

Model Updating using operational data

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Synopsis

Model Updating for validation and tuning of simulation in structural dynamics simulation is a long established method. Standard software "easy to use" is available on the market since more than 15 years (e.g. FEMtools [1]).

The classic approach consists in correlating modal analysis data, because the uncertainties are restricted to structural parameters independent of operational loads. The produced reference data (natural frequencies and mode shapes) is quite stable and of acceptable quality.

However it is often desirable to correlate and update models using operational data. This is the case, if it is not possible to perform a modal analysis or if the structural behaviour changes significantly under operational load. A such updated model would automatically guarantee the validity to operational conditions.

The paper shows the correlation of different types of ODS-data and discusses its suitability for model updating.

1 Introduction

Validation of finite element models by correlation with experimental data, specifically modal analysis data, has developed to an established method in structural dynamics. The classic approach tries to minimize the error of the eigenfrequencies by modification of physical parameters. The correlation between mode shape pairs is chosen as a side function to guarantee that only the eigenfrequencies of correlated shapes are used as response function.

The method is further developed to be applied in connection with measured operational data. In practical applications a number extensions to the classic approach were developed which are discussed hereafter.

2 Application of updating methods

2.1 Outline of the classic updating approach

In principal it is possible to correlate various structural computational results with test data (Fig. 1). Updating procedures developed at the basis of modal analysis. Experimental modal analysis is comparatively cheap and easy to apply. It delivers natural frequencies with a relatively with small scatter and mode shapes which reveal global informations of a structure. On the FEM-side linear modal analysis is independent of external forces. Thus the validity of the results, eigenfrequencies and eigenvectors depend only on uncertainties of structural properties.

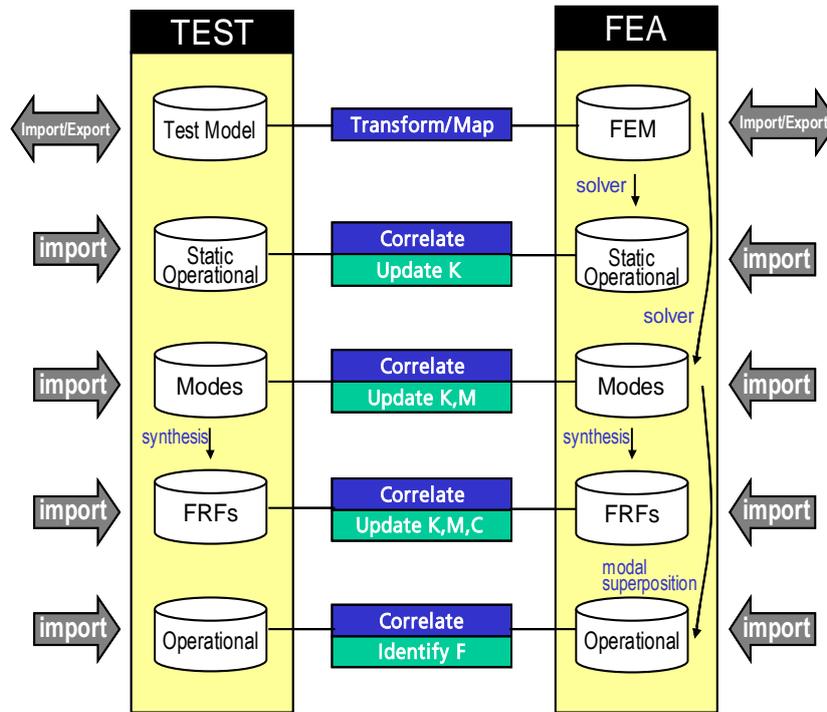


Fig. 1: Correlation of Test and FEM

Figure 2 shows the updating steps. The figure also relates specialized software for each validation step. The data transfer must be guaranteed by integrated interfaces. The heart of the procedure is the software FEMtools [1] which connects the “real world” with simulation. The software supplies the database, routines and surfaces of two different models. To provide consistent data the FEM-interfaces not only handle mesh-data but also binary data like results files and element matrices (Ansys: rst-file, emat-file, Nastran: op2-file).

