MODEL UPDATING FOR STRUCTURAL DYNAMICS: PAST, PRESENT AND FUTURE OUTLOOK

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SUMMARY: During the past two decades, finite element model updating using experimental data has matured from attempts to directly calibrate system matrix coefficients until today's semi-automatic iterative techniques. State-of-the-art approaches provide the flexibility that is needed to update virtually any input parameter, at either a local or a global level. Despite the large number of contributors to the research, only few commercial implementations have emerged that combine all necessary supporting tools and enable interaction with standard solvers. In this presentation, the entire model updating process is reviewed and some successful methodologies are highlighted. Based on the author's own experiences over the past 20 years, a number of practical solutions are presented that allowed to remove past barriers, increase user productivity and widen the field of application. The paper concludes with current trends and an outlook to the future of the technology.

KEYWORDS: model updating, structural dynamics, validation.

1. INTRODUCTION

To successfully make the move to digital prototyping, and thereby reduce the number of physical prototypes, simulation of product performance should be provided with a measure of confidence and validated against experimental data.

Model updating is defined as the process of quantifying the differences between finite element analysis results and corresponding reference data, and then modifying the numerical values of the input parameters in the model, or the model itself, to obtain a valid model. Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended use of the model ("are the physics right?"). This is different from verification, which is the process of determining that the intentions are met by the model implementation, and which may require correcting the model ("checking the input decks"). If parameter variability is included in the finite element model, then model updating can also refer to the precision attained by a probabilistic model.

The need for model updating stems from the uncertainty that is inherent to any attempt to represent reality by a mathematical model. Uncertainty is the mainly caused by lack of knowledge and may exist in all aspects of the modelling process. In practice, physical element properties (material, geometry) are selected as updating parameters to improve accuracy. They may also be used as indicators for stiffness or mass modifications that are required because of deficiencies in the model caused by inadequate meshing or level of detail. Variability, which can be considered as a specific type of uncertainty, refers to the variation of the physical input parameters that is mainly caused by manufacturing tolerances or in-service operation conditions.

In this paper some fundamental issues with model updating that have long time occupied researchers in this field are reviewed. The practical implementation of state-of-the-art model updating methods is briefly described as well as some common applications. Finally, emerging trends and topic for future research are presented.

2. HISTORICAL PERSPECTIVE

2.1. Analytical versus Experimental Analysis

The finite element method has made significant progress during the period 1960-1980 to satisfy the needs of the aerospace and later on, the automotive industries. Most FE companies that are still leading the way today were founded during that period. They have been increasingly successful to popularize finite element analysis and adapt it to the needs of modern engineering. Integration between pre- and postprocessor and solvers allowed cutting the time required to prepare a model for analysis and interpret results. More recently, integration with CAD systems, and automated meshing have further improved productivity. Thanks to the digital revolution, the cost of computing has sufficiently decreased to allow widespread use in all fields of simulation. Whereas analysis was initially used as tool for verification and troubleshooting of existing designs, the focus is now moving to applications like in upfront design space exploration and multi-physics optimization. The need for confidence in simulation results is imposing the implementation of quality assurance standards. The cornerstones of these standards are verification, validation and model updating.

In parallel to the analytical worlds, the digital age has enabled significant progress in experimental techniques for structural dynamics [1]. It took only a few decades to grow from dual-channel and early modal analysis to the multi-channel mobile acquisition systems of today. Research in modal parameter identification has produced a range of methods that have now become remarkably stable and hold potential for automation. Application of modal parameters for validating finite element models has been an important driving force since the 1980s. It is therefore that model updating and related methods are considered a spin-off from modal testing. Papers are published at the same conferences and in the same journals. With the changing role of testing in the virtual prototyping age, and the growing awareness of the CAE community for quality assurance, it can be expected that model updating will move closer to the CAE world.

Finite element analysis and experimental modal analysis are complementary methods that both have strengths and weaknesses. A finite element model is most suitable for design purposes but has a priori unknown accuracy. The amount of input and output data that is produced can be overwhelming. Modal testing produces a relatively small amount of reference data but with accuracy and precision depending on the operator, and the type of data (high for resonance frequencies, low for modal displacements and damping). Moreover, linearity is assumed.

2.2. Uncertainty in Simulation and Test

Uncertainty, including variability, exists in both simulation and test. It is important to recognize the sources and types of uncertainty and classify them hierarchically. With respect to variability, it is useful to understand how small variations in input parameter propagate through the structure and manifest itself in the output.

