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NON-DESTRUCTIVE DETERMINATION OF SERVICEABILITY AND LOAD BEARING CAPACITY OF FLOOR SLABS USING DYNAMIC METHODS

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ABSTRACT

Due to dwindling resources and the aging of the building infrastructure, many future activities in civil engineering will focus on building conversions and refurbishments. The key prerequisite in this case is the verification of the serviceability and the load bearing capacity towards the certification authorities. In most of the practical cases the current loading status, the internal stresses and deformation under static loads are unknown. As a result, the immanent load reserves can't be exploited, which often leads to a very conservative approach or even to demolition. Refurbishing of existing slabs means dealing with many uncertainties. Material properties like densities or elasticity modules as well as geometries or boundary conditions are often unknown. For this reason there's a strong need to make efficient use of all information derived from measurements under static and dynamic test loads. In this context, in the field of modal analysis especially output-only methods utilizing only response measurements have proved particularly powerful. The big advantage is that the exciting forces need not to be measured. As a consequence high demands on signal analysis and the subsequent system identification are made.

This paper describes a procedure to automatically update a numerical model by means of a prior identification of modal parameters with the Frequency Domain Decomposition (FDD). The modal parameters are used to calibrate the numerical model, which uses a-priori information on the construction. The updated model is subsequently capable to describe the dynamic behavior of the slab within the considered frequency range. The different steps of the methodology are shown using the example of a wooden beam ceiling.

KEYWORDS : *serviceability, load bearing capacity, output-only modal analysis, Frequency Domain Decomposition, system identification, model updating.*

INTRODUCTION

Traditional Experimental Modal Analysis (EMA) uses measured excitations (inputs) and system responses (outputs) to identify modal parameters by means of Frequency Response Functions (FRF) or Impulse Response Functions (IRF). During the last decades multiple algorithms – from Single-Input/Single-Output (SISO) to Multi-Input/Multi-Output (MIMO) - in time and frequency domain have been developed. A good overview of the theoretical background and recommendations for experimental applications is given in [1]. In contrast to EMA the Operational Modal Analysis or Output-Only Modal Analysis (OMA) only uses the measured outputs under natural excitation for parameter identification. This approach has proven as a powerful tool, since it offers, as for example shown in [2], the possibility to investigate the real system under its natural boundary conditions without the need to apply (and measure) an artificial excitation. In return, great demands are made on the whole process of data evaluation [3]. Cunha et al. [4] give a summary of the historical

development of system identification in civil engineering. Here it becomes apparent that OMA more and more replaces EMA.

Widely-used - in terms of an ad hoc evaluation of measured data – is the Fast Fourier Transformation (FFT) of time histories of single sensors. In contrast to this, procedures capable of treating several sensors simultaneously are more powerful, especially when mode shapes have to be identified. To gain an energetic quantification of the identified modal frequencies, a transformation into frequency domain is profitable. In this paper, the identification of the modal parameters of a wooden beam ceiling with the Frequency Domain Decomposition is presented. A detailed description of the theoretical background of the method is given, for instance, in [5], an algorithm for an automated FDD is discussed in [6].

1 APPROACH AND THEORETICAL BACKGROUND

To end in a verification of the load bearing capacity and serviceability for a certain existing floor slab in the context of building conversions and refurbishments, several work steps have to be undertaken. Fig. 1 shows the whole process. Mainly step 1 is characterized by a variety of uncertainties. This paper focuses on step 4 and 6.

