

**APPLICATION OF SENSITIVITY ANALYSIS AND FINITE ELEMENT
MODEL TUNING ON A CAR BODY**

EDDY DASCOTTE

DYNAMIC ENGINEERING
AMBACHTENLAAN 21
3030 HEVERLEE**ABSTRACT**

A general system for finite element model tuning (SYSTUNE) is applied on the real-life FE model of a car body. This system uses an iterative parameter modification procedure based on resonance frequency sensitivity computations. The entire solution procedure is demonstrated step-by-step including dynamic analysis, correlation analysis, sensitivity analysis and parameter estimation.

INTRODUCTION

SYSTUNE is a general system for tuning and correction of finite element models by integrating test (Experimental Modal Analysis) and numerical analysis (Finite Element Analysis) results. The theoretical backgrounds and some applications of the program were discussed in [1-3]. Hereafter the different steps that are involved when integrating test and analysis are demonstrated on a large, real-life finite element model of a car body. The analytical modal analysis of this model was done using the NASTRAN analysis code. All available data and results were then interfaced with SYSTUNE for further processing.

INTEGRATION OF TEST AND ANALYSIS

Analytical analysis methods like the Finite Element Analysis (FEA), allow to predict the dynamic behavior of a structure from an approximately, discretised representation of its geometry and physical properties. This method has gained enormous popularity since FEA codes are now available on the entire hardware platform, ranging from PC's to mainframe computers. Moreover, the method has found applications in almost all engineering disciplines.

However, idealizations and assumptions made during the modellisation process, together with possible uncertainties of physical parameter properties, accuracy problems or just blind faith of inexperienced engineers, can lead to serious misinterpretations of analysis results. Therefore validation of analytical analysis results with experimental data must be an integral part of the product development and optimization cycle.

In the field of structural dynamics, Experimental Modal Analysis (EMA) is a widely used and accepted solution to create a model from measurements taken on an actual structure. This technique yields reliable values for the resonance frequencies and indications on the mode shapes.

The confrontation of two separate modal data bases, i.e. the analytical and the experimental, should lead to an improved FE model in terms of corrected values for the physical parameter values that were used to describe the behavior of the structure (material properties, geometrical properties, boundary conditions, ...).

Finite element model tuning is a creative, decision-based process which requires access to various analysis and diagnosis tools (figure 1). This is best accomplished through an interactive environment that allows to obtain results quickly and efficiently. Utilities are offered in SYSTUNE for this purpose such as a powerful free-formatted command language, descriptive tables, color graphics, etc.

The integration of test and analysis results allows to develop some wider applications like design optimization and material identification: the generalization of the object function, by including not only modal data, permits to evaluate the effect of design modifications and to compute the optimal structural changes required to the initial prototype to meet the performance criteria.

On the other hand, if material properties are used as unknown parameters, the FEM tuning procedure will yield corrected values for initial estimates for these parameters. This may be particularly useful if complex composite materials are involved for which only some indicative factory data for the engineering constants is available. Moreover, these values generally depend on the manufacturing conditions and should therefore be tuned separately for each case.

The program also offers a solution to certain needs for structural monitoring and quality control. This is done by comparing the actual behavior of a structure against a reference model, either at given time intervals or on a series of manufactured parts. The discrepancies between the modal properties can then be interpreted in terms of structural efficiency.

APPLICATION ON A CAR BODY

A. OVERVIEW

Some of the analysis tools available in SYSTUNE will be demonstrated hereafter i.e. data management, dynamic analysis, correlation analysis and parameter tuning.

The car body geometry that is used in this example is initially modelled in NASTRAN by means of the following elements (figure 2):

- 316 CBAR elements (bar element);
- 310 CELAS2 elements (elastic spring elements);
- 192 CQUAD4 elements (membrane-bending element);
- 70 CTRIA3 elements (membrane-bending element);
- 130 RBE2 elements (rigid elements).