Uncertainty in simulation results manifests itself in two main classes: physical uncertainty and numerical uncertainty. There exist four main levels at which physical uncertainty becomes visible, namely

- Boundary and initial conditions
- Material properties - modulus of elasticity, yield stress, local imperfections, etc
- Geometry - shape, thickness, manufacturing and assembly tolerances, etc.
- Loads - earthquakes, wind gusts, sea waves, blasts, shocks, impacts, etc.

Uncertainty is further increased because many of these properties may vary substantially with temperature, frequency, or load level.

The following types of numerical uncertainty can be identified:

- Conceptual modelling uncertainty - lack of data on the physical process involved, lack of system knowledge.
- Mathematical modelling uncertainty - accuracy of the mathematical model validity.
- Discretization error uncertainties – the choice of element types, mesh density, level of geometrical detail.
- Numerical solution uncertainty - rounding-off, convergence tolerances, integration step.
- Human mistakes - programming errors in the code or wrong utilization of the software, mistakes in data or units.

These types of uncertainty may or may not exist regardless of the physics involved. An example of the exhibit of numerical uncertainty is the different results that may be obtained by two finite element codes, using the same finite element model. Indeed changing solver, computing platform, or element formulation can be possible causes of significant differences.

In a deterministic model it is assumed that all parameters can be set to their nominal values and that there is no variability. Any adjustments required to the input parameters are justified because of combined effects of different forms of uncertainty. Test data serves as reference data in model validation and is used as targets for the model updating methods. However, it is clear that uncertainty also exists in testing. Possible causes of physical uncertainty are related to:

- Test definition – fixture, mounting procedure, excitation method, transducer location, sensor weight, dynamic loading.
- Instrumentation – calibration, distortions, cabling noise.
- Data acquisition – digital signal processing, measurement and filtering error.

Techniques like experimental modal analysis are also subject to numerical uncertainty in the mathematical models that are used for modal parameter estimation.

Given the increasing complexity of engineered structures, and the many sources of uncertainty, it is clear that deterministic models have almost reached their limitations of practical usefulness and in future need to be complemented by probabilistic simulation.

2.3. Issues with Model Updating

Four major related issues have dominated past research in deterministic model updating methods:

- Mismatch between the number of degrees of freedom used in FE and test model.
- Selection of the updating parameters
- Selection of the updating algorithm
- Selection of the residues

Some excellent surveys have been published that review these issues [2-8]. A brief overview is presented hereafter.

2.3.1. Mismatch between FE and Test Models

Model updating would be a trivial task if it were possible to obtain accurate test data at all degrees of freedom N of the finite element model. A single mode shape or frequency response vector would enable direct correction of N parameters. However, in practice the test degrees of freedom correspond only to a small fraction of the analytical ones. This mismatch between analytical and test models can be addressed in the following ways:

1. Expansion of the test data to size of the analytical model.
2. Reduction of the analytical model to the measured degrees of freedom. This type of reduction is also referred to as Test Analysis Model (TAM). It involves a transformation of the system mass and stiffness matrices.
3. Truncation of the analytical result vectors to the mapped degrees but without reducing the analytical model.

All these methods have been the subject of numerous papers describing many variants, and discussing their benefits and the disadvantages. The requirements of the updating algorithm that is used and the application of the updated model will impose the method that can be used. If expansion of the test data or reduction of the analytical model use a transformation matrix that is computed from the analytical data, which is to be validated, then the subsequent model updating process will be adversely affected. Moreover, if reduced system matrices are updated, no physical meaning can be associated to the updating results because there is no longer a direct relation between element properties and updated matrix terms. As a result, preference will be given to truncation of the analytical results even though this choice implies that an iterative updating algorithm will be used.

2.3.2. Selection of Updating Parameters

The selection of updating parameters is an important issue that has generated a lot of discussion about the usability of model updating results. An updating parameter can be selected at the level of individual element matrix terms, at element matrix or at sub-matrix level, or more practical, at the element properties level. Furthermore, elements can be grouped so that parameters can span all element matrices or properties in the group. Making this selection is not an easy task but is critical to the outcome of any model updating analysis. There is a chance that parameters that should be updated were not included in the selection. One may choose too include all possible parameters in order not to miss any necessary change, but such strategy is often prohibited for numerical reasons in the updating algorithms, not the least because of the continuously growing size of finite element models.