Work step	Instrument	Result
1. BASELINE STUDY	site inspection → planning documents	type of floor slab, material, dimensions, boundary conditions
2. MEASUREMENT PREPARATION	numerical model → experience	sensor positions, placement and type of excitation
3. MEASUREMENT	measuring chain →	system response
4. EVALUATION	system identification → SID-Tool (Matlab)	modal frequencies, mode shapes, (damping), boundary conditions
5. MODELING	FEM (Ansys) →	calculation model
6. MODEL UPDATING	FEM (Ansys) → Vali-Tool (Matlab)	updated calculation model, characteristic value for dynamic bending stiffness
7. TRANSFER dynamic → static	experiments → tables / literature	characteristic value for static bending stiffness
8. SUPPORT STRUCTURE PLANNING	static/dynamic → calculation	verification of load bearing capacity and serviceability

Figure 1: Overview of whole procedure in the context of building conversions and refurbishments

Frequency Domain Decomposition

Because of the complexity of the procedure, only the basics are summarized. A detailed description is given in [5]. Fig. 2 shows the different steps to be performed. The illustration is partly taken from [4], some additions of the authors are implemented. FDD belongs to OMA procedures. Starting with the measured time histories of the system responses, two ways are possible to obtain the Singular Values. The first possibility is the calculation of the power spectral density function by means of the Welch method [7]. The other is to go via the calculated correlation functions to gain the estimated power spectral density function by use of the Wiener-Khintchine-transformation. Formulas can be taken from [8].

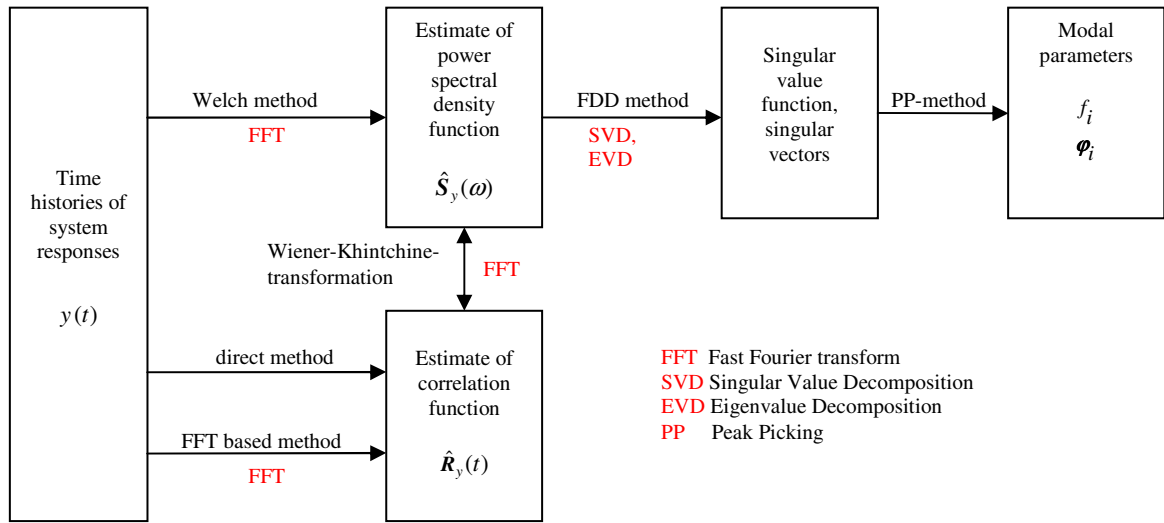


Figure 2: Sequence of work steps in Frequency Domain Decomposition

According to Brincker et al. [3] a very illustrative way is chosen to obtain Singular Values by writing the system response in modal co-ordinates:

$$y(t) = \varphi_1 \cdot q_1(t) + \varphi_2 \cdot q_2(t) + \dots + \varphi_i \cdot q_i(t) = \Phi \mathbf{q}(t) \quad (1)$$

with the mode shape matrix Φ and the column vector $\mathbf{q}(t)$ containing the modal coordinates. Now the covariance matrix of the responses can be calculated as

$$\begin{aligned} C_{yy}(\tau) &= E\{\Phi \mathbf{q}(t + \tau) \mathbf{q}(t)^T \Phi^T\} \\ &= \Phi C_{qq}(\tau) \Phi^T \end{aligned} \quad (2)$$

where $E\{\}$ is the expectation operator.

