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NEW STRATEGIES FOR MODEL VALIDATION USING MODAL TEST DATA

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Abstract

The technology that today we call “Modal Testing” (or “Experimental Modal Analysis”) became a practical reality in the early 1960s, at just about the same time that finite element methods were being developed. Throughout the ensuing 40 years, the primary application of modal testing has been to providing a means of validating the mathematical models that FE methods, and others, provide for the dynamic analysis of engineering structures exposed to vibration environments. However, in the past 5-10 years, dramatic developments in computation capabilities have resulted in a growing imbalance between the theoretical prediction methods and the associated experimental testing methods, particularly in respect of the time (and cost) required to undertake each type of analysis. As a result, there is a growing reluctance to continue with the traditional testing activities that are necessary to validate the models that will be used to design structures. This situation has led to the need for improved testing techniques and this paper describes a number of new ideas and experimental procedures that offer a dramatic improvement in the cost-effectiveness of modal testing for model validation. In summary, these new experimental techniques provide a means to close the widening gap between analytical and experimental activities, which is characterised by (a) marked differences in time and cost demands to acquire the relevant data in the two approaches, and (b) striking differences in the numbers of degrees of freedom typically used to describe the structure’s behaviour (100,000s in theoretical models and 100s in tests). Enhancements in testing procedures which can provide order-of-magnitude reductions in testing time, at the same time as order-of-magnitude increases in measurement degrees of freedom, are described. Together, these offer a powerful new approach to model validation using test data.

1. BACKGROUND

Modern engineering for high-performance and critical structures, such as those used in aerospace, defence, and other industries, relies on mathematical models to perform numerical simulations and optimisation in order to design the most reliable and efficient structures and machines. It is important that these are models are 'valid' and so procedures to provide a formal validation check, prior to the use of models for final design optimisation, have become a standard activity. It is important to note that a valid model is one which is fit for the purpose for which it has been constructed. In other words, it must be capable of delivering the required information (stresses, critical speeds, temperatures, etc) with the required accuracy. A valid model is not the 'correct' model (or incorrect), it is one which is good enough.

For much of the past 40 years, one of the primary applications for the technology known as modal testing, or experimental modal analysis, has been to provide a check on the validity of the theoretical models which are used to provide critical data on the structural dynamics characteristics of structures and machines which are exposed to dynamic environments. This has generally been undertaken by using the theoretical model to predict the vibration modal properties of the structure(s) of interest, then to undertake a forced vibration test on the actual structure(s) and to extract the vibration modes from the measured responses, and to compare or 'correlate' the two sets of modal properties.

While this basic sequence of events has remained more or less the same throughout the 40 years, the expectations of what this process can 'deliver' have changed considerably. At first, all that was expected was that the measured results would 'confirm' the predictions to the subjective satisfaction of the analyst. In some cases, there might be some adjustment to the model in order to bring the two sets of data closer into line. This was the situation in the 1970s, and is illustrated in Figure 1(a). With time, the comparison process became more rigorous, and the use of the MAC from the early 1980s became a routine way of quantifying the differences between two sets of mode shapes. In the late 1980s and early 1990s, model updating became popular as a way of systematically adjusting a theoretical model based on the differences found between its predicted modal properties and those measured in tests. In the same period, it became possible to improve the efficacy of the modal tests by appropriate Test Planning, a process which guides the best choice of suspension, excitation and response measurement degrees of freedom from the very large number of possible options, a choice not made easier by the (by now) commonplace situation of theoretical models having literally tens of thousands of degrees of freedom, a number simply not approachable by conventional measurement methods.

Of course, it must be remembered that during this same four decade period, the corresponding modelling and analysis methods have developed beyond all recognition of the capabilities available in the 1960s, when finite element methods were in their infancy. Against these developments in prediction capabilities, measurement techniques have changed relatively little, in comparison. By the early years of the new century, tests were beginning to fall from favour because of (i) their relatively high cost (by comparison with the low cost of computational activities); (ii) the time required to set up and undertake tests, and (iii) an unacceptable level of unreliability, or inability to meet the analyst's expectations of providing a fully accurate and reliable model at the end of the validation-by-test process.