On the other hand, if more parameters than updating equations (test data) are selected, then the system of model updating equations becomes underdetermined, and hence a non-unique solution is obtained. Numerous strategies and methods have been developed to aid the analysts in determining the dominant errors in the analytical mass and stiffness matrices and thus guide the parameter selection.

2.3.3. Selection of the Updating Algorithm

Model updating algorithms can be classified into three categories: direct methods, gradient-based iterative method and explorative methods.

Direct methods were the subject of early research in the 1970s until early 80s. It theory, the mass and stiffness matrices can be constructed directly if all the modes of a structures were measured at all the degrees of freedom. In practice, however, availability at only a small fraction of the degrees of freedom requires expansion of the incomplete measured mode shapes. Even though direct methods are computationally efficient and robust, there are some disadvantages that have prevented their success for practical applications:

- The updated system matrices may not have physical meaning and there is no relation to changes of physical parameter changes. Such black box approach is not acceptable from an engineering point of view.
- The test data need to be expanded, usually based on the analytical data, and this will introduce additional uncertainty in the process. It is not acceptable to change the reference data by using data that comes from a model that needs to be validated.
- Reduction of system matrices introduces error.

Nevertheless, there are applications where these methods could be useful i.e. for the updating of reduced matrices that are used in the analysis of assemblies.

Iterative methods minimize an objective function that quantifies the distance between analytical and corresponding experimental results. This distance metric is a non-linear function of the updating parameters and can be minimized using first-order gradients in a iterative procedure. These methods provide a great flexibility in the choice of response residues that are used to define the objective function. At each iteration, correction factors can be applied to the system mass, stiffness and damping. The correction factors can be directly related to changes of the physical properties of the finite elements. This provides the analyst with complete control on the choice of updating parameters, and updating results can be evaluated in terms of physical significance. The selection of parameters can be based on uncertainty analysis, analysis of correlation with test, and sensitivity of the objective function for changes of the parameters. Because the objective function can be freely defined, expansion of the test data is not required if only residues are considered for locations or frequencies that are measured and in common with the analytical model. Disadvantages are the computational cost of iterative re-analysis of the analytical model, and the dependency of the updating results on the choice of residues and updating parameters. Nevertheless, the advantages of these methods over direct methods have justified their implementation in commercial software.

Explorative methods, or non-gradients methods can be used to minimize the model updating objective function. Such techniques like genetic algorithms, DOE/RSM, and Monte Carlo optimization require massive re-analysis of the system responses for perturbed parameters. Such approaches were only to be considered for simplistic or highly reduced mathematical models with only few updating parameters due to constraints in computational resources. Modern computers and computing clusters, however, have significantly increased to size of models and number of parameters that can be analyzed.

2.3.4. Selection of the Residues

The choice of residues used by the updating algorithms is function of the purpose of the simulation model and practical considerations. In general it is desirable to seek a maximum amount of reference data because this will increase the number of equations that can be used in the updating algorithm. The following classes of residues can be identified:

- Mass (weight, center of gravity, mass moments of inertia).
- Static or pseudo-static displacement and strain.
- Modal residues (frequency, mode shapes, MAC, mode shape orthogonality).
- Non-modal residues (discrete FRF amplitudes, FRF correlation functions).
- Operational shapes.

Each class of residues enables updating of specific parameters that relate to the system mass, stiffness or damping matrices of the analytical model.

2.4. Barriers to the Industrial Use of Model Updating

For many years there has been a wide gap between finite element analysts and test engineers. Although engineering managers at all levels have long ago recognized the benefits of processes that combine the analytical and experimental approaches for product design and analysis, their implementation in many cases was prohibited because of practical and cultural reasons. A number of technological and organizational changes in recent years have made it possible to remove these obstacles:

- Powerful and affordable workstations now offer sufficient horsepower to run industrial finite element analysis as well as all kinds of test systems.
- Computers are now connected by networks so that data files can be easily moved from one system to another.
- Maturing methods for model updating are now available in commercial software. Applications have generated interest from engineers not directly involved with research on these topics.
- Technical centers now bring people with different backgrounds together under the same one roof with easy access to test labs and simulation tools.

New applications and growing acceptance in industry will accelerate removal of any remaining barriers. More efforts are required to provide continued education of FE analysts and test engineers in the form of theoretical and practical courses, as well as handbooks and best-practice guidelines.