Assuming the modal co-ordinates to be uncorrelated and the mode shapes to be orthogonal, the response power spectral matrix from the Fourier transform is

$$S_{yy}(\omega) = \Phi S_{qq}(\omega) \Phi^T \quad (3)$$

where the power spectral density matrix $S_{qq}(\omega)$ is of diagonal form. Eq. (3) is at the same time a singular value decomposition of the response spectral matrix.

2 IDENTIFICATION OF MODAL PARAMETERS FOR A WOODEN BEAM CEILING

The investigated floor slab is located in an apartment building in Hannover originating from the Wilhelminian period. It's constructed as an inserted floor. Fig. 3 shows the cross section, Fig. 4 the ground plan and the measuring setup.

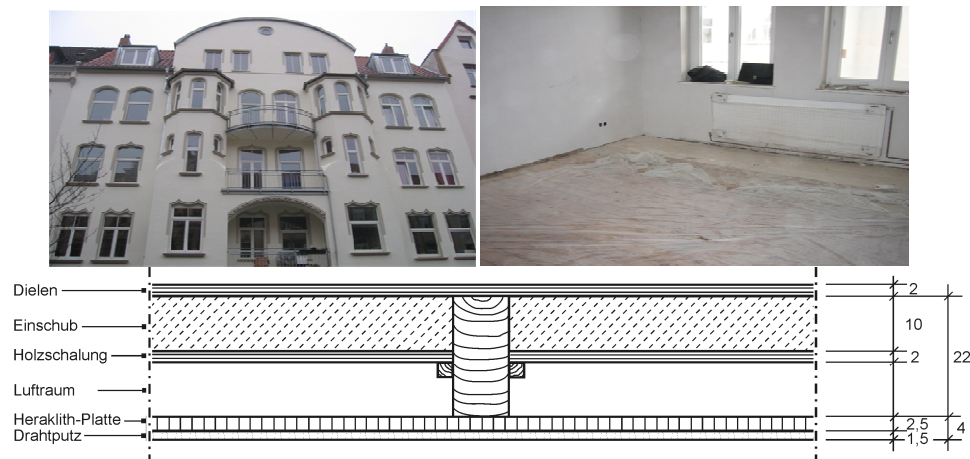


Figure 3 (top, left): Apartment building in Hannover; (top, right): Wooden beam test ceiling; (bottom): Cross section of ceiling [9]

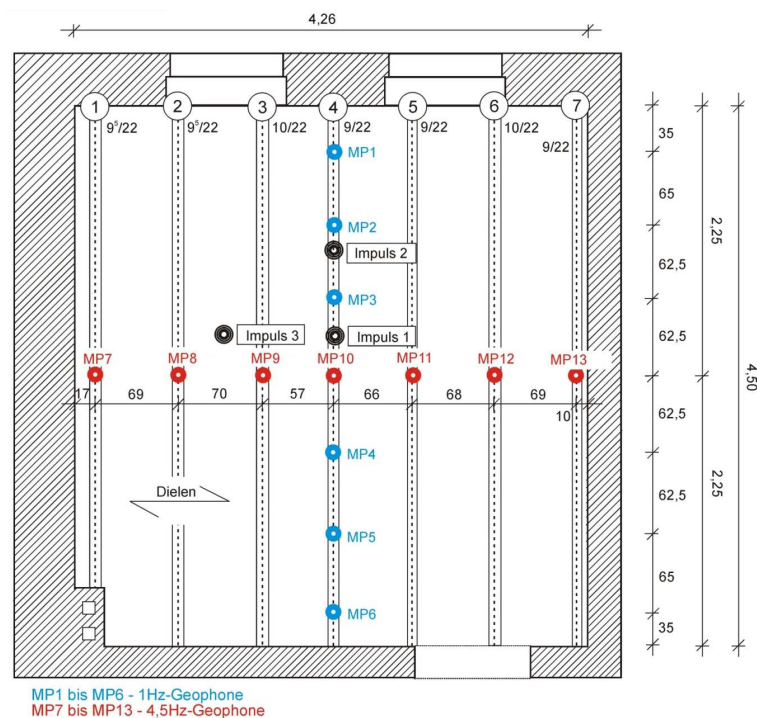


Figure 4: Ground plan, measuring setup and positions for impulsive load application [9]