2. DEVELOPMENTS IN THE MODEL VALIDATION PROCESS

At this stage, with project engineers challenging the need and value of undertaking tests to validate sophisticated FE models for design purposes, it became necessary to re-visit the whole validation procedure to see how it might be updated to make it more compatible with the current timescales and capabilities of modern modelling and computation techniques. The two major concerns were:

- (i) cost and, importantly, time required to conduct modal tests for model validation;
- (ii) ambiguity in many results from model adjustment or updating exercises,

Both have been addressed in an attempt to develop a significant improvement on the cost-effectiveness of model validation and the result is to add two additional steps to the validation process, namely: **test strategy**, and **model verification**.

One of the problems identified with the traditional approach to model validation is that in order to test a complete structure, it is necessary to wait until all the components have been assembled before starting the measurements. In an era where design cycles are constantly being shortened, the delays that such a requirement can place on the model validation process can simply eliminate it from effective contribution to the design, as this may have had to be fixed before the prototype test structure has been built! At the same time, it is felt that there is quite a lot of wastage in current test procedures: much of the data measured in a typical test end up not being used, and only a small fraction of the data actually measured really contribute significantly to the final quantitative output. A drastic shortening of the testing time is clearly necessary and in order to achieve this, a new procedure referred to as Test Strategy is proposed. This is discussed in more detail in the next section.

The second generic problem (of obtaining successfully updated models) is believed to be related to the possibility that the preliminary models which are to be validated are insufficiently detailed to be able to describe the actual behaviour of the real structure. This can arise if the model has insufficient or incorrect degrees of freedom in which case no amount of model updating (which is a process of correcting inaccurate parameters) can succeed (if the necessary parameters are omitted from the model). To check for this feature, an additional step of Model Verification is proposed, to alert the analyst to the possibility that the model is inadequate for the stated purpose and thus cannot be validated.

The addition of these two steps to the process results in a model validation procedure which is illustrated in Figure 1(b) and the rest of this paper will discuss the major features of these new steps, and introduce some new techniques ion both the measurement and modelling processes that are used in the development of valid models for complex and critical structures.

3. TEST STRATEGY

The essential task of the test strategy process is to identify exactly which tests should be undertaken, which data measured and how they should be processed to yield the information that is required to complete the validation process. Essentially, this involves identifying which of the components in the whole structure are most critical to the analysis for which the model has been constructed; which elements in those high-priority components are responsible for its importance in the whole system analysis; and which modes of the priority components are most influenced by the particular elements which are important. More detailed exposition of the new approaches can be found in references [1] and [2], both of which describe applications to aero engine structures, such as that shown in Figure 2.

At the end of this test strategy process, we shall have identified a small number of modes in a fraction of the structural components which are the most important data that can be obtained from a test and which strongly influence the validation process. In practical terms that results in – perhaps – just 10-20% of the components being critical to the whole structure's dynamics, and for these, model validation can be most effectively performed by checking – perhaps – just 3 or 4 vibration modes of each of those critical components. The effective elimination of 80-90% of the individual components is, perhaps, intuitively understood. The selection of just a few modes is less obvious: in fact, each component's dynamics will be dominated by a small number of elements, and it is only the modes which are sensitive to those elements which contain valuable information. What is found is that the important modes are often not simply the lowest 5 or 10 modes (which is what is conventionally chosen for a model validation process). Rather, it is often found that only 3 or 4 modes are required, but these may be found scattered amongst the first 30 or 40 modes. Figure 3 illustrates this feature in a specific application, from reference [1].

It is worth noting that previous practice advised the inclusion of modes with natural frequencies significantly higher than the frequency range of the eventual dynamic analysis, and thus demanded a heavy burden on the test schedule. Now, this is explained by the test strategy which reveals that a small number of the higher-frequency modes **are** significant: if we know which ones, then only these need to be measured; if we do not know which, then all modes up to a relatively high frequency limit must be included, thereby involving the test in a considerable inefficiency.