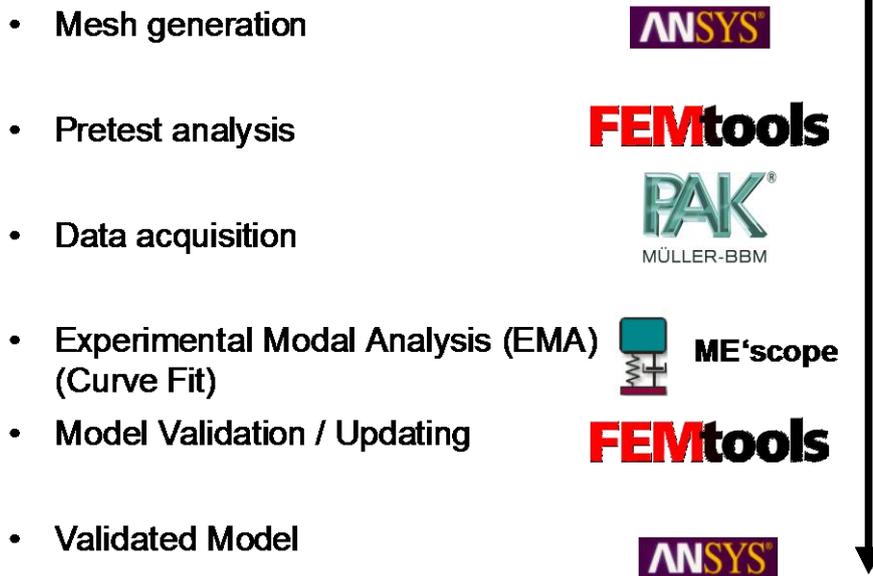


Fig. 2: Example of validation steps

The updating steps are

1. Pretest analysis

Ideally a finite element model already exists before testing which can then be used for a “virtual” test. Various functions support the selection of a reference point and the roving points to scan the mode shapes experimentally.

2. Testing, Data acquisition

Recording of the dynamic response to a defined excitation signal (hammer, electrodynamic shaker etc.). Evaluation of frequency response functions FRF.

3. Experimental Modal Analysis (EMA)

Determination of eigenfrequencies and mode shapes: by fitting the FRF curves the parameters of a modal model is estimated.

4. Correlation

- Geometric correlation: the testing points are paired with the nodes of the FE-model.
- Pairing of the test mode shapes with the FE-mode shapes according to the degree of correlation (MAC).
- Comparison of the eigenfrequencies: the deviation of the test eigenfrequencies to the computed eigenfrequencies indicate global imprecise assumptions.
- Global mode shape correlation: computation of the modal assurance criterion (MAC) quantifies the shape correlation.
- Local correlation: The amplitudes of the normalized mode shapes are correlated at single DOF. Alternatively FRF are correlated. Local parameter deviations are identified.

5. Updating (figure 3)

- Global response functions such as eigenfrequencies are chosen as residues.
- Uncertain parameters to be tuned are selected on a global level, in further steps they can also be tuned on a local level.
- Sensitivity analysis: the linearized relations of the response functions to the parameters are computed.
- Estimation of the updated parameters: numeric algorithms like least square and Bayesian estimation are commonly in use.
- Re-resolution of the system, correlation of the response functions, convergence check and repetition of the iteration steps.

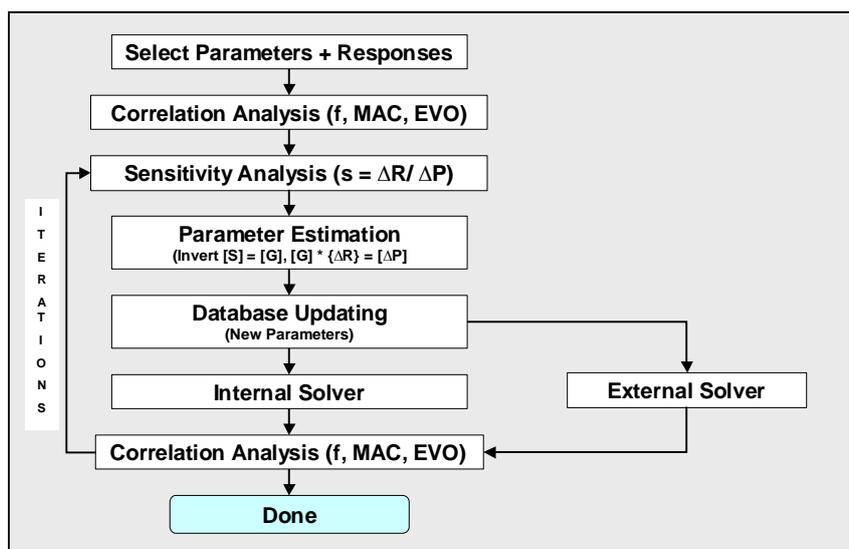


Fig. 3: Flow chart of the updating process

2.2 Updating with reference to Operational Modal Analysis (OMA)

Operational modal analysis has become popular within the recent years. Dealing with large structures where artificial loading is difficult to apply the method was developed mainly civil engineering. By averaging response spectra with random excitation (wind, traffic, background noise) mode shapes can easily identified at spectral peaks. Using advanced stochastic techniques or deconvolution the input signal is filtered from the output spectra. The resulting Pseudo-FRF spectra can be treated with classic curve-fit algorithms to identify the natural frequencies, mode shapes and even modal damping. In turn, the result may again be used as reference for model updating.