The modelling strategy is such that main parts of the car body (roof, front and rear windows, ...) are separately modelled and then interconnected by means of the CELAS2 and RBE2 elements. Hence, the values to be used for the elastic spring stiffnesses (CELAS2) are considered to be the most difficult to estimate. However, other parameters like the shell thicknesses and the beam cross-sectional properties also have to be examined. Since the structure is analyzed freely suspended, no boundary conditions have to be considered.

The actual dynamic behavior of the car body is compared against a reference behavior. In practice, this reference behavior is the experimentally obtained modal data (resonance frequencies, mode shapes).

The solution procedure consists of the following steps:

- STEP 1 : enter the actual FEM and modal data of the car body.
- STEP 2 : enter the reference modal data of the car body.
- STEP 3 : select the reference resonance frequencies as the system responses to which the actual model will be tuned.
- STEP 4 : examine the correlation between the actual data and the reference data.
- STEP 5 : select a number of parameters that will be used for sensitivity analysis and model tuning
- STEP 6 : compute and evaluate the sensitivities of the resonance frequencies for parameter changes.
- STEP 7 : run an iteration procedure to modify the parameters for which the resonance frequencies showed enough sensitivity such that the actual modal data matches the reference modal data.

B. DATA MANAGEMENT

The first step of the procedure is to collect all available data into an internal data base. Since the existing data is stored as NASTRAN output files, an interface program is used to translate these files into the SYSTUNE neutral format.

Other such direct interfaces are available (e.g. for ANSYS, SYSTUS, SMS/STAR, ENTEK/EMODAL) or interfaces are based on structural data formats like e.g. the Universal File or CAD*I formats. These latter formats are supported by a growing number of system developers.

The type of data required by SYSTUNE are the mesh description (node coordinates, element definition, physical properties), modal data (eigenfrequencies, mode shapes) and the element mass and stiffness matrices.

C. DYNAMIC ANALYSIS

If the FEM mesh description and the element matrices are available, the dynamic analysis module in SYSTUNE, based on the Lanczos algorithm, allows to compute the resonance frequencies and mode shapes of the FE model. If this modal data is already available, as in this example, this step can be skipped.

18 eigenmodes, including 6 rigid body modes, were computed externally. The modes of concern to the analyst are modes 10, 11, 12 and 13 (table 1). These are the bending and torsion modes between 27 Hz and 42 Hz. A typical torsion mode is shown in figure 3.

D. CORRELATION ANALYSIS

The correlation between two sets of modal data can be expressed in terms of the differences between the resonance frequencies and the modal displacements. In general, a set of FEM data will be correlated against a set of EMA data but FEM/FEM and EMA/EMA correlation is also possible.

Correlation can be based on visual comparison of mode shapes or on numerical values such as :

- the Modal Assurance Criterion (MAC) [4];
- the EigenVector Orthogonality (EVO);
- Correlation Coefficients (CC).

An important part of the procedure is the 'pairing' of experimental and analytical modes. This can be done manually or by using a criterion such as the MAC. Automatization of this pairing is especially important when the FE modes which correspond to EMA modes are not appearing in the same order. Then with each iteration, the pairing has to be verified since the mode shape sequence may have been changed.

MODE NO.	ORIGINAL MODEL FREQ. (Hz)	MODIFIED MODEL FREQ. (Hz)	DIFFERENCE (%)	MAC (%)
(6 rigid body modes)				
7	6.77	6.77	0.01	100.
8	11.32	11.32	0.02	100.
9	17.34	17.48	0.77	99.4
10	27.21	29.95	8.76	96.0
11	33.13	33.74	1.82	70.9
12	33.53	35.39	5.53	90.4
13	41.21	43.85	6.41	97.2
14	43.21	45.71	4.13	85.4
15	47.35	49.75	5.06	53.3
16	49.17	51.01	3.73	57.0
17	53.95	54.33	0.70	51.5
18	54.24	55.61	2.52	88.8

Table 1. Comparison between resonance frequencies.

For the car body, tables 1 was assembled showing the reference and actual resonance frequencies, differences and the MAC values between the corresponding mode shapes.

Figure 4 shows a 3D representation of the MAC matrix.