4. MODEL VERIFICATION

4.1 Models with insufficient DOFs. As mentioned earlier, the widely-used model updating methods are only capable of correcting model parameters which have erroneous values. They do not have the capacity to introduce additional parameters, should these be necessary. As a result, modelling errors such as insufficient mesh density, or oversimplification of complex geometries or boundary conditions, cannot be corrected by these methods. If such deficiencies exist, and model updating is applied regardless, then changes will be introduced to parameters which **are** in the model to compensate for the absence of others, and updated models with physically unsustainable features will result. There are a number of methods to check the capability of the model to represent the tested structure's behaviour, and they are collectively referred to as model verification methods. Some of the recent ones are described in reference [4] and illustrated in Figure 4. This shows an example based on two plates connected over a central area. By using correlation coefficients of the measured and predicted mode shapes it possible to show that the simpler model (on the LHS; no flexibility across joint) cannot describe the measured vibration behaviour whereas the other model (RHS; with joint flexibility admitted) can.

4.2 Joints. This example introduces one of the most common weaknesses in the structural dynamic modelling of practical structures: the question of how the interfaces between connected components are to be represented. Frequently, it is assumed (as in the simpler model above) that a 'solid' joint between two components is, in effect, a perfect connection while, in practice, almost all joints introduce a significant amount of damping and often a non-trivial flexibility to the structure. The diagram in Figure 5 illustrates one such situation: measurements on the subassembly shown revealed that there was a significant flexibility introduced by the bolted flanged joint which connected the two casing modules, in contrast to the modelling expectation of a 'rigid' joint. This flexibility was discovered during validation tests for the casing structure and showed also that there was as a significant damping contribution, and that both this and the flexibility were non-trivially non-linear, these all resulting in a significant re-think of the models that had been produced before continuing with the whole engine model construction. As a general rule, joints and interfaces need to e considered as components, and included in all assembly models. Otherwise, verification errors may be widespread.

5. DEVELOPMENTS IN MEASUREMENT TECHNOLOGY

In addition to the introduction of these two new processes to the validation method, three developments on modal testing technology are also worth mentioning

5.1 Non-linear behaviour. The first of these follows neatly from the previous comments on joint effects. These, and an increasing number of other effects, exhibit a degree of non-linear behaviour that cannot be simply ignored. Modern methods for measurement of FRF and other vibration response data used for modal analysis are increasingly sensitive to signs of nonlinear behaviour and should be used as a first line of detection of nonlinearities, so that the appropriate specialist methods can be used, as appropriate. While it is commonly accepted that non-linear systems do not possess modes in the classical sense, they do exhibit frequency response characteristics which, although more complex than those of their linear counterparts, are definable and measurable – such as the examples shown in Figure 6, taken from some measurements made on the structure shown in Figure 5.

5.2 Laser measurement of MDOF responses. A second recent trend in modal testing technology is the increasing use of lasers for what are described as 'field' measurement methods. These provide the means of measuring response at 1000s or 10000s of points, in contrast to the more conventional methods using discrete fixed transducers, which are limited to 10s or at best 100s of measurement points (or degrees of freedom). Some new measurement techniques have recently been developed using the standard scanning LDV, albeit in a non-standard mode by scanning the measuring laser beam continuously, rather than stepping from one point to the next, as is usually done. Some measurements made on a cylindrical casing structure are shown in Figure 7: see ref [5].

5.3 Test planning. Lastly, it is worth mentioning some recent developments in the Test Planning area: specifically, in a refined and significantly more efficient method of selecting measurements DOFs so as to get the best conditioned information from measured mode shapes. This is a new algorithm called OPTISET, and has been published very recently [6].