Figure 4 left shows the average APS-spectra measured on a bridge structure. The identified modes were used to calibrate the simulation model of the bridge for further design of vibration dampers (figure 4 right).

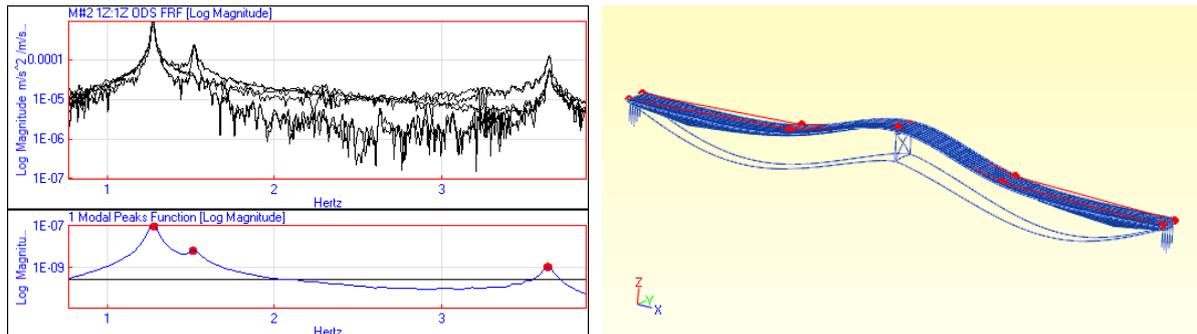


Fig. 4: OMA of a bridge: left: ODS-FRF background noise measurements and modal peaks-function. right: Correlation of OMA - mode shapes with the simulation model.

The method is by now widely used also in automotive applications [4]. For good results broad band signals are desired. Dealing with typical automotive problems the noise signal is “disurbed” by deterministic signals in the orders of the rotation speed. If these signals are dominating the overall spectra, the pseudo-FRF can also be gained by order tracking. The ODS-FRF show the appearance of regular FRF data with phase shifts at resonant peaks after deconvolution. In turn classic curve-fit algorithms are applicable.

2.3 Correlation of ODS and inverse updating of dynamic forces and pressures

If simulation models are validated to a sufficient degree also operational deflection shapes based on operational response spectra are correlated. The amplitude residue is used to update the load model.

The same gradient approach as used for classic model updating is applied. The estimated forces are defined in their position and their orientation on the structure.

Figure 10 shows the muffler of an exhaust system [3]. The operational deflection shape at a critical frequency has been recorded and correlated with the structural simulation model. In parallel a fluid model was generated and a first estimate of the pressure distribution has been computed and applied on the structural part as load. In a decoupled analysis the modal contribution of the fluid pressure was updated to fit the ODS-data of the solid structure.

The sketches in figure 5 depict the simulated deflection shape (top left), the superposition with the test data (bottom right) and the pressure distribution on the interior surface (middle) of the cavity. The matrix (bottom left) represents the DAC (“Displacement assurance criterion”) reflecting the degree of correlation of deflection shapes between test and simulation in analogy to the MAC.

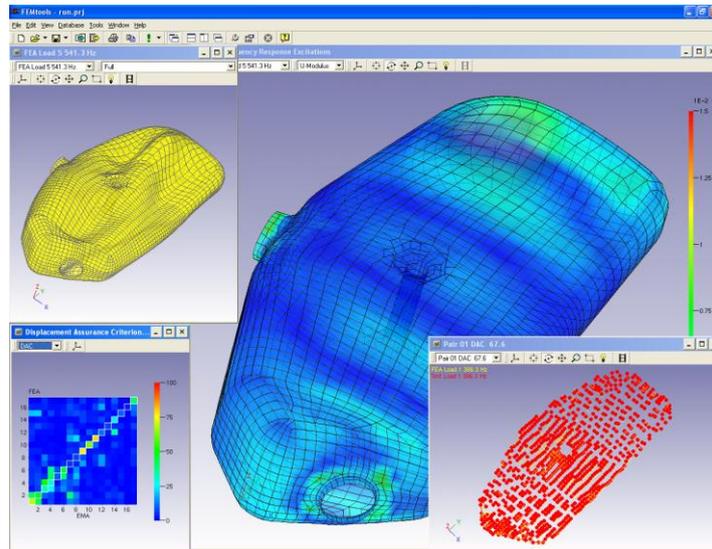


Fig. 5 Correlation of ODS and inverse updating of the dynamic pressure inside a muffler cavity .