E. PARAMETER SELECTION

Since a FE model usually consists of numerous parameters, making an optimum selection of parameters is a most critical task. The program therefore allows to easily compare results from different parameter selections and provide tools to assist in the selection process. It is important only to use design parameters in order to maintain physical insight in the tuning process. Parameters that can be selected are element material properties (Young's elastic modulus, mass density, spring stiffness), element geometrical properties (beam cross-sectional properties, plate/shell thickness) and nodal properties (boundary conditions, lumped mass properties). Parameter value constraints, by specifying lower and upper bounds, can be applied as well as weighting factors [6].

F. SENSITIVITY ANALYSIS

Sensitivity analysis is the technique with which, by deriving structural response functions to physical FEM parameter values, the user can obtain a feeling of the type and location of the parameters that determine the dynamical behavior of the structure. These derivatives (or sensitivities) are stored in a sensitivity matrix which is used for further model tuning and optimization.

Analyzing this matrix yields information on the sensitive and insensitive zones of the structure. It has no use to select parameters for which the response function shows little sensitivity. Sensitivity analysis thus allows to optimize the parameter selection.

Figure 5 shows the sensitivity envelope for rotational spring stiffness changes (CELAS2). This envelope curve is obtained by adding all sensitivities for modes 7 to 18. It can be seen that parameters 1, 2, 9 and 10 can be eliminated from the parameter selection since none of the modes shows significant sensitivity.

Figure 6 shows the envelope curve that is obtained if the shell thicknesses are selected as parameters. Only a few elements have important influence on resonance frequencies. Since in this model all element thicknesses are uniform and well-known, this parameter type was not retained for further use.

G. MODEL TUNING

The parameter changes required to obtain correlation between reference and actual modal data are calculated using a Bayesian technique [5]. The resulting parameter changes are used to re-calculate mass and stiffness matrices yielding new resonance frequencies and eigenvectors which match the reference values more closely. An iteration process can then be continued until the convergence criterion is satisfied. It consists of the following steps:

1. Selection of parameters and responses;
2. Pairing of the analytical modes and experimental modes;
3. Computation of the sensitivity matrix;
4. Computation of updated parameter values;
5. Updating of the internal data base;
6. re-calculation of the modal response data;
7. Testing of the convergence criterion;
8. Return to 2. until the convergence criterion is satisfied

Figure 7 shows the rotational spring stiffness modifications that were required to obtain satisfactory correlation. Note that a number of stiffnesses were reduced to zero. From this it can be concluded that the rigid joints simulated by these springs have to be modelled as pin joints.

CONCLUSIONS

An integrated, general applicable system for analysis, correlation and merging of data and results from FEM and EMA was applied on the real-life model of a car body. Even applied on large, complex models, the program has proved to be flexible and easy-to-use while allowing for maximum controllability and interpretability. Moreover the program can be operated independently of external analysis codes and be interfaced to all formats..

ACKNOWLEDGEMENTS

The FE model of the car body courtesy by HAWTAL-WHITING STRUCTURES Ltd., United Kingdom.

REFERENCES

- [1] E. Dascotte, P. Vanhonacker, 'Development of an Automatic Mathematical Model Updating Program', Proc. 7th IMAC, Las Vegas, Nevada, February 1989.
- [2] E. Dascotte, P. Vanhonacker, 'Finite Element Model Tuning in Practice', Proc. 14th International Seminar on Modal Analysis, September 1989, Leuven, Belgium.
- [3] E. Dascotte, 'Practical Applications of Finite Element Model Tuning Using Experimental Modal Data', Proc. 8th IMAC, Orlando, Florida, February 1990.
- [4] R.J. Allemang, D.L. Brown, 'A Correlation Coefficient for Modal Vector Analysis', Proc. 1st. IMAC, Orlando, Florida, 1982.
- [5] J. Collins, G. Hart, T. Hasselman, B. Kennedy, 'Statistical Identification of Structures', AIAA journal, 12/2, February 1974, 185-190.
- [6] DYNAMIC ENGINEERING, SYSTUNE User's Manual.