6. DEVELOPMENTS IN MODELLING

While the emphasis of this paper is deliberately on the testing side, as it is believed that significant enhancements to those activities are possible by more focused use of existing measurement technology, there are some interesting developments in the parallel theoretical modelling arena. One of the reasons for needing to validate the models used for design of complex engineering structures is that these models tend to be rather smaller (and thus more economical) than those which experts would advocate using. It is hoped that by updating them with data from real physical structures, the economical model size can be matched by a high fidelity of simulation. As we have seen, the cost of such approach is transferred from a large computer model to an expensive test program. A compromise approach is being developed using a new generation of mathematical models called 'supermodels'. These are FE models of individual components that are constructed with a much higher precision and mesh density than is customary for the individual components that eventually make up the whole structure model. These component supermodels are used in place of the test structures to provide the reference data that are used for validation of the 'standard' models for the design. Two examples are shown in Figure 8, and have demonstrated the advantages and potential of this approach in practical cases.

The primary benefits of supermodels, as compared with test structures, are that they can be available much earlier than any hardware can be manufactured and the data they yield are plentiful and noise-free. The drawback is that they are still approximations to the real structure, and will not reveal any idiosyncrasies, non-linearities etc. that are not deliberately introduced to the model. Clearly, experimental tests cannot be eliminated from the process completely: by using supermodels they may effectively be displaced from a central role inside the design loop for each new structure to an off-line role of developing correct supermodelling methods for the various types of structure that will be required. Further details of this approach can be found in references [7] and [8].

7. CONCLUDING REMARKS

In this paper we have sought to introduce some new concepts in the processes used to validate structural dynamics models of critical structures using modal test data. The major feature introduced is the concept of a test strategy, whereby the optimum test is defined for the specific requirements of a given model. By this approach, an order of magnitude reduction in time and cost (and wasted measurements) can easily be gained.

Intermediate checks on the verifiability of a provisional FE model can be made to avoid fruitless updating efforts on models which are fundamentally flawed and so incapable of representing the test structure to the extent which is required of it.

Some relatively new laser-based measurement methods suitable for modal testing at the level required by the new validation procedures have been introduced. Lastly, the concept of supermodels has been discussed as a possible replacement for the more routine tests in the future, and a means of placing physical tests outside the design loop which imposes ever-greater pressures of time and cost on the use of experiments in the validation of new designs.

REFERENCES

[1] D J Ewins "Modal Testing: Theory, Practice and Applications"
[2] S. Perinpanayagam & D. J. Ewins "Test Strategy for Component Modal Test for Model Validation" Proceedings ISMA, Leuven, Belgium. 2004
[3] J. V. Garcia &D. J. Ewins "Test Strategy for Aero-Engine Structural Dynamic Model Validation" Proceedings ISMA, Leuven, Belgium. 2006
[4] G. C. Chen & D. J. Ewins "FE Model Verification for Structural Dynamics with Vector Projection" Mechanical Systems and Signal Processing, Vol 18, 2004, pp. 759-757
[5] C.W. Schwingshackl, A.B. Stanbridge, C. Zang, D.J. Ewins "Full-field vibration measurement of cylindrical structures using a continuous scanning LDV technique" IMAC XXV, Orlando, 2007.
[6] P. M. Daborn, P. R. Ind, K. Garraway "Development of New Automated Modal |test Planning Algorithm" Proceedings IMAC XXV, Orlando, Fl. 2007
[7] D. W. Fotsch "Development of Valid FE Models for Structural Dynamic Design" PhD thesis, Imperial College London, 2001
[8] C. Zang, C.W. Schwingshackl, D.J. Ewins "Supermodel validation for structural dynamic analysis of aero-engine components" Proc. IMAC XXV, Orlando, 2007