3 Example

3.1 Setup

The different techniques shall be illustrated by an investigation of a test example. Fig. 6 shows a small electric motor on a mass mounted on springs. The springs are attached to a base plate.

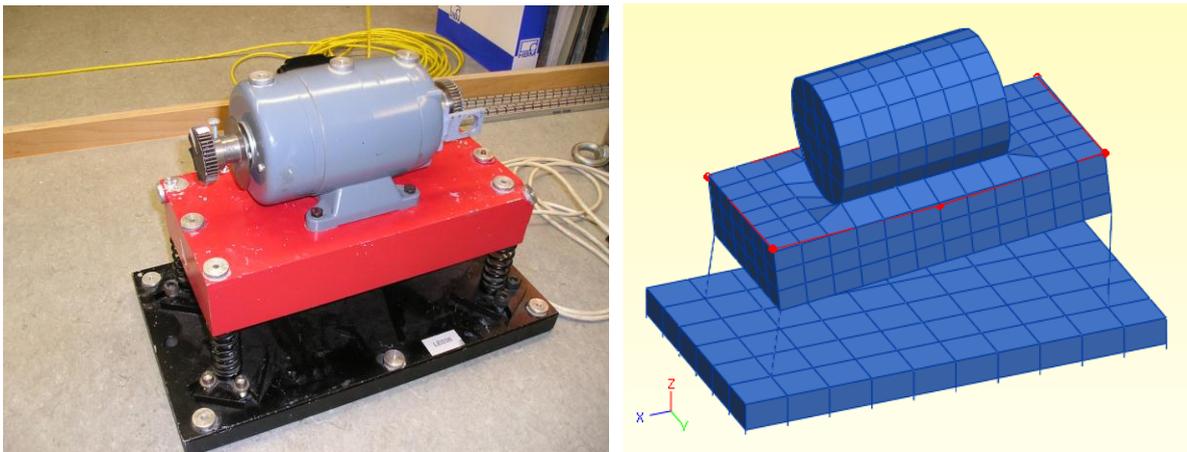


Fig. 6 left: mounted motor block, right: simplified simulation model (blue) superposed with test mesh (red), correlation of the 5th mode

On this system the following investigation steps were performed:

Experimental Modal Analysis

- Updating of stiffness parameters, reference: EMA
- Updating of damping parameters, reference: FRF

Operational Deflection Shape Analysis (ODS of 1st order track)

- Updating of structural parameters, reference: OMA
- Updating of forces, reference: ODS
- Updating of structural parameters, reference: ODS-FRF

3.2 Updating using EMA data

To identify the rigid body modes and the spring stiffnesses the mounted mass was excited by a roving hammer with one reference test point. The bottom plate was fixed.

If the initial boundary or connection stiffnesses between two components can only be roughly estimated, it is recommended to use DOE-methods first to create a response surface which can be correlated with measured data. In a second refined step gradient based updating is performed according to figure 3.

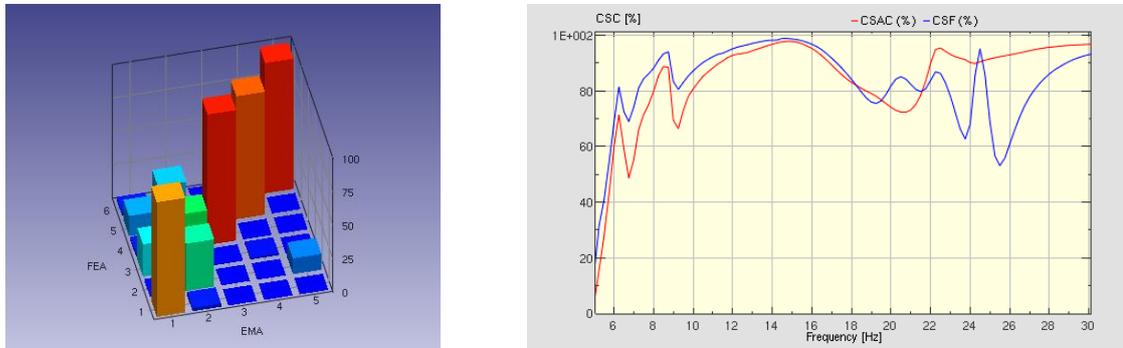


Fig. 7 Updating results: left: MAC-Matrix as mode shape correlation, right: Correlation of FRF, Cross Signature Assurance (red curve) and Cross Signature Scale Factor (blue curve)