3. REVIEW OF CURRENT PRACTICE

3.1. The Practical Model Updating Process

Model updating tools are now available in commercial software, either as add-ons to test software, add-ons to finite element software or as stand-alone tools. The latter are preferred because they integrate all necessary tools and can be combined with any FE or test solution. Because FE model updating is a knowledge and decision-based process that requires interactive access to a multitude of tools for database management, response and parameter selection, and numerical tools for correlation analysis, sensitivity analysis and parameter estimation. This is best achieved in a dedicated environment. It is important that the user interface, graphics, analysis and reporting tools can be customized and extended so that they can be integrated in any existing CAE environment and adapted to the requirements of the users. The different components of a stand-alone model updating tool are very briefly described hereafter.

3.1.1. Database Management

A stand-alone tool for model updating uses a relational database to contain all FE and test data. Keeping all data in memory and organized in separate tables ensures the fastest response times for interactive search, verification, editing and visualization. To prepare for analysis, a number of database operations may be required. They include coordinate system transformation to keep all FE and test data in the same global reference system, mode shape realization, and the creation of sets of elements based on topology, material or geometry.

3.1.2. Data Translators and Solver Integration

Two-way access is required between the model updating database and data files that contain the finite element and test data. The FE model and any relevant results like element matrices, mode shapes, FRFs and operational shapes must to be imported and prepared for correlation with test data. It must be possible to export an updated FE model so that it can be re-analysed by a finite element program of choice. After re-analysis the new results must be re-imported and again be correlated with test data to evaluate the improvement. A driver script can be used to automate these steps. Once a driver is configured, the external finite element software can be used as if it is part of the updating software. Export of test models is useful for applications of pretest planning that generate a test model from a reduced FE model.

Alternatively to driving an external finite element program, the model updating tool may incorporate itself an element library and solvers. This allows for faster re-analysis in sensitivity analysis and parameter estimation.

3.1.3. Pretest Analysis

Success of model updating depends to a large extend on the availability of sufficient and well-distributed quality test data. When a baseline finite element model of a structure that is sufficiently representative of the real structure is available, then this model can be used to identify and select important mode shapes, and select optimal sensor locations. Using criteria like observability or mode shape orthogonality, test engineers can optimise the number and position of sensors and locate optimal locations and directions to measure and excite the structure. Virtual testing is the process of simulating the real test by applying the excitation loads and postprocessing time or frequency domain results as if they were test data.

3.1.4. Correlation Analysis

The first step in correlation analysis is to transform the models to a common reference coordinate system. Next the test model is mapped onto the FE model to find the degrees of freedom that are common in both the FE and test model. Once the table with mapped degrees of freedom is established, it is decided if the FE model will be reduced or truncated, or the test data expanded. In most cases, truncation will be the preferred way. Numerical mode shape correlation criteria can now be computed and evaluated in order to identify similar mode shapes. Modal Assurance Criterion (MAC) [9] or modal orthogonality checks can be used for this purpose. Unless modes that are well-separated and sufficient test data is available, this task can be surprisingly difficult. Special attention must be paid to axisymmetrical structures with double modes. An alternative is to use FRFs. After a one-to-one relation between analytical and experimental results is defined, the response residuals can be computed to check the correlation in terms of the objective function that will be minimized by the updating algorithm. Local correlation tools to analyze spatial distribution of differences and similarities may be helpful in parameter selection. Note that the same tools can be used for FE-FE and test-test correlation.

3.1.5. Parameter and Response Selection

The most important decisions to be made by the analyst are about the choice of updating parameters and target responses. To a large extend, these choices determine the updating method that will be used, the time required for the analysis, and the chances for successful convergence. The choice will be based on background information, correlation and sensitivity analysis results, and the purpose of the updated model. The software should facilitate selection of all possible physical element properties (material, geometry), lumped properties (e.g. mass) and damping (modal, viscous, structural), to be updated either a local or element set level. Relations between parameters can be defined if necessary to maintain physical conditions. The software manages the property cards and removes the hassle of manually creating new property cards as new element sets are created. This way there are no practical obstacles to experiment with every parameter selection because it is not yet realistic to automate this task. The largest possible choice of target responses should also be made selectable. All structural responses that can be measured should be selectable as updating targets as well as correlation targets for criteria like MAC or FRF correlation functions (see 2.3.4).