For the experiments 13 velocity sensors were used, six of them as 1Hz-geophones (MP1 to MP6, blue marker in Fig. 4), the others (MP7 to MP13, red marker in Fig. 4) as 4,5Hz-geophones. As excitation, impulsive loads applied with a 25-kg sandbag were chosen. To activate both symmetric and anti-symmetric mode shapes the excitation points were positioned as shown in Fig. 4 (black markers). To ensure reproducibility three impulses were applied per excitation point. The sampling frequency was 500 Hz.

Fig. 5 shows the Singular Value function with the first modal frequencies obtained from system identification with FDD. Maximum energy is found in the first global bending frequency. The related mode shape is shown in Fig. 6. The course of the mode shape close to the supports gives information about the boundary conditions of the ceiling. The result in MP6 indicates a partial rigid restraint, whereas the result at the opposite edge of the ceiling in MP1 rather points to a simply supported edge. This information, which can only be obtained from measurements, is essential for updating numerical models as mentioned in section 3. Two important aspects should be pointed out in connection with the excitation. The positions of the excitation points have to be planned carefully, keeping in mind that an ideal loading in terms of system identification in OMA

1. occurs under natural conditions (ambient or operational) and
2. should have a multiple-input character, particularly with regard to cases where closely spaced modes have to be identified.

In our example it is easy to see that both requirements are not met. The impulsive loading with a sand bag does not reflect operational conditions and the excitation is limited to three locations concentrated in the middle of the ceiling. Consequently, the identification of higher or closely spaced modes would not be possible. Thus, from the Singular Value function in Fig. 5 it can be seen that only the first three modal frequencies can be reliably detected, because for frequencies above 17,5 Hz the energy content is too small. Nevertheless - due to the fact that human induced vibrations are our main interest here – the described approach, which concentrates on the very low frequency range, appears to be feasible. The same applies for the impulsive load induced by a falling sandbag: In contrast to a stationary excitement it's much easier to operate. Nevertheless, its scope of application is restricted corresponding to the limited energy input.

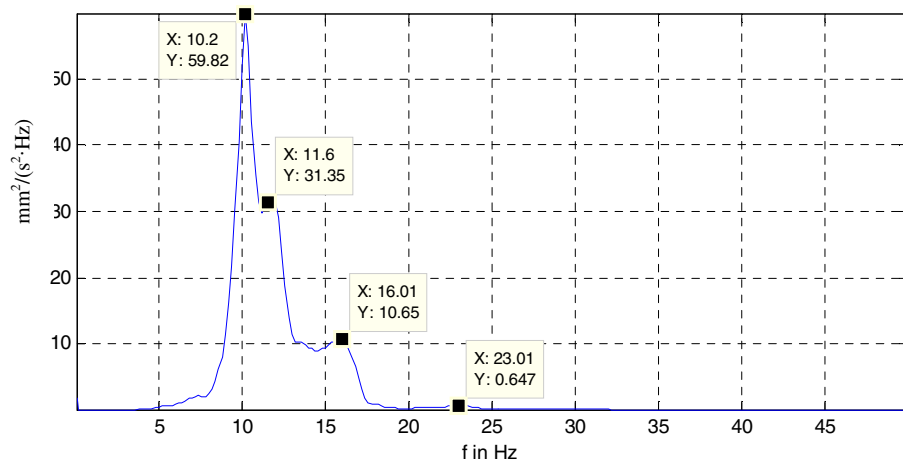


Figure 5: Singular Value function for a typical impulse [9]