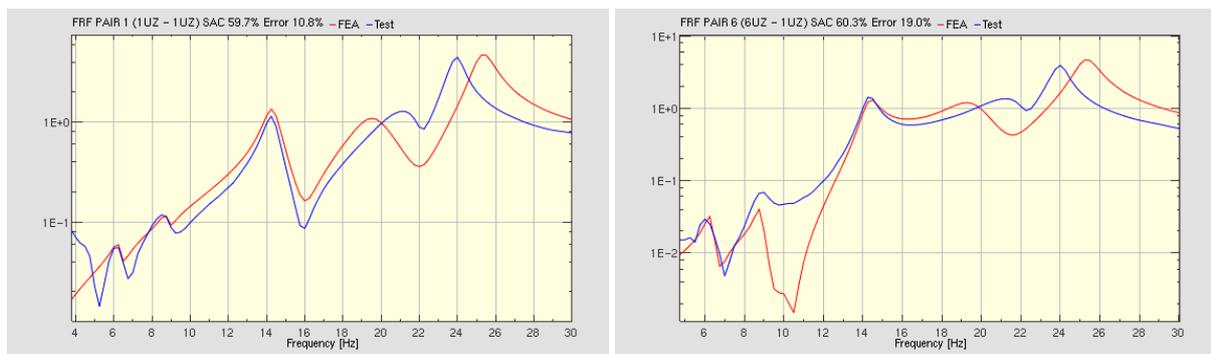


Fig. 8 bottom: Correlation of single FRF (blue: Test, red: Simulation)

The first three natural frequencies of the rigid body modes are well matched with an error $< 1\%$. Since only vertical reference excitation has been measured the axial horizontal mode is poorly correlated ($MAC < 40\%$). The upper two modes are well matched but with a frequency error of about 10% . This is mainly due to the more beam like behavior of the springs in the real structure. By consequence the FRF-correlation in the range above 18 Hz is decreased (CSAC, figure 7 right, figures 8). The Cross Signature Assurance Criterium CSAC is computed by averaging the normalized quadratic spectral product of paired test and simulation response [2]. It ranges between 0% to 100% of spectral correlation e.g. of FRF. This criterium expresses the shape correlation between measured and predicted response spectra. The Cross Signature Scale Factor CSF in addition reflects the amplitude correlation of the spectra.

3.3 Updating using OMA-data

For the output-only modal analysis existing data of a run-up of the motor was taken. The order spectra of the first order shown in figure 9 (left) revealed that the bottom plate was mounted on an elastic layer. By deconvolution and double-integrating modified ODS-FRF

were computed to extract the mode shapes, natural frequencies and modal damping (figure 9, right). The frequency and the shape data then served as reference to identify the stiffness properties of the elastic layer.

The coupled lower eigenmodes of the two masses up to 15 Hz were again well matched by updating with a frequency error < 1 %.

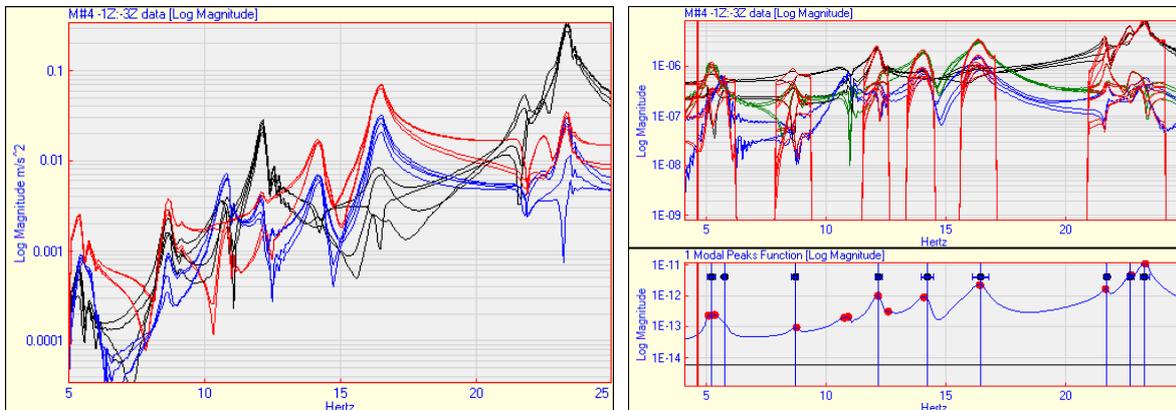


Fig. 8 left: ODS-FRF (order track of the 1st order of rotation), m/s² (black: vertical, red: lateral, blue: axial);
right: processed ODS-FRF, fit functions (red), modal peaks function

