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Adjustment or updating of models

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Abstract. In this paper, first a review of the terminology used in model adjustment or updating is presented. This is followed by an outline of the major updating algorithms currently available, together with a discussion of the advantages and disadvantages of each, and the current state-of-the-art of this important application and part of optimum design technology.

Keywords. Model updating; model correlation; analytical model; experimental model; optimum dynamic design.

1. Rationale and ground rules for model adjustment

The subject of model updating, in which an initial theoretical model constructed for analysing the dynamics of a structure can be refined, corrected or updated, using test data measured on the actual structure, has become one of the most demanding and demanded applications for modal testing. The stakes are high – if the process can be performed successfully, then the approximations and limitations which are inherent in current analytical (i.e. finite element) modelling can be identified and corrected on a case-by-case basis, and the correct ways of overcoming them in future designs learned in the process. On the other side, the costs of both modelling and of testing are high and, if the updating processes are not successful, then much time, effort and credibility may be lost. It is important therefore that the fundamentals of the subject are well understood, as also its scope and limitations, and the demands placed on those who wish to pursue such an application.

The subject has become a very extensive one, with already one textbook and several hundred papers devoted to its details. It is not realistic to attempt to condense all this material into a single section of this text, or even into a single paper, but what we shall seek to do is to lay down the fundamentals of the subject, as these must be mastered before any attempt is made to use the detailed methods of updating themselves. We shall present some definitions and propose some ground rules which are considered necessary as the basis for the development or implementation of model updating in practical situations. We shall then, in the following sections, present a very concise summary of each of the major algorithms for the updating problem together with some discussion of how and when each of these might be considered for use in practice.

First, it is appropriate to state some definitions for use throughout the rest of this text, noting the precision and subtlety of distinction between these various terms.

Analytical model – A model comprising $N \times N$ mass and stiffness matrices, usually based on finite element modelling methods, sometimes including an associated damping matrix, or modal damping factors. While the model is defined in terms of these spatial parameters, it is understood that any of the corresponding modal or response parameters can be obtained by suitable analysis of the given matrices.

Experimental model – A model consisting orginally of a set of FRF data (or equivalent) from which a limited modal model can be obtained by modal analysis of the measured response functions. It is generally assumed that the experimental model comprises an $m \times m$ eigenvalue matrix and an $n \times m$ eigenvector matrix, both of which are usually complex.

Valid model – A model which predicts the required dynamic behaviour of the subject structure with an acceptable degree of accuracy, or 'correctness'. This criterion is itself subject to qualification, not only in terms of the precision of the various parameters – natural frequencies, response amplitudes etc. – but also in their extent. A series of different levels of 'correctness' have been proposed in this respect, as follows.

- *Level* 1: Prediction (by the model and accurate to specified precision) of the various modal properties extracted from modal test (i.e. measured natural frequencies, and mode shapes defined at measured DOFs) in frequency range covered by the test.
- *Level* 2: Accurate prediction of measured response functions in the frequency range covered by the test.
- *Level* 3: Accurate prediction of measured modal properties, including at unmeasured DOFs, in the frequency range covered by the test.
- *Level* 4: Accurate prediction of response properties over the measured frequency range but including unmeasured DOFs.
- *Level* 5: Accurate prediction of response properties over the full frequency range and at all DOFs (this implies an 'exactly-correct' model).

Data – Quantitative items which describe specific features of a model or a structure, or its response or other dynamic behaviour.

Information – In effect, *independent* items of data that can be used together to solve problems of model adjustment, correction and updating. The amount of information available must generally be equal to or greater than the number of unknowns or variables for a unique solution to be available.

Localisation (or location) – The process of locating the whereabouts of differences between two models. Equivalent to the specification of the parameters to be updated: a necessary step before updating can take place.

Optimisation – The process of determining a set of values for given parameters such that a pre-defined objective (penalty) function is minimised. In the context of model updating, it is to determine the values for a predefined set of model parameters such that the discrepancy between measured and predicted dynamic behaviour is minimised. Only in cases where all the erroneous parameters have been located and included in the optimisation process can an'exact' updating be performed. In all other cases, the solution is a compromise of unknown quality.

Reconciliation – The process of explaining the origins of differences between two models which result in there being discrepancies observed in their respective dynamic behaviour (usually measured by comparison with predicted, but may be applied to two different analytical models).

Updating – The process of correcting the numerical values of individual parameters in a mathematical model using data obtained from an associated experimental model such that the updated model more correctly describes the dynamic properties of the subject structure (see above for a discussion of 'correctness').