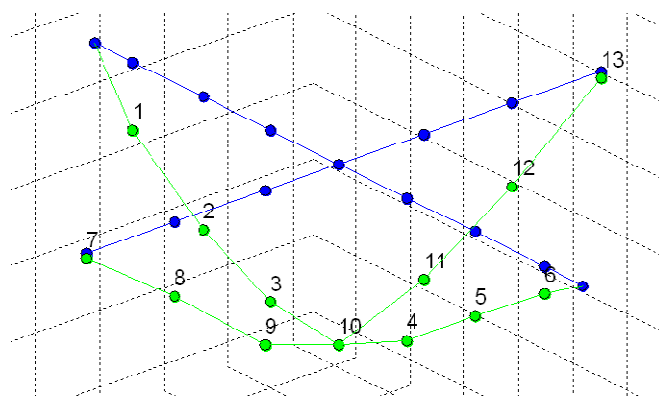


Figure 6: Identified first mode shape [9]

3 NUMERICAL MODELING AND AUTOMATED MODEL UPDATING

To verify load bearing capacity and serviceability for the relevant static and dynamic load cases towards the authorities, numerical models of the construction are needed. The process of modeling in the field of building conversions and refurbishments is characterized by a lack of important information concerning materials, stiffnesses, boundary conditions etc. Another important requirement in practice is efficiency. Since time is the most important cost driver, numerical models have to be as detailed as necessary and as simple as possible. To overcome these difficulties a modeling procedure is suggested, mainly based on the prior identification of mode shapes and modal frequencies. For our wooden beam ceiling a parametric numerical model was synthesized in ANSYS under the following assumptions :

- wooden beams : Bernoulli beam elements,
- wooden floor : standard shell elements,
- disregard of the different positions of centers of gravity for beams and floor,
- additional masses are considered by an increase of the beam's density in terms of a compensational density, starting value: $\rho_{\text{ers}} = 4790 \text{ kg/m}^3$,
- modulus of elasticity (beam), starting values: $E_{\text{II}} = 10000 \text{ MN/m}^2$, $E_{\perp} = 300 \text{ MN/m}^2$
- Poisson's ratio for wood: $\nu = 0,2$,
- boundary conditions: simply supported in vertical direction at both ends of each beam, no vertical support on the two edges parallel to the beams. The wooden floor is supported in horizontal direction.

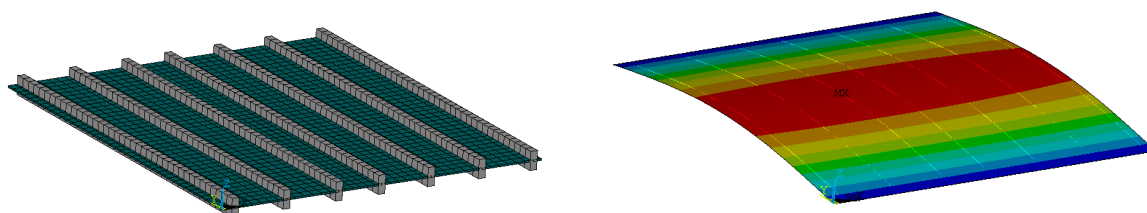


Figure 7 (left): Finite Element Model; (right): First mode shape of the initial model [9]

A modal analysis of the initial model delivers a first modal bending frequency of 2,80 Hz (the related mode shape is shown in Fig. 7), which differs significantly from the identified one (10,1 Hz – see Table 1). This impressively shows how ad-hoc modeling typically fails to represent the real dynamic behavior of a structure. The process of the subsequent model updating is based on the work of Haake [10]. It uses selected parameters to adapt the modal frequencies of the initial model to the identified ones gained from measurements as described above. The automated procedure is based on Newton's iterative method for finding zeros. Fig. 8 shows exemplary the process of model updating for the wooden beam ceiling. For calibrating the numerical model to the lowest two identified eigenfrequencies, two sensitive - and at the same time unknown - parameters are chosen – the elastic modulus and the compensational density. After a few iteration steps, the error criterion is reached. To end in a good accordance not only with the identified modal frequencies but also with the first mode shapes the boundary conditions have to be updated, too. This was done manually by implementing linear elastic spring elements with rotatory stiffness at the model edges. Finally, as shown in Table 1, the modal frequencies No. 1 and 2 of the updated model are in very good agreement with the identified ones. The first mode shape of the updated model is shown in Fig. 9. For frequency No. 3 the relative error is acceptable. Higher modal frequencies can hardly be updated due to the uncertainties for frequencies above 17,5 Hz due to the low energy content (see Fig. 5).

