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EXPERIMENTAL MODAL ANALYSIS BASED ON NON-CONTACT MEASUREMENTS WITH A COMMERCIAL MICROPHONE ARRAY

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Experimental modal analysis (EMA) is a tool for measuring the dynamic properties of structures under vibration excitation. In order to improve the understanding of the structural dynamic behavior of complex structures, modal parameters, such as eigenfrequencies, damping ratios, and mode shapes are of high importance. Furthermore, based on the mode shapes, the structural integrity of a component can be assessed and monitored. Usually, EMA results are also used in research and development for the validation and optimization of numerical models (Model Updating). The advantage of a non-contact measurement of the vibration patterns is that there is no damage or contamination of the material surface. In addition, the modal quantities are not contaminated by the additional weight of vibration transducers, so that the dynamic response of the system is not influenced by the measurement itself. In contrast to other non-contact methods (e.g. laser vibrometers), the use of a suitable microphone array allows the simultaneous detection of the entire surface vibration covered by the array. Time-consuming, selective measurements of individual measuring points and the merging to point clouds are therefore no longer necessary. The modal analysis method is demonstrated in experiments on application-oriented, large-area structures. The parameter of interest, the mode shapes, are determined by measuring the pressure fluctuations in the near field of the structure. A commercial 120-channel microphone array with an integrated optical camera (Fibonacci120 AC Pro by gfai tech GmbH) is used for this purpose. The integrated optical camera allows to assign the measured system response to the corresponding surface section. The entire surface of the examined structures is covered by the planar microphone array, which has a diameter of 1 m. Measurements with a laser vibrometer are used to validate the data obtained from the microphone measurements. The modal assurance criterion (MAC) is used to compare the mode shapes determined by both methods.

Keywords: ACOUSTIC CAMERA, SONAH, MODAL ANALYSIS

1. Introduction

Strong structural vibrations not only cause disturbing noise, but can also lead to structural wear at high amplitudes or long operation durations. Modal models can be used to identify structures that vibrate strongly or are tending to load fractures. After a structural excitation by a defined force (e.g. by means of an impulse hammer or a shaker), the structural response can be recorded by measuring, for example, the surface vibrations.

By referencing the system response with the introduced force, the structure-dependent modal parameters such as mode shapes, eigenfrequencies, damping ratios can be determined. With the information obtained, it is possible to analyse the structural dynamic behaviour of even complex structures. Furthermore, the modal parameters will also be used, for example, in design processes, for predicting vibration behaviour at certain operating points or for identifying structure-critical geometries. Usually the structural vibrations are captured by acceleration probes or by using laser Doppler vibrometry (LDV). However, the measuring effort for the scanning of a large number of individually defined surface points is very high. In addition, the vibration system can be detuned by attaching additional sensors. Recent studies show that non-contact measurement or excitation methods can be used, especially for the analysis of very light or sensitive structures [1].

Therefore, this paper concentrates on the possibility of determining the eigenmodes by sound pressure measurements with a microphone array. In current studies, such as [2], qualitative investigations of the determined modes have already been carried out, whereby the used algorithms usually provide unsatisfying results. In this paper the measured pressure fluctuations are assigned to the surface vibrations using the near-field holography method SONAH („Statistically Optimal Near-field Acoustical Holography“) [3]. Furthermore, the analyses of the data collected by a commercial microphone array (Fibonacci120 AC Pro from gfai tech GmbH) are carried out with the software „NoiseImage“. In order to evaluate the quality of the eigenmodes determined, they are compared with those from LDV measurements and the theoretical vibration modes from a finite element analysis (FEA) using the modal assurance criterion (MAC) [4]. The latter is a statistical indicator for the comparability of two mode shapes.

2. Theoretical Background

The determination of modal parameters based on experimental data is called experimental modal analysis (EMA). These parameters are usually obtained by curve-fitting algorithms. In contrast to EMA, which is based on experimental data, FEA uses analytical equations of motion for a structure using finite element modeling (FEM). Thereby the modal parameters are solutions of the resulting system of equations. The FEM results discussed in the following were created with helf of the software called WaveImage. The MAC is often used to compare analytical mode shapes with experimentally determined mode shapes.

2.1 Experimental Modal Analysis

For this paper the EMA module of gfai tech´s software WaveImage is used. The evaluations are based on the frequency response function, which is determined from the measured force excitation and the measured system response. The modal parameters are determined from the frequency response function using the Polyreference Least Squares Complex Frequency (POLY-LSCF) algorithm [5]. The POLY-LSCF algorithm uses (weighted) least square approaches of multiple-input-multiple-output frequency response functions. The stability diagrams determined during the analysis allow an easy analysis even of complex systems with highly damped modes and/or large modal overlap. Further information on mathematical implementation and validation using experimental and numerical models can be found in the work of Peeter et. all [6] and Phillips et. all [5].