3.1.6. Sensitivity Analysis

Sensitivity coefficients quantify the variation of a response value (e.g. resonance frequency or mass) as a result of modifying a parameter value. Sensitivities are not only used by the updating algorithm to find the necessary parameter changes, they are also helpful to gain insight in the structure, determine important parameters, and thus refine selection of updating parameters. Methods to compute sensitivities should be available for every possible combination of responses and parameters. For explorative analysis using local parameters at every element of the model, the number of gradients that must be computed can become very large. An array of methods based on finite differences and differential approaches should be available. Fast approximate methods that produce colour-coded displays with sensitivity distribution are required to encourage analysts to use this type of investigations.

3.1.7. Parameter Estimation

An iterative model updating algorithm that minimizes the weighted distance between FE and test, has been successfully used by the author in a wide range of industrial projects during the past 20 years. This method, also referred to as Bayesian parameter estimator or weighted least squares, uses weighting matrices that are the inverse of the covariance matrices of the updating parameters and measured targets [10]. If no statistical information is available, estimates of scatter based on uncertainty analysis or judgement can be used instead. The algorithm has the advantage that it can be used for practically every type of residue and updating parameters. It can easily be complemented to provide the analyst with control on parameter modification constraints. With the proper parameter selection, the algorithm has proven to produce very satisfactory results in terms of speed and the capacity to obtain a balanced and smooth convergence. In order cases, lack of convergence could be related to the parameter selection or too heavy constraints on the parameters. This reliance on a suitable parameter selection currently prevents a complete automation of the updating process. The method can also be used in a probabilistic model updating process as was demonstrated in [11-12]. Probabilistic analysis also holds the potential to identify natural relations between parameters, between responses and between parameter and responses. More research and experience is required to check if this is indeed the route to automated parameter and target selection.

Some recent additions have further expanded the applicability of the method:

- Simultaneously updating the parameters that are common in variants of the FE model [13]. For example, solar panels for satellites can be tested during different stages of deployment and for each stage there is a FE model. This provides a richer set of test data to serve as references for updating element properties that are common in all configurations. Such properties can be, for example, the joint stiffness or material properties.
- Superelement-based model updating to support a bottom-up modeling and test methodology. In this approach the different components that constitute an assembly are first modeled, tested and updated separately. Updated components are 'frozen' by reduction to Craig-Bampton superelements. Repeated tests at different phases of the assembly that allow focusing on the modeling of joints. Component modes synthesis is used to obtain the responses of the assembly.

3.1.8. Structural Dynamics modification

If the updating software includes a modal solver for fast approximate re-analysis then this tool can be used to rapidly apply and analyze the effect of structural changes to the dynamic response of structures without the need for re-meshing and re-analysis in a full FEA solver [14]. In case no acceptable parameter updates can be found, it may be required to re-investigate the geometrical level of detail that was used in the modelling. For example, the effect of adding or removing lumped mass or a stiffener beam can be quickly evaluated.

3.1.9. Force Identification

A finite element model with validated mass, stiffness and damping modelling can be used for forced response simulation. Operational deflection shapes can also be measured and then correlated with the predicted shapes. In a similar way as updating of physical element properties, forces can be adjusted to improve the correlation of operational shapes. If forces are not known, then they can be obtained with a direct inverse solution [15].

3.2. Conclusions

Model updating is process and successful updating depends on decisions made during every contributing step. Based on experience, a number of guidelines can be formulated:

- Set realistic goals for the updated model. These goals are function of the purpose of the finite element model.
- Check if the FE model has all the necessary features. In current practice, the level of detail and mesh density are not considered as updating parameters.
- Develop a systematic approach for the selection of parameters and responses. Consecutive updates of different groups of parameters leads to better results than combining all parameters in a single analysis. This selection should be based on a hierarchy defined by the uncertainty, sensitivity level and the type of test data that is available. Ideally the following sequence should be used: updating of mass and mass distribution based on measurement of weight, center of gravity and the mass moments of inertia; (ii) updating of stiffness parameters using static displacements; (iii) updating of mass and stiffness parameters using modal residues; (iv) updating of damping using FRFs; (v) identification of forces using experimental operational deflection modes.

Due to the explorative nature of model updating, fast and near-optimal approximate solutions for sensitivities and parameter estimation are preferred in an initial phase. This improves responsiveness of the software and stimulates investigation in the behavior of a structure by evaluating alternative solutions.