Verification (of a model) – The process of determining whether a given model is capable of describing the behaviour of the subject structure, if all the individual model parameters are assigned the correct values. A model may not be verified if it lacks certain features which are present in the actual structure since, in this case, no amount of parameter correction can compensate for the errors embedded in the basic model. In some texts, this same issue is discussed in terms of 'model order' with concern focused on whether or not the analytical model is of sufficient order to represent the observed behaviour. However, as with some other features of the subject, sheer quantity of DOFs may not be sufficient to ensure adequacy of a model. There must be sufficient freedom in the appropriate regions of the model.

Validation (of a model) – The process of demonstrating or attaining the condition that the coefficients in a model are sufficiently accurate to enable that model to provide an acceptably correct description of the subject structure's dynamic behaviour. It is clear that a model which is not verified cannot be validated, and, indeed, that such a validation procedure should not be attempted on an unverified model.

A set of ground rules can be constructed from the above definitions. It is first necessary to decide upon the level of accuracy, or correctness which is sought from the adjustment of the initial model, and this will be heavily influenced by the eventual application of the refined model.

Then, it is necessary to determine whether or not the initial model can be updated, a difficult task which, in effect, calls for it to be verified. This means ensuring that all the important features of the actual structure are included in the model, even if only approximately at the outset, and that there are no actual features which have been omitted from the model. Of particular concern at this stage are the inclusion of sufficient flexibilities at the joints of an assembled structure and, most importantly, of sufficient fineness of mesh such that the model has converged. Model updating cannot be used to improve a model which is too coarse; only to refine one which is basically correct, but inaccurate in some of its components.

Next, it is necessary to determine the order of the problem, and by that is meant to establish how many of the model's coefficients need to be corrected. This is, in effect, the same task as locating the regions which contain all the errors to be corrected, but it is necessary to identify all of these so that the full scale of the problem – the number of unknowns to be identified in the updating process – is established. Sometimes referred to as 'locating the errors' or as 'specifying the updating parameters', this step is one of the most difficult yet most critical in the whole updating process.

The last stage before actual computation of the updating corrections themselves involves the specification of the data which need to be obtained in the validation tests so that the updating procedure can succeed. This is not simply a question of quantity of measured data (as is often thought to be the case) but, more importantly, of its selection so that the maximum amount of *information* about the experimental model is made available from the measured *data*.

Once all these preparatory stages have been undertaken, it is possible to embark on the updating calculation itself, with the equation to be solved defined in as satisfactory a state as possible. There are several numerical difficulties encountered in the process of performing an updating computation and most of these derive from ill-conditioned matrices which are themselves the result of poorly-defined equations together with a general insufficiency of useful information.

2. General methods of model updating

Before offering a synopsis of the different methods of updating themselves, it is appropriate to describe the general classes of method which are available. It is convenient to group them first into two major types.

- *Direct matrix methods*: Those methods in which the individual elements in the system matrices are adjusted directly from comparison between test data and initial analytical model prediction.
- *Indirect, physical property adjustment methods*: In which changes are made to specific physical or elemental properties in the model in a search for an adjustment which brings measured and predicted data closer together.

The first of these two groups is generally of non-iterative methods, all of which share the feature that the changes they introduce may not be physically realisable changes. They are simply new values for individual elements in the system $[M]$ and $[K]$ matrices, some of which may be applied to elements which are initially (and which, for reasons of the model configuration or connectivity should remain) zero. They generally require complete mode shape vectors as input but are, nevertheless, computationally very efficient. They have as their target the ability to reproduce the measured modal properties of m natural frequencies and mode shapes.

The second group is of those methods that are in many ways more acceptable in that the parameters which they adjust are, or at least are much closer to, physically realisable quantities. In the simpler versions, a single correction factor might be applied to the entire elemental stiffness submatrix for a particular (finite) element, but this is much more supportable than a correction factor which introduces a finite value into an off-diagonal stiffness matrix element which links two physically disconnected DOFs. Methods in this second group are generally iterative and, as such, considerably more expensive of computer effort. To offset this disadvantage, they generally work with incomplete mode shape vectors (mode shapes defined at the n DOFs of a typical modal test in place of the complete N DOFs of the full analytical model which are required by most of the first group of methods).