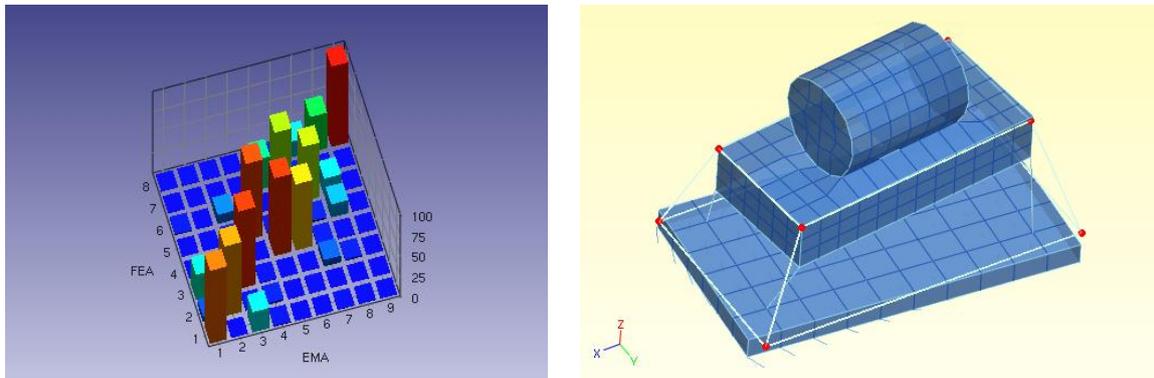


Fig. 9 left: MAC-matrix between mode shapes, OMA and simulation after updating;
right: correlation of the first torsional mode

3.4 Force Updating using ODS

To identify the unbalanced forces on the bearings of the motor, a DOF mask at the nodes at bearing 1 (DOF x, y, z) and bearing 2 (y, z) was defined. Taking the updated model the forces were determined to fit the simulation ODS with the test order tracks (note: If the test-FRF at the bearings would have been available, the dynamic forces could have preferably been determined by matrix inversion of the test data - a method which is typically used in Transfer Path Analysis (TPA)).

The resulting force spectra do not show a quadratic increase of the unbalanced mass forces with rotation speed as would be expected. They merely reflect the error in the modal data. A shift of natural frequencies produces a maximum with a neighbouring minimum of the force spectrum. Reliable data is only produced within frequency ranges where the natural frequencies are perfectly matched and the mode shapes are correlated to 99 %.

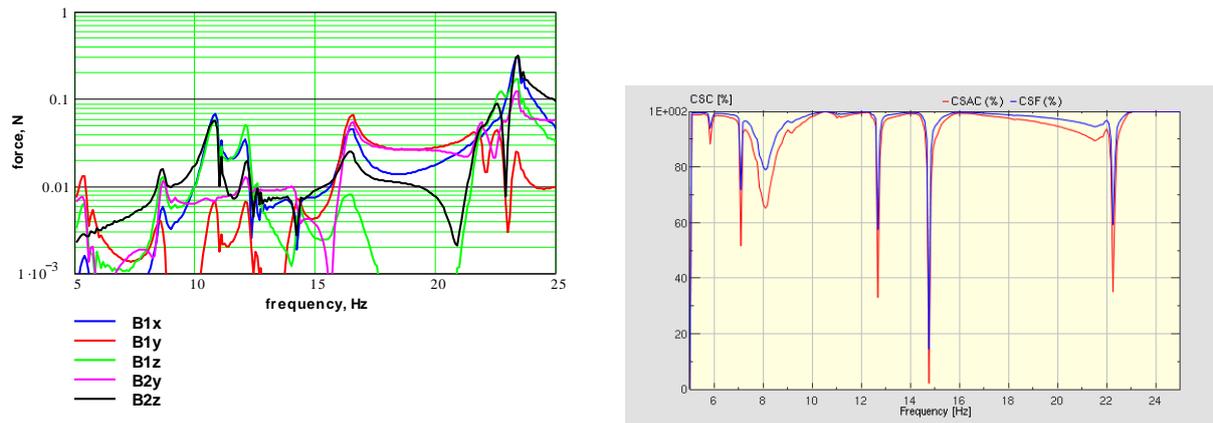


Fig. 10 left: spectra of dynamic forces, B1, B2 ... bearings;
right: Cross-correlation functions of the ODS-FRF of the mounted mass

Cross-checking the computed response spectra are correlated with the ODS-FRF of the order tracks.