4. APPLICATIONS

4.1. Local Parameter Updating and Model Refinement

The use of multiple targets to be matched by a simulation model i.e. resonant frequencies, mode shapes, frequency response, etc. may require local changes of stiffness and mass. With sensitivity analysis and model updating of local parameters it is possible to visualize the areas in a model that need changes. This can be interpreted as areas where the fidelity of the model needs to be reviewed. In practice this may require adding geometric detail, remesh, or increase mesh density.

4.2. Global Parameter Updating

Using relevant material data that applies to the model at hand is critical to improve the realism of simulation. Variations due to manufacturing or operating conditions may have significant influence on the predicted structural responses and cannot be neglected. Updating of global material properties has proven to be an efficient methodology to obtain material data in a non-destructive way. In a similar way, geometrical properties like beam cross section properties can be easily identified. In recent years, this method has been demonstrated for identification of [16-17]:

- Slender pultruded beams with complex cross-sectional geometries.
- Laminated composites plates and sandwich materials.
- Orthotropic material directions in rolled steel plates.
- Filament-wound cylinders and pressure vessels.
- Properties of coated metallic plates (thermal barriers).
- Local variations in the Young's modulus of cast iron parts.

Model updating enables fast identification using tests that reproduce real-life operating conditions. Using non-contact excitation (e.g. speaker) and measurement (e.g. laser), the test setup can be easily adapted to be used in temperature-controlled environments to obtain properties as function of temperature or other controlled conditions.

4.3. Geometrical Model Reduction

Modern assembled structures typically have complex geometries requiring millions of degrees of freedom. Even relatively simple structures may have bolted or welded connections between members that can be difficult to model without resorting to a high fidelity mesh. The computational burden involved in analyzing a model of such large order can be significant. In many cases the level of detail can be significantly reduced if equivalent properties are used for the remaining elements. These are values assigned to physical properties (for example element thickness or spring stiffness) so that they provide the same mass and stiffness as the corresponding detailed structure. FE model updating can be used as a method to modify the properties of elements in a coarse mesh to become equivalent properties. In this case, results obtained with the high fidelity mesh serve as reference data.

4.4. Structural Health Monitoring and Damage Identification

A finite element model, updated using the observed dynamic characteristics of a damaged structure, can be compared against a reference model of the undamaged structure. The parameter changes are then evaluated and interpreted for the purpose of structural health monitoring, damage detection or quality control.

5. CURRENT TRENDS, CHALLENGES AND OPPORTUNITIES

Model updating is a complex process that bridges finite element analysis and testing. Therefore, trends and future advances in model updating to a large extend are function of the progress made in these complementary disciplines. Continuous upgrades of computing resources will have a major impact on all aspects of engineering analysis. The digital revolution is also leading to a new generation of testing devices that hold the potential to the enable a whole range of new applications for model updating.

5.1. Trends in Finite Element Analysis

One of the most important challenges for finite element analysis is how to treat increasing complexity that is associated with sub-assemblies and assemblies. While simulation and testing at component level is now fairly standard, understanding of the physics of joints, or contacts in general, is often still lacking. While non-linear analysis was previously the exclusive domain of only a few industry sectors, the need to incorporate non-linear elements is now recognized on much wider scale. Finite element software specializing in non-linear analysis capabilities are quickly gaining market share. Increased complexity also arises from the use of advanced materials (e.g. ceramics, heat shields, coating layers, composites etc.) that introduce only approximately known elastic properties. These properties may no longer be uniform or isotropic. Finally the need to couple different analysis codes for multi-physics simulation or fluid-structure interaction has a significant impact on the required efforts in modelling and running the analysis.

With increasing complexity of structures, uncertainty and variability on the input data increase as well. Even the chaotic behaviour of some non-linear structures under realistic operating conditions should be recognized and taken into consideration. The manufacturing process and the environmental conditions are important sources of variability. Including these in the simulation is one of last frontiers in finite element analysis. The use of integrated test and analysis is being recognized as probably the only way to come up with the sophisticated models that can deal with these complexities.

The size of finite element models has been growing since its inception and follows the continuous upgrades of computing resources in terms of CPU performance, addressable memory, disk space and, more recently, network communication speeds. Recently UGS Inc. reported that a 200 million degrees of freedom models could be solved (linear static analysis) entirely in memory in less than 8 hours CPU time. There is a strong belief that more degrees-of-freedom automatically lead to a better model. This may be true for the geometrical discretization but does not necessary provide a solution for the complexities of joints, or the material uncertainty. Such large models are not efficient for daily use. It is recommended to generate models with the right level of detail in every phase of the product development process, or for the specific type of analysis at hand. A high accuracy is not required in early stages of the development, e.g. to enable design space exploration. However, when decisions are based on approximation models, it is desirable to know and control the level of accuracy attained by these models.