Developments are continuing in methods of both groups, although it is the second group that has emerged as the most widely used in general practical application. As a preface to the following sections which summarise each of the main approaches, it should be stressed that the subject is still relatively immature and that success in its application is not assured. One important feature of this state of development is that while successes are often reported, these are quite case-dependent. This is taken as a sign that the essential technology is there for the developing, but that the necessary developments are not yet complete. Potential users of the methods should therefore be forewarned but encouraged!

In the following sections, we shall summarise the essential features of the following methods. Two recent surveys (Imregun & Visser 1991; Mottershead & Friswell 1993) provide a useful entree to this subject for such purposes, and a recent book on the same subject by Friswell & Mottershead (1995) provides details of some, if not all, of the methods currently developed. The methods summarised below include, from the first group, the direct matrix updating (DMU) method and error matrix method (EMM), and from the second group, the eigendynamic constraint method (ECM), inverse eigensensitivity method (IESM), and response function method (RFM).

3. Direct matrix updating

The direct matrix updating method was one of the earliest to be developed for industrial application, dating back to the 1970s. In its basic form, applied to an undamped system, the method performs an adjustment first on the system mass matrix and then uses the result to perform a similar adjustment on the stiffness matrix. The method requires the model and the input mode shape data for the full set of DOFs. This normally presents a problem for the experimental model description and so one of the expansion methods would normally be applied to the incomplete measured mode shape vectors to prepare them for application in this method.

The formula for the updating is simply defined, as follows.

$$[\triangle M] = [M_A][\Phi_X][m_A]^{-1}([I] - [m_A])[m_A]^{-1}[\Phi_X]^T[M_A], \tag{1}$$

where

$$[m_A] = [\Phi_X]^T[M_A][\Phi_X],$$

followed by:

$$\begin{aligned}[\Delta K] = {} & [M_A][\Phi_X][\Phi_X]^T[K_A][\Phi_X][\Phi_X]^T[M_A] + [M_A][\Phi_X][\lambda_X][\Phi_X]^T[M_A] \\ & - [K_A][\Phi_X][\Phi_X]^T[M_A] - [M_A][\Phi_X][\Phi_X]^T[K_A].\end{aligned} \tag{2}$$

Additional constraints can be added to restrict the adjustments to the mass and stiffness matrices which these formulae introduce so that they are more consistent with the physics of the system. It can easily be seen that the solution obtained is not a unique one, by any means. This can be shown mathematically (by the fact that there are a large number of $[\Delta M]$ matrices which will satisfy the basic requirement of equations (1) and (2) as well as heuristically by the fact that the model is of order $N \times N$ and no requirement has been stipulated for the properties of the modes after mode number m. This means that there exist a large number of models which satisfy the specified constraints but all of which have different properties for the unspecified modes. It is clear that a solution obtained in this way is a numerical solution and not a physical one.

4. Error matrix methods (EMM)

In this method, an alternative approach is suggested for the task of determining the adjustments to the elements in the mass and stiffness matrices. The method uses the concept of 'error matrices' that have already been introduced in the previous section, which are the matrix differences between the experimental (X) and analytical (A) system matrices, as follow,

$$[\Delta M] = [M_X] - [M_A]; [\Delta K] = [K_X] - [K_A]. \tag{3}$$

We are, in effect, interested in determining these two error matrices. It can be seen that direct computation of the mass or stiffness error matrix is hindered by our inability to specify $[M_X]$ or $[K_X]$. Although there exist direct transformations between the modal properties and the spatial properties, in the form of,

$$[M] = [\Phi]^{-T}[\Phi]^{-1},$$
$$[K] = [\Phi]^{-T}[\omega_r^2][\Phi]^{-1}, \tag{4}$$

these are only valid in cases where the modal matrices are complete – i.e. contain all modes and all DOFs – and so are not applicable in the general practical case where only m modes are identified and these defined at only n DOFs. The EMM seeks to obtain an estimate for the error matrices using the following approach which is based on the contribution of the known modes to the system flexibility and inverse mass properties. Thus, we may write:

$$[\Delta K] = [K_X] - [K_A],$$
$$[K_X]^{-1} = ([I] + [K_A]^{-1}[\Delta K])^{-1}[K_A]^{-1}$$
$$\approx [K_A]^{-1} - [K_A]^{-1}[\Delta K][K_A]^{-1} + ([K_A]^{-1}[\Delta K])^2[K_A]^{-1} + \ldots, \tag{5}$$

and similarly for the mass properties, leading to the EMM formulae,

$$[\Delta K] \approx [K_A]([K_A]^{-1} - [K_X]^{-1})[K_A],$$
$$\approx [K_A]([\Phi_A][\omega_{Ar}^2]^{-1}[\Phi_A]^T - [\Phi_X][\omega_{Xr}^2]^{-1}[\Phi_X]^T)[K_A]$$
$$[\Delta M] \approx [M_A]([\Phi_A][\Phi_A]^T - [\Phi_A][\Phi_X]^T)[M_A], \tag{6}$$

in the application of which the data for as many or as few modes as required can be included, although special precautions must be taken if these data are incomplete in the sense of DOFs included.