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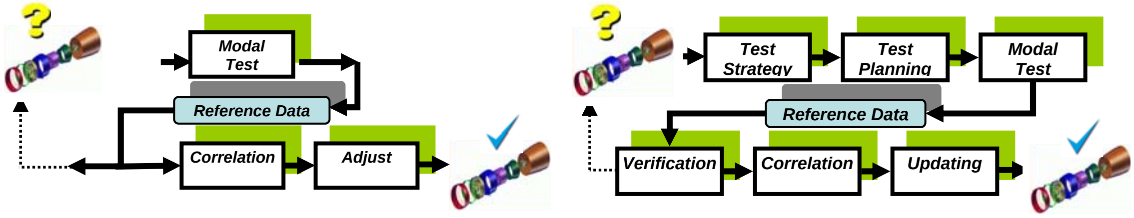


(a) (b)

Figure 1 Schematics of model validation procedures (a) 1970s (b) 2000s

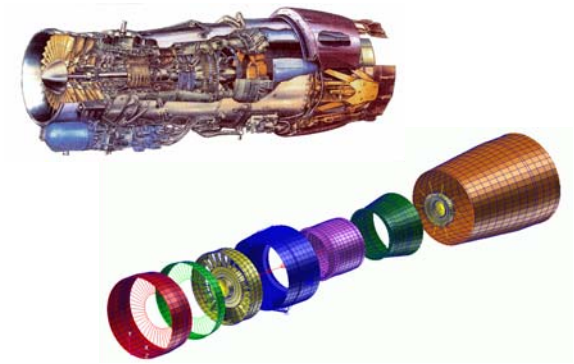


Figure 2 Complex aerospace structure and its constituent components

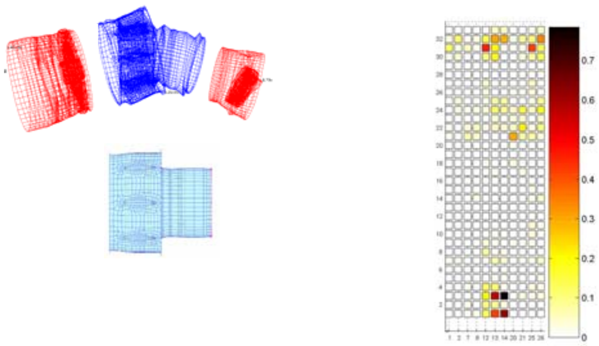


Figure 3 Example of significant modes of subassembly structure

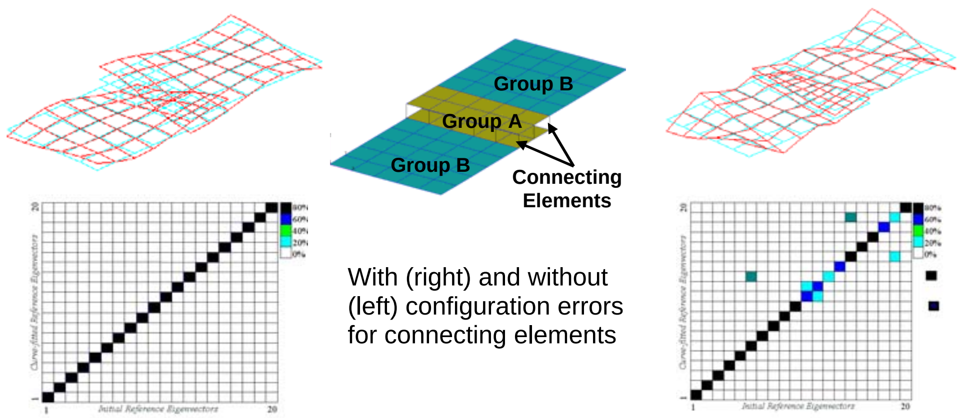
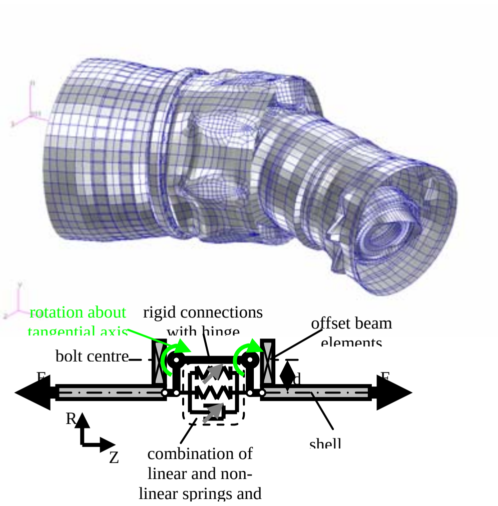