These ongoing evolutions in how finite element analysis is used in current and future practice, place a major responsibility with engineering managers. Controlling the cost to keep the time required for building a valid model or a series of models with varying level of detail (including meshing, verification and validation, refinement and updating) is a major challenge. This can not only realized by improvements in the software and workflows, but also requires a human resources management that facilitates continued education in methods and software training. Furthermore, the deployment of quality management systems, standards and best practices related to simulation in all industries is just a matter of time.

Finite element analysis has become an essential tool to support virtual product development and is increasingly being used in upfront design and decision-making. There is a tremendous potential for better engineered products thanks to massive computing resources, more realistic simulation models and the use of optimization tools. The CAE industry is predicted to grow with double-digit numbers every year during the next decades. As model updating is an important link in the chain of CAE tools, new developments and investments in fundamental and applied research that are driven by the needs of industry will benefit from significantly larger budgets than in the past.

5.2. Trends in Testing

New measurement technology has been introduced that have the potential to revolutionize the performance of model updating methods and change the way model updating is conducted. Scanning laser vibration measurement technology (Doppler) or other full field measurements like Electronic Speckle Pattern Interferometry (ESPI) or digital image correlation are now used in 2D and 3D measurements. Ideally there will no longer be an issue with non-measured degrees-of-freedom, although internal or invisible locations can still not be measured. In structural dynamics, it is expected that these new techniques can produce more modes at greater accuracy, at least in a shorter amount of time than with classic accelerometer-based setups. Furthermore, the range of reference data that can be measured in sufficient quantify and accuracy is extended to displacement and strain. Such test can play an important role in identification on non-linear material behaviour using mixed numerical-experimental methods. The possibility to speed up testing will allow repetitive testing in order to produce point clouds of test data that be exploited as reference data for statistical correlation and updating.

Other technologies that will prove useful are tools for reverse engineering like laser scanning and photogrammetry. They can be used to accelerate and automate verification of geometry to identify differences between ‘as-designed and modelled’ and ‘as-built’.

Better and faster simulation tools will enable virtual testing of structures. Virtual testing is the process of using a baseline finite element model to simulate the entire static or dynamic test. This way different alternatives can be examined at relatively low cost so that the real test can be considered as most appropriate and optimal for the purpose of correlation with simulation. Given the need to compress the time available for testing, such an approach can increase efficiency and productivity. Also, missing important reference data, which is too often the cause of failure in model updating, can be avoided.

As a result, it can be expected that CAE groups will increasingly steer and order tests for validating their models on an 'as needed' basis. This is a major change compared to the past when CAE and test were competing worlds. Finally, structural dynamics testing will see increased usage of output-only modal analysis. This technique to measure under operating conditions, with real boundary condition and without the necessity to measure forces, has matured in the past years. Because there is no need for controlled artificial excitation, output-only modal analysis has enabled modal-based validation and updating of finite element models for civil engineering. The potential to use model updating for damage identification and assessment of structural integrity has generated significant interest. This application will continue to drive research for methods and test devices in the coming years.

5.3. Trends in Computing

The recent upgrade of mainstream computers from using 32-bit processors to 64-bit processors removes a major bottleneck in addressable memory for engineering analysis. Previously such systems were available at high expense in terms of hardware, software and system management. While 32-bit systems are limited to 2 GB or 3 GB of practical addressable memory, 64-bit systems can address 2^{64} bytes or approximately 18 million TB. In practice, however, the addressable memory is limited by the amount of installed RAM and limitations imposed by the operating system. With the availability of relatively low-cost processors from Intel and AMD, the release of 64-bit versions of Windows (XP and Vista are both available in 64-bit versions) and Linux, and decreasing costs for RAM memory chips, model size will no longer be an issue. Other beneficial evolutions include faster networks (Gigabyte), unlimited low cost disk space, multi-processors systems and computing clusters.

With these new computing platforms, the size of finite element models can grow well beyond the now practical limits of 1-10 million degrees of freedom. If deemed necessary, high fidelity models of complete structures can be constructed and solved without the need for reduction or synthesis methods. However, computational times will probably still be significant for such models especially in view of multiple re-analysis for design space exploration, updating, optimization, or probabilistic analysis. The need for model simplification, reduction and synthesis (using superelements or hybrid models that include components identified from tests) will remain in order to maximize computational efficiency.