5. Eigendynamic constraint methods (ECM)

The alternative series of updating methods start with the family that can be called the eigendynamic constraint methods. This series of methods is of an essentially different formulation from the previous ones in that the variables to be solved in the updating equations are no longer the individual elements on the mass and stiffness matrices, but instead are correction factors, a_i, and b_i, that are applied to the individual (finite) element submatrices of mass and stiffness, $[m^i]$ and $[k^i]$, which are then corrected to $(1 + a^i)[m^i]$ and $(1 + b_i)[k^i]$ respectively.

Based on considerations of the orthogonality conditions, and of the basic relationship between the eigenvalue and the eigenvector for each individual mode,

$$\{\phi_X\}_i^T[M_X]\{\phi_X\}_i = 1,$$
$$[K_X]\{\phi_X\}_i - \lambda_i[M_X]\{\phi_X\}_i = \{0\}, \tag{7}$$

it is possible to construct a set of equations which take the form,

$$[A]\begin{Bmatrix} a_i \\ b_i \end{Bmatrix} = \{B\}, \tag{8}$$

where $[A]$ is an $(m \times (N+1)$ by $(N_1 + N_2))$ matrix constructed of the experimental eigenvalues and eigenvector elements and $\{B\}$ is an $(m \times (N+1)$ by 1) vector composed of unity or zero values, depending on the orthogonality conditions. In these expressions, $N =$ the number of degrees of freedom in the model, while N_1 and N_2 are the numbers of mass and stiffness elements to be corrected respectively. As with other formulations of the same type, a solution of this equation is possible under the conditions that the problem is over-determined, and that will depend upon the relative magnitudes of the number of modes included (m) and the numbers of unknown correction factors, N_1 and N_2. The main drawback of this method is that it requires spatially-complete eigenvectors and although unmeasured elements can be substituted by expansion of interpolated values, this is a feature of some limitation and the methods are not widely used today.

An earlier version was widely used as a residual force method which used only the second of the two criteria given in (7) above.

6. Inverse eigensensitivity (IES) methods

The method in this second series which has gained most popularity and is perhaps the most widely used today is that referred to here as the 'Inverse Eigensensitivity Method' or IESM. This is based on the approximation to the dynamics of a modified system based on the properties of the initial (original system) together with the first-order sensitivity functions of those properties. This method shares the feature in the preceding eigendynamic constraint method that the differences between the original model and the adjusted model can be represented by a set of correction factors, a_i and b_i, applied to the elemental mass and stiffness matrices, $[m^i]$ and $[k^i]$. The underlying equations are as follows:

$$\{\phi\}_r \approx \{\phi_A\}_r + \sum_{i=1}^{l} \frac{\partial\{\phi_A\}_r}{\partial a_i} a_i + \sum_{i=1}^{l} \frac{\partial\{\phi_A\}_r}{\partial b_i} b_i,$$

so that

$$\begin{aligned} \{\Delta\phi\}_r &\approx \sum_{i=1}^{l} \frac{\partial\{\phi_A\}_r}{\partial a_i} a_i + \sum_{i=1}^{l} \frac{\partial\{\phi_A\}_r}{\partial b_i} b_i, \\ \Delta\lambda_r &\approx \sum_{i=1}^{l} \frac{\partial\lambda_{Ar}}{\partial a_i} a_i + \sum_{i=1}^{l} \frac{\partial\lambda_{Ar}}{\partial b_i} b_i, \end{aligned} \tag{9}$$

and these can be expressed in a matrix format which can be used to solve for the unknown correction factors, a_i and b_i as follows:

$$\left\{ \begin{matrix} \{\Delta\phi\}_1 \\ \frac{\Delta\lambda_1}{\lambda_1} \\ \cdot \\ \cdot \\ \{\Delta\phi\}_m \\ \frac{\Delta\lambda_m}{\lambda_m} \end{matrix} \right\} = \begin{bmatrix} \frac{\partial\{\phi_A\}_1}{\partial a_1} & \cdots & \frac{\partial\{\phi_A\}_1}{\partial a_i} & \frac{\partial\{\phi_A\}_1}{\partial b_1} & \cdots & \frac{\partial\{\phi_A\}_1}{\partial b_i} \\ \frac{\lambda\partial_{A1}/\partial a_1}{\lambda_1} & \cdots & \frac{\lambda\partial_{A1}/\partial a_i}{\lambda_1} & \frac{\lambda\partial_{A1}/\partial b_1}{\lambda_1} & \cdots & \frac{\lambda\partial_{A1}/\partial b_i}{\lambda_1} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \frac{\partial\{\phi_A\}_m}{\partial a_1} & \cdots & \frac{\partial\{\phi_A\}_m}{\partial a_i} & \frac{\partial\{\phi_A\}_m}{\partial b_1} & \cdots & \frac{\partial\{\phi_A\}_m}{\partial b_i} \\ \frac{\partial\lambda_{Am}/\partial a_1}{\lambda_m} & \cdots & \frac{\partial\lambda_{Am}/\partial a_i}{\lambda_m} & \frac{\partial\lambda_{Am}/\partial b_1}{\lambda_m} & \cdots & \frac{\partial\lambda_{Am}/\partial b_i}{\lambda_m} \end{bmatrix} \left\{ \begin{matrix} a_1 \\ \cdots \\ a_1 \\ b_1 \\ \cdots \\ b_1 \end{matrix} \right\}. \tag{10}$$

This equation can be written in simpler form as,

$$\{\Delta\nu\} = [S]\{p\}, \tag{11}$$

where $\{\Delta\nu\}$ is a vector containing the test/analysis differences in modal parameters, $[S]$ is the matrix of sensitivities for the initial analytical model, and $\{p\}$ is the vector of correction factors for the mass and stiffness elemental submatrices.

Solution of this equation takes the form,

$$\{\Delta p\} = [S]^{+}\{\Delta\nu\}. \tag{12}$$

In this formulation, it is found that it is not necessary to provide spatially complete eigenvectors. Of course, solution of (12) is approximate because of the simplifications and the incompleteness of the data but can be arranged in an iterative process whose convergence relies on the validity of the assumptions and the condition of the underlying data provided by the analyst. Various techniques can be introduced to speed up or to improve the condition of the solution, including –

- grouping of individual elements into super-elements, which has the effect of reducing the number of variables in preliminary calculation (location of super-elements containing errors can be used to retain and to remove these elements from subsequent iterations);
- regularisation of the sensitivity matrix, $[S]$, to improve its numerical condition;
- elimination of selected elements from the solution following analysis of their influence on the stability of the solution (some elements are often found to be inherently poorly conditioned and must be removed from the analysis, even if these elements contain errors of modelling).

7. Response function methods (RFM)

The last type of updating method summarised here shares several features with the two preceding ones but has one marked difference in that it is based on comparisons of measured and predicted response functions, instead of modes. The basic method, of which there now exist a number of variations, is called the Response Function Method (RFM) and uses a very similar formulation to that given in the previous section for the IES method, with the solution equation being,

$$\{\Delta H\} = [R]\{p\}, \tag{13}$$

where $\{\Delta H\}$ represents a vector of differences between measured FRFs and the corresponding predicted values, $[R]$ is a matrix containing FRF data derived from the measured data set and from theoretical predictions and $\{p\}$ is, once again, the vector of (unknown) correction factors whose values represent the solution to the updating equation. There are several features of this type of updating method which possess advantages over the other modal-based methods discussed before. Amongst these features are –

- the large number of data which are available in this format (by comparison with modal data);
- the automatic inclusion of damping in the measured data;
- the lack of requirement to provide correlated mode pairs (as is necessary to construct the vector $\{\Delta\nu\}$ in the preceding methods);

- the potential for application in the higher frequency ranges where extraction of modal parameters may become very difficult on structures with relatively high modal density and/or damping.

8. Discussion

8.1 *General comments*

In the preceding sections, we have summarised some of the major updating algorithms which are currently available. In this section, it is appropriate to provide some discussion concerning the applicability and the limitations, advantages and disadvantages of these various options. Whereas only five specific methods have been presented (and there do exist yet more) these do include the basic versions of the two methods whose various versions are in widespread use at present – the inverse eigensensitivity method (IESM) and the response function method (RFM).