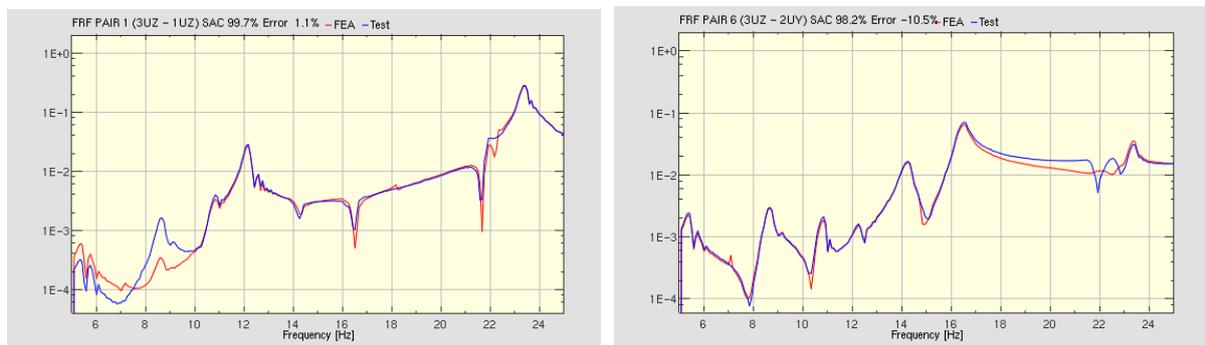


Fig. 11 Correlation of the ODS-FRF at the mounted mass

Figure 12 shows the displacement assurance criterium (DAC) in which the correlation between each ODS, test and simulation is quantified.

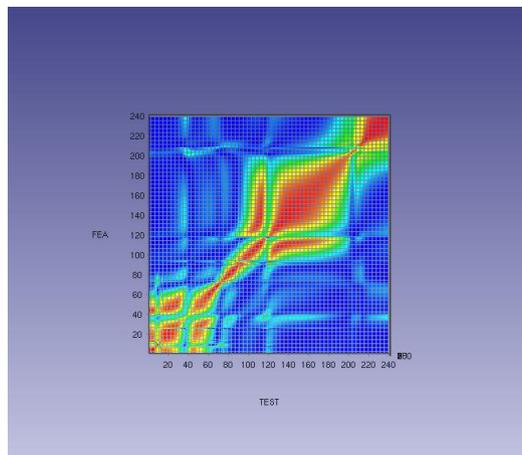


Fig. 12 Displacement Assurance Criterium: Correlation between test ODS and predicted operational shapes of the mounted mass.

3.5 Updating of structural parameters using ODS-data

In a last step a refined tuning of the stiffness parameters of the elastic layer was carried out by correlation of the ODS-data. Based on the given FRF-sensitivities $\partial H_{i,j}(f)/\partial P$ the partial

derivatives of the ODS-FRF $w(f)$ is straightforward assuming that the external forces do not depend on the parameter P .

$$\frac{\partial w_i(f)}{\partial P} = \frac{\partial H_{i,j}(f) F_j(f)}{\partial P} \quad (1)$$

Choosing the ODS-FRF as responses in two narrow frequency ranges about the resonance peaks at 5 Hz ... 6 Hz and at 11 Hz ... 13 Hz the sensitivity to global stiffness parameters of the elastic layer is computed. The sensitivity matrices are shown in figures 13 for the FRF (left) and the ODS-FRF (right).

The error in the ODS-FRF's is then minimized by the usual iteration involving Bayesian parameter estimation.

The result in this example only shows better correlation in the range between 11 Hz to 13 Hz governed by vertical displacement (figures 14). As FRF-based updating generally requires good initial correlation to be further improved, this is even more true for updating using ODS-FRF where a combination of uncertainties of excitation forces are multiplied with the sensitivities. Therefore it takes an even higher effort to choose the right responses. Here the question is what pair of ODS-FRF shall be selected in which frequency range.