FIGURES

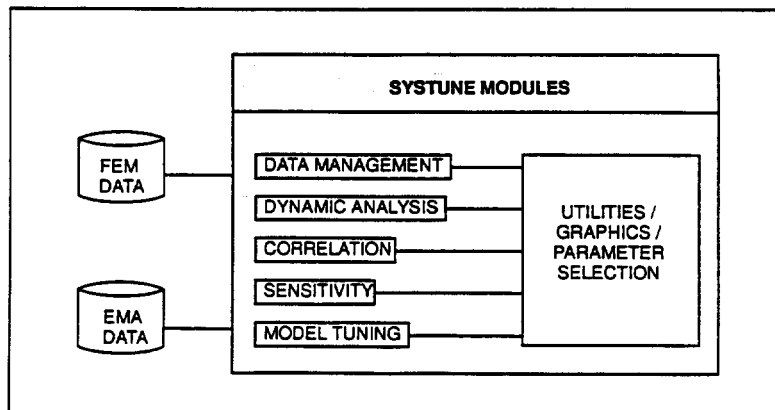


Figure 1 : SYSTUNE Modules.

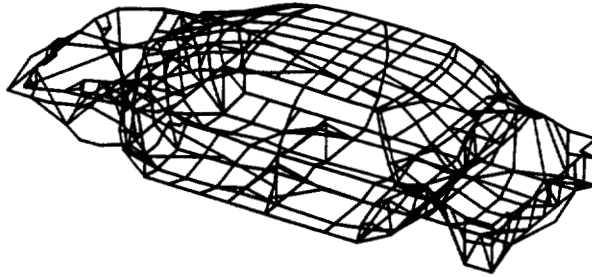


Figure 2 : Finite Element Model of the Car Body.

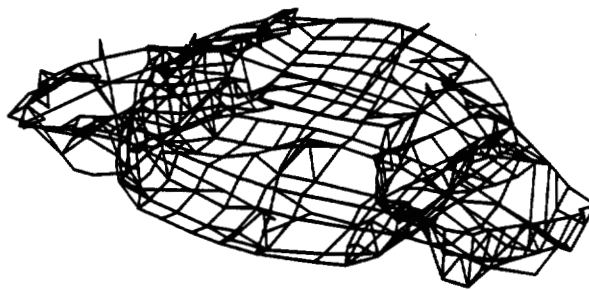


Figure 3 : Mode Shape 13 (Torsion).

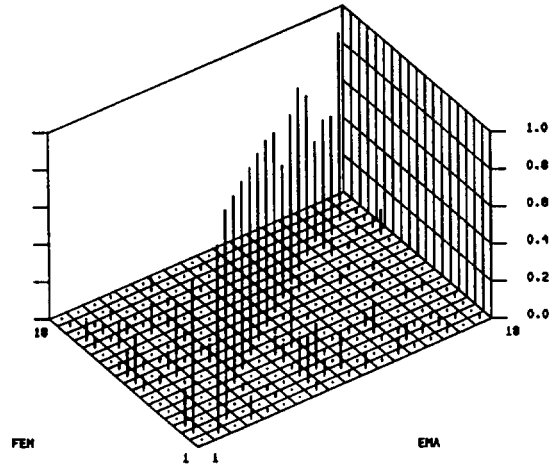


Figure 4 : 3D Visualization of the MAC Matrix.