Figure 4 Example of model verification check



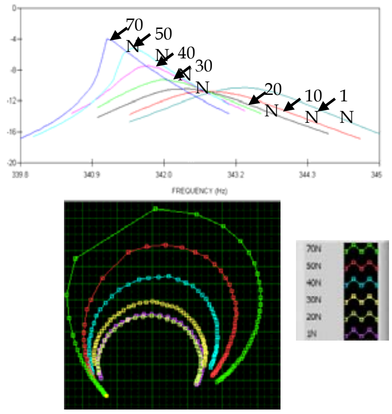


Figure 5 Typical joint in structural assembly **Figure 6 Evidence of non-linear behaviour**

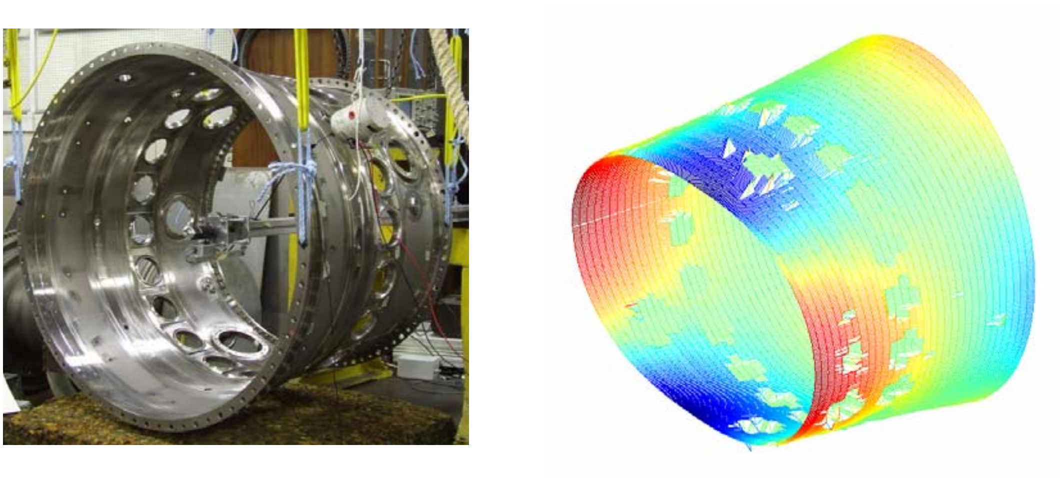
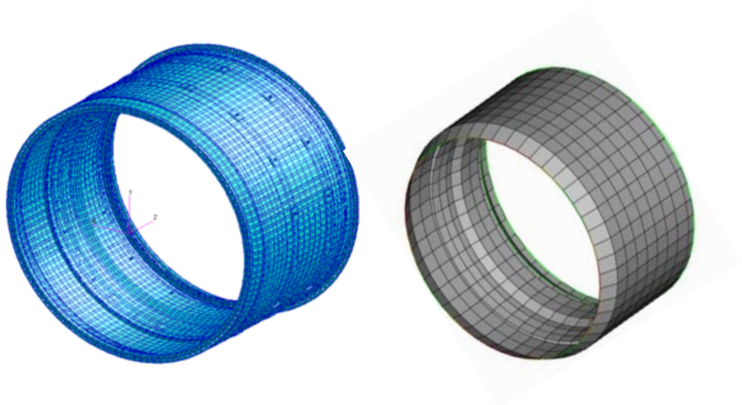


Figure 7 Scanning LDV measurement of cylindrical structure modeshape



Solid supermodel:
155520 nodes,
25365 elements

Design model
816 nodes
1104 elements

(a) **(b)**

Figure 8 Examples of supermodels (a) with standard design model (b) with test structure