The earlier methods were based on computing changes made directly to the mass and stiffness matrices. Such changes may have succeeded in generating modified models which had properties close to those measured in the tests, but these resulting models cannot be interpreted in a physical way. In other words, it is not easy to justify what the required changes represent in terms of changes to the actual mass and stiffness distributions in the model. As a result, it is difficult to learn anything from the exercise which would enable the modeller to develop better initial models on subsequent occasions, and this is generally one of the aspirations of a model updating exercise. In any event, the success rate of these methods is quite variable, and clearly at the mercy of the choice of the measured data provided by the modal test.

The later methods, which seek to find correction factors for each individual finite element or, in the limit, for each design parameter relating to each finite element, have emerged as the main hope for updating technology even though they generally require a much greater computation effort – they are all iterative, in contrast to the direct formulae of the earlier methods. However, this feature, and the specific formulations which actively seek to minimise the ill conditioning which can result from such methods, means that these methods are more likely to yield useful results from the process, as well as numerically more correct models.

8.2 *Philosophy of model updating*

It is an essential requirement that any initial theoretical model that has to be subjected to an updating procedure be updatable, no matter what the specific algorithm used. The difference between validation and verification has already been discussed in this paper and the same issue re-appears here. By ‘updatable’ we mean that the theoretical mode, which is the subject of the updating process, must contain all the features necessary to describe the observed dynamic behaviour of the test structure. This does not mean that the initial model must have the correct values for the various elements, or features in the model, just that these features must be present. For example, if there is a flexible joint between a beam and a plate to which it is attached, then it is essential that such flexibility be included in the model. If a rigid connection is assumed in the model, then there is no element at the junction point whose stiffness can be updated in the next phase and that renders the model unacceptable for this process. If the reverse situation applies: – a flexible joint is assumed in the model but the actual behaviour is that of an effectively rigid joint, then the flexible element can be updated to have a very high stiffness and the model is applicable. This means that the initial models must have more rather than fewer DOFs and this, in turn, means that many initial models may well be unsuitable for updating. Methods are required to test for the updatability of models as this property can be very difficult to determine.

Assuming that the models are basically updatable, then the problem is one of arranging that the specific updating solution attempted be an over-determined one. At the outset, most updating problems are under-determined, and thus insoluble, as a result of the greater number of (unknown) correction factors to be determined than the number of independent items of information available from the test. The critical task to be undertaken prior to application of the chosen updating routine is that of localisation of the errors, so that there are a smaller number of active variables (elements whose properties need to be updated) than there are equations provided by the measured data. While there are several procedures for this localisation process, they all involve a degree of operator skill, or 'art', and require further development before becoming the robust, case-independent tools that are needed.

8.3 *Practical use of updating methods*

It is appropriate to add some comments on the practicalities of using these updating methods on real structures. It is often found that a trial-and-error approach is required in order to establish the 'best' selection of parameters to be included in the updating, this being done by making a selection, trying to update the model using that selection and reviewing the degree of success attained. Then another (equally plausible) m set of parameters are selected and the process repeated. Behind this apparently hit-and-miss approach is the rationale that when (or if) the correct choice of parameters is found, then a much closer match between test and analysis will be obtained than the best that can be achieved with an incorrect, or only partially correct selection of parameters. It is often possible to obtain a 'best-fit' solution to a problem such as this but, as mentioned earlier, 'best' may not be very good.

8.4 *State-of-the-art of model updating technology*

Finally, to summarise the state-of-the-art of the various algorithms currently available for the task of updating an initial finite element model, it is seen that there are several different approaches already, with others almost certain to be developed and it is not clear which is the best. Most of the methods have been tested and demonstrated on simulated cases in which the two models – the initial analytical and the 'experimental' both share identical configurations. This type of proof of performance must be regarded with some scepticism. It is true that all methods must perform satisfactorily on such test cases but these are simply the first of a series of such tests to which the methods must be subjected, later ones featuring the important property that the two models are significantly different. There are very few methods available at the present time to test the suitability of a model for updating, and these are urgently required to replace the 'skill' element which is an essential part of successful updating.

9. Conclusion

In this paper, we have introduced the concepts of model updating and then summarised a number of recent and current algorithms which are available for undertaking the task. The current state-of-the-art of model updating has been discussed and it is noted that further developments in the methods are likely and that certain additional techniques are required in order to permit the widespread use of model updating on practical structures.

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