analysis process. Some of the algorithms used to extract modal parameters can be surprisingly sensitive to the small deviations (from linear characteristics) which accompany the presence of slightly nonlinear elements in the structures.

Figure 5 shows a typical series of FRF plots for a slightly nonlinear system when these response functions are ‘measured’ or computed using different excitation patterns. For a linear system, the results would all be identical, but for a nonlinear one, the results are excitation-specific and show various types of distortion. These distortions can have quite dramatic consequences on some of the modal analysis methods, but an understanding of these effects, and an ability to detect their presence, means that alternative test procedures can be used so that the nonlinear effects are not only prevented from contaminating the measurement and analysis processes but can actually be quantified and included in the model. Methods which are relatively simple extensions of conventional linear modal analysis are now available and constitute major enhancements to the modal testing procedures.

4.3b *Damping:* Related to the general problem of nonlinearity is the particular topic of damping and of how to model it. The actual physical mechanisms of damping in structures

Figure 5. Nonlinear FRFs.

are many and complex, and most attempts to describe the dynamic behaviour of damping elements with any degree of realism will result in very complicated and certainly nonlinear expressions. Unfortunately, there is no simple and representative model which describes the cocktail of these mechanisms that makes up the ‘damping’ of any individual structure. Our attempts to use viscous dashpots (or structural/hysteretic dampers) for this role yield only very approximate representations which often have the same effect on the modal analysis procedures as do nonlinear effects in general.

Some methods of displaying the essential FRF data are better at showing the significance of the type of damping model that is used to define that behaviour, and some, like the inverse-FRF plots (of dynamic stiffness vs frequency) can reveal subtle differences of damping type with much greater clarity than can others. Nevertheless, the extraction of meaningful damping quantities from measured FRF data is much more difficult than is the case for the corresponding inertia and flexibility properties. This is partly a problem associated with the measurement techniques themselves (damping effects are usually an order of magnitude smaller than the corresponding mass and stiffness effects), partly because the underlying equations of motion are much more complex and not least because the features which influence damping – joint tightness, surface finish, temperature, wear, etc. – are themselves rather variable and unrepeatable from day to day, build to build, and structure to structure.

Notwithstanding these comments, damping is clearly an important factor in the behaviour of structural dynamics. It directly influences the levels of vibration which are experienced by a structure undergoing both forced and free vibration and so continued efforts must be made to characterise it better and to ensure that its effects are more repeatable and predictable in structures.

5. Concluding remarks

In this paper, we have sought to explain the important role which testing, and particularly modal testing, has to play in the overall design task with respect to dynamics. The essential

features of a modal test have been described and some of the critical aspects identified and discussed. The current state-of-the-art of modal testing has been reviewed, with near-term developments and advances identified. Finally, some of the current limitations which face the application of modal testing in practical situations have been re-visited.

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