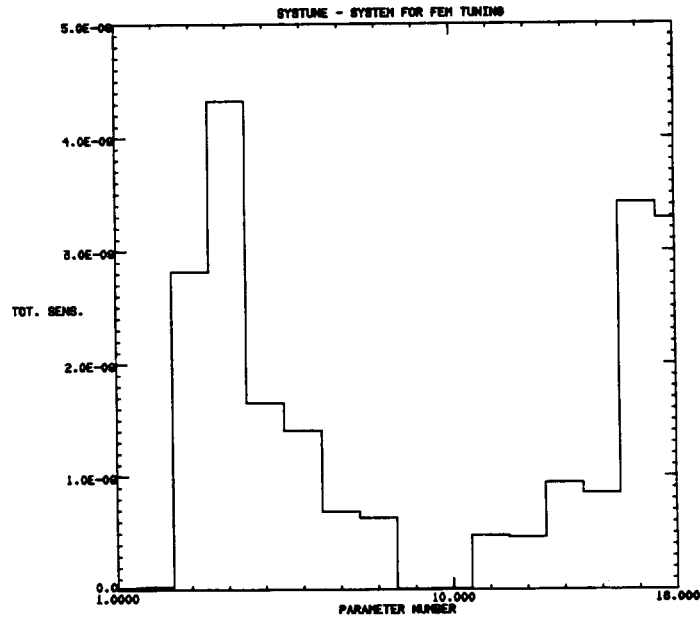


Figure 5 : Sensitivity Envelope Curve for Spring Stiffnesses.

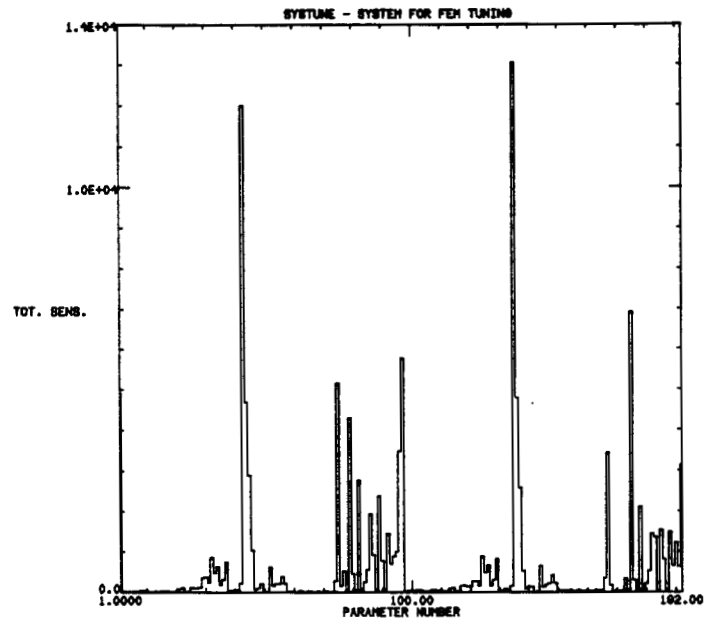


Figure 6 : Sensitivity Envelope Curve for Plate Thicknesses.

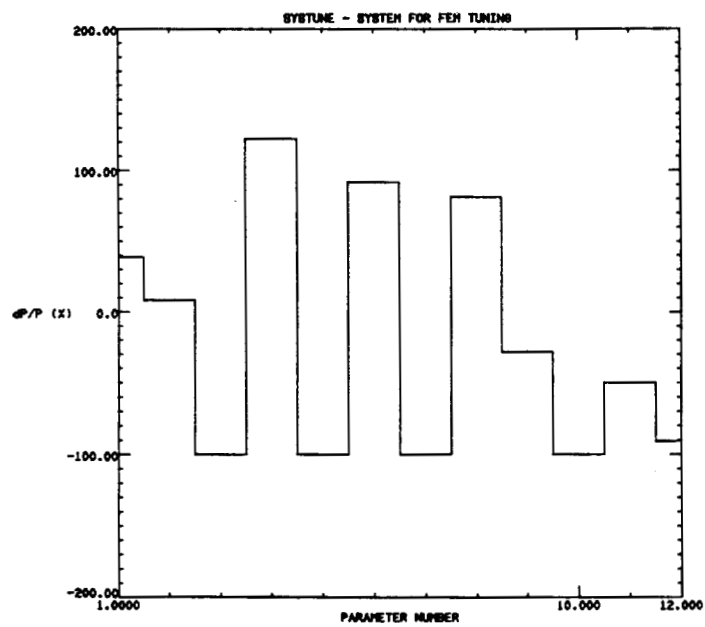


Figure 7 : Parameter Modifications.