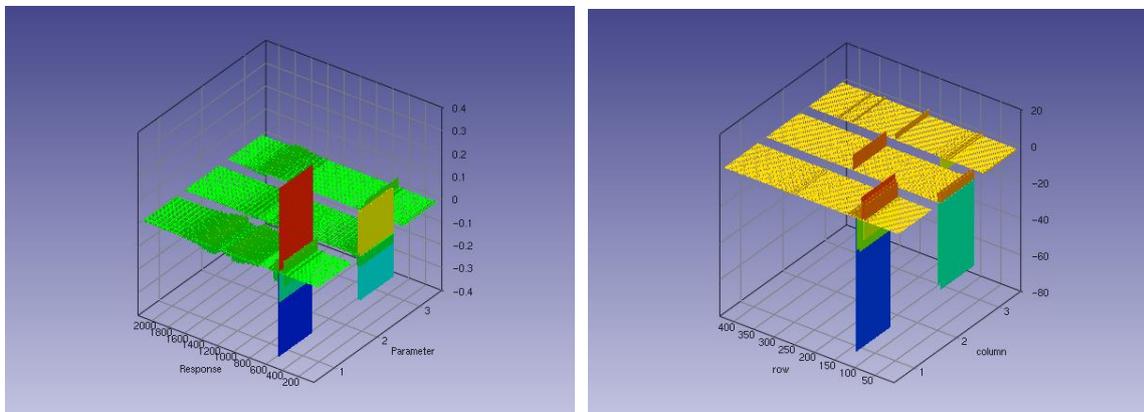


Fig. 13 left: sensitivity matrix of the FRF to the global stiffness parameters of the elastic layer right: corresponding sensitivity matrix of the ODS-FRF.

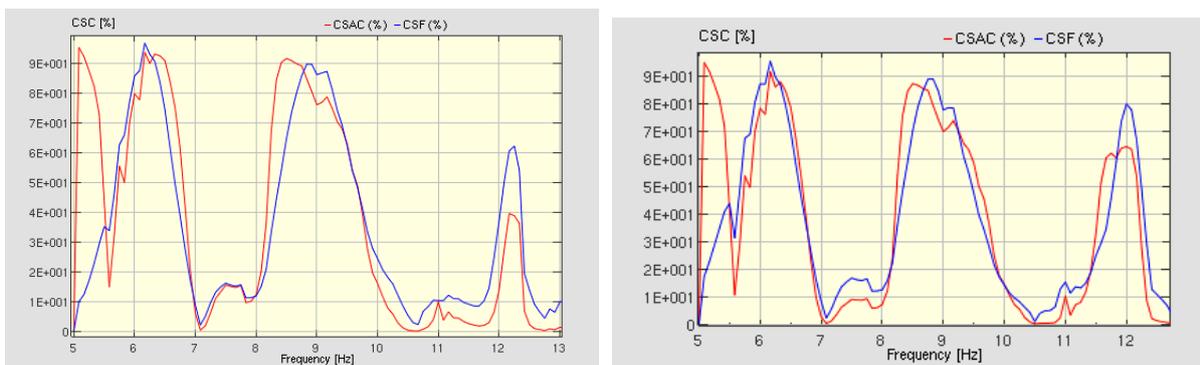


Fig. 14 cross correlation spectra before (left) and after (right) updating based on the response of the base plate.

4 Summary

Within the recent years experimental investigations for identification of dynamic structural behavior with the direct use of measured operational data has become more and more popular. The reasons are various, mainly to rely on data under operational conditions rather than laboratory conditions without realistic excitation.

It has been shown that the operational data can be exploited in various ways for model updating. However since operational forces are involved, which are generally not measured simultaneously, the degree of uncertainties of the reference database increases. In analogy to the classic strategy the residues shall be chosen in sequential steps reflecting the degree of uncertainty:

1. EMA: If possible, an experimental modal analysis provides basic data and understanding of a structure and thus should always be at the start of an updating process. Starting by correlating natural frequencies and mode shapes in a second substep FRF-based updating may be performed to further refine structural parameters and damping.

2. OMA: By output only modal analysis the uncertainties of the excitation forces can more or less be eliminated. It is therefore recommended to include this step. It also provides an advanced insight about the stability of natural frequencies and mode shapes under operational load.

3. ODS based force identification: The load model can be validated.

As was shown, reliable results are only found within frequency ranges with high correlation.

4. ODS based updating: Like FRF based updating this step can be chosen for final refinement of structural data to improve correlation. Since the sensitivities of ODS data to the excitation model is much higher than to structural parameters such as stiffness, it is obvious that the assumed load model must be absolutely reliable. Otherwise the errors in the load model are accumulated in the structural parameters.

To implement the necessary routines in the progress of model updating it is of great advantage to rely on a specialized CAE environment. The updating software FEMtools combines the required basic properties:

- Easy to use and user-friendly GUI for standard tasks,
- flexible access to the database and option to customize the fundamental algorithms,
- bidirectional data interfaces to test and simulation software (exchange of binary data).

5 References

- [1] Dynamic Design Solutions N.V. (DDS), FEMtools Version 3.3.0, 2008
- [2] E. Dascotte, J. Strobbe, "Updating Finite Element Models using FRF Correlation Functions", Proceedings of the 17th International Modal Analysis Conference (IMAC), February 1999, Kissimmee, Florida.
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- [4] Brincker, R., Anderson, P., Moller, N., "Output-Only modal testing of a car body subject to engine excitation", Proc. Of the 18th international modal analysis conference San Antonio, Texas fev. 7 – 10, 2000.