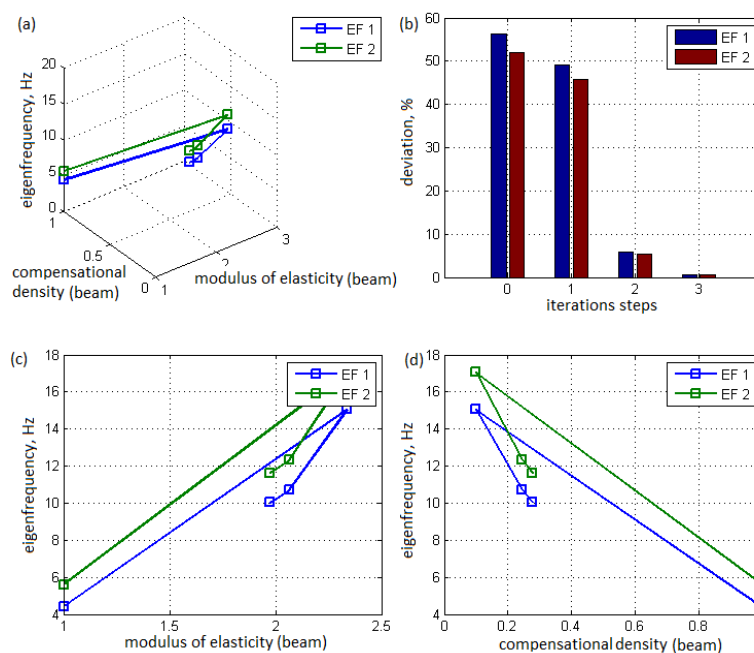


Figure 8: Model updating with two validation parameters for a wooden beam ceiling, (a) Process of model updating, (b) Deviation of identified eigenfrequencies, (c) Dependency on elastic modulus, (d) Dependency on compensational density [9]

Table 1: Comparison of modal frequencies from numerical model and from system identification [9]

	Modal frequencies in Hz				
	f_1	f_2	f_3	f_4	f_5
Identified with FDD	10,1	11,7	16,1	22,8	25,0
Initial numerical model	2,80	3,04	3,72	5,27	7,71
Relative error in %	72,3	74,0	76,9	76,9	69,2
Updated numerical model	10,04	11,63	15,18	20,71	29,01
Relative error in %	0,6	0,6	5,7	9,2	16,0

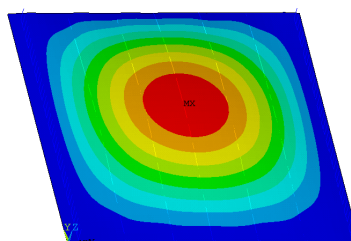


Figure 9: First mode shape of the updated model [9]

4 CONCLUSIONS

A procedure is described to automatically update a numerical model by means of a prior identification of modal parameters with the FDD. The modal parameters are used to calibrate the numerical model, which uses a-priori information on the construction. The numerical model, in such a way validated, is suitable to model the dynamic load bearing behaviour of the ceiling in the low frequency range. As a result, validated numerical models can be used for the proof of serviceability and bearing capacity under static and dynamic loads within the framework of building

conversions. The objective of the ongoing research at ISD is to extend the automated procedure to the updating of mode shapes gained from numerical simulations by using the information of realistic boundary conditions from the identified mode shapes. Additionally, in case of material nonlinearities like cracks, the difference between the bearing capacity under static and dynamic loads has to be considered in detail and needs to be implemented into the model validation process.

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