5.4. Trends in Model Updating

If the traditional definition of model updating was to modify parameters in the finite element model in order to reduce the difference with test, then the new mission statement should be that model updating is about reducing uncertainty in simulation while taking into account the variability on the input parameters and test data, so that simulation results can be presented with a measure of confidence. This is required to successfully make the move to digital prototyping, and thereby reduce the number of physical prototypes.

Even with high fidelity models that more closely or exactly represent the geometry of the structure, uncertainty remains in material properties, damping and the physics involved with various types of joints and contacts. It will be difficult to guarantee that the high fidelity model has captured all effects of interaction between components. In this 'top-down' approach, testing is used to validate the model and introduce global or local adjustment of physical properties where needed.

An alternative vision is to consider a model as being constructed from building blocks. Each block represents a relatively simple component that can be modelled and updated using dedicated tests. Once the validated models of the components are available, the work shifts to modelling and identification of the connections between components. This 'bottom-up' approach is suitable for assembled structures as it requires the availability of individual components for testing as well as partially assembled structures for dedicated tests that stress joints. Although this method satisfies the need for more test data in order to deal with many local updating parameters, the time required to perform such extensive testing may limit its practical use to occasional projects that are intended for generating knowledge and insight in structural behaviour. However, by testing each component and each joint individually, there is chance that unnecessary efforts are made to identify zones that will not be stressed in the assembly. The best approach will be determined by the purpose of the finite element model, the characteristics of the structure and the possibilities for testing at component level.

The introduction of variability on the input parameters has been demonstrated in several papers and strategies for statistical correlation and probabilistic model updating are available. Deterministic methods to update the means of randomized parameters can be complemented by a second step to identify or update the statistical properties that characterize their variability. However, given the implications of these probabilistic methods on the computational times, and the difficult to satisfy the need for experimental reference data for scatter, their introduction into commercial software is still in an early phase.

Model updating will play an important role in applications like structural health monitoring and material identification. These applications will benefit from advancements in testing (full field 2D and 3D measurement) and data processing (output-only modal analysis algorithms, photogrammetry, digital image correlation). Easier measurement of displacement, velocity, acceleration, strain, pressure or temperature will enable consolidation of model validation and updating for structural dynamics with other field of simulation e.g. thermal, acoustics.

The need to validate and update models for nonlinear analysis and with more realistic damping leads to a growing interest in non-modal methods. Local and frequency-dependent damping requires the use of direct solvers to compute structural response in the frequency domain. Simulation of complex and highly transient phenomena like drop tests or plastic deformation requires solution in time domain. Frameworks used for model updating will have to be extended with tools like design of experiments and response surfaces methods in order to support these advanced simulation types. These extended capabilities, enabled by massive computing capacity, will contribute to creating more accurate simulation models that can be used with confidence for decision-making, which is a prerequisite to realizing the full potential of CAE in the next decades.

6. CONCLUDING REMARKS

The past 30 years have seen a steadily increase of interest in model updating from researchers primarily active in other fields. The development of the technology has long time been nourished by the experimental modal analysis community. The needs of structural dynamics analysts for reference data in test-analysis correlation and subsequent model updating quickly became a major motivator for doing tests.

Today model updating has reached maturity for a whole range of industrial applications. Initial skepticism or overly high expectations has made room for a more realistic approach. A growing awareness for the need of quality assurance in CAE, the entrance of a new generation of engineers and removal of most practical obstacles related to computing and communication has put model updating on the short list of engineering managers seeking to remain competitive in a future that will heavily rely on simulation-based design.

Research is shifting to applications that incorporate model updating and to more advanced topics like multi-physics simulation and non-linear dynamics. This is in unison with the current trends in finite element analysis. The challenges for model updating that are ahead of us are certainly not less than the ones the previous generation of researchers had to face.

In the long term, model updating has the potential to become a separate science that is closely interacting with the fields of meshing, simulation, verification, validation and design optimization. There can be no simulation without a reality check. If the required accuracy is not met, then a model should be updated prior to using it for design optimization. Furthermore, model updating, and inverse methods in general, will enable mixed numerical-experimental techniques that can be embedded in a range of vertical applications that address the needs of various industries.

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