2.2 Modal Assurance Criterion

The MAC is defined as the normalized scalar product of two modal vectors v_i, v_j [4]

$$\mathrm{MAC}_{ij} = \frac{\left|v_i^H v_j\right|^2}{\left(v_i^H v_i\right)\left(v_j^H v_j\right)}\ , \tag{1}$$

where $(\cdot)^H$ is the complex conjugate transpose (Hermitian) of a matrix.

The MAC is a statistical indicator that can be used as a measure of the quantitative comparability of two modal forms. A MAC value of 0 indicates that the modes are not consistent and a value of 1 represents a fully consistent mode shape [4]. Therefore, the MAC matrix (cross correlation of all modes in a given range) obtained by EMA and/or FEA consists of zeros, except in the diagonal where the values are close to 1. Under certain conditions, such as a stationary, linear system state, the MAC can also be taken as a criterion for the orthogonality of the compared modes. However, the MAC values must be interpreted according to the measurement situation: On the one hand an insufficient local resolution of two orthogonal mode shapes can lead to high MAC values, while on the other hand lower values can be achieved e.g. by noisy measurement signals [4].

2.3 SONAH

Acoustic near-field holography describes a method of estimating the sound field on the source surface by measuring the acoustic quantities (usually sound pressure or sound velocity) at a small distance from the source surface. The requirements on the microphone array when using traditional nearfield acoustical holography (NAH) are very high. A uniform microphone arrangement is required, where the array covers the entire sound source. In addition, the minimum microphone distance must be less than half the wavelength at the highest frequency of interest. However, SONAH does not have these restrictions: It can not only work with irregular arrays, it also gives good results when the array is smaller than the source [3]. The latter is due to the fact that, unlike traditional NAH, the strong spatial window effects do not occur [7].

The publication of Puhle et. al [8] describes, among other things, the mathematical implementation of two advanced NAH methods such as SONAH and HELS (Helmholtz equation Least-Squares). In addition, Puhle et. al. also qualitative validates the experimentally determined mode shapes from acoustic measurements using SONAH and HELS with LDV-measurements. This work continues the investigations by concentrating not only on the amplitudes of the calculated surface oscillations, but also on the complex amplitude including the spatially distributed phase. Thus, the MAC is used to quantify the quality of certain mode shapes using FEM, LDV and SONAH.

3. Measurement Setup

The system response of a stainless steel plate to a force excitation was investigated. The stainless steel plate (600 mm x 600 mm x 4 mm) with holes (7 mm in diameter) in each corner was attached to a frame with rubber bands. Thus free boundary conditions can be assumed on the entire surface. In order to get a power transmission only normal to the surface, the plate was excited by a shaker (PCB SmartShaker with integrated power amplifier, model K2007E01) via a thin stinger (diameter approx. 2 mm). The stinger with force sensor (PCB type 208C02) was mounted in the upper right corner of the plate, see Fig. 1 (left). The excitation signal was white noise with frequencies up to 1kHz. The response of the plate to the excitation was measured with an LDV and a microphone array. In order to obtain the best possible signal-to-noise ratio, the acoustic measurements were performed in an anechoic chamber.

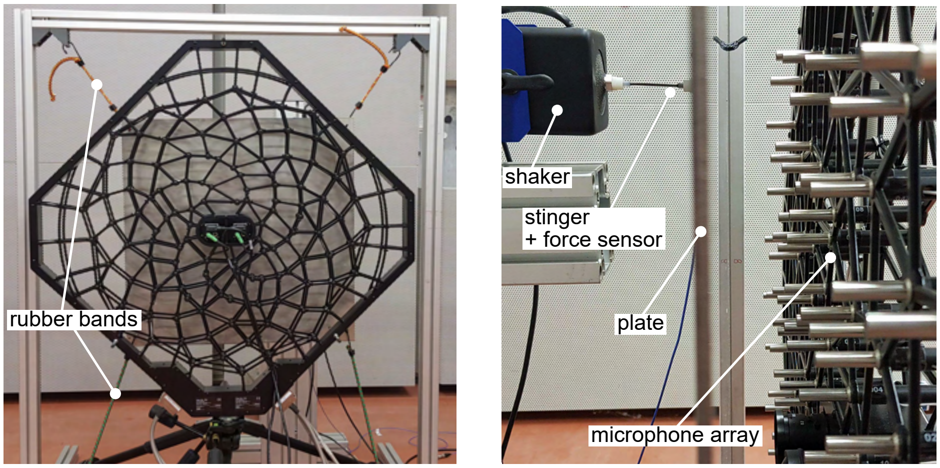


Figure 1: Setup for measuring the acoustic sound field with a microphone array (Fibonacci120 AC Pro, gfai tech GmbH) in an anechoic chamber. Left: alignment of shaker, plate and microphone array; Right: rubber band mounted plate with parallel microphone array.

The acoustic array used (Acoustic Camera Fibonacci 120 AC Pro by gfai tech GmbH) is a multifunctional array and is suitable for SONAH as well as acoustic beamforming. The array was aligned parallel and centered to the plate so that all 120 microphones had a distance of $14\,\mathrm{mm}$ ($\pm 0,5\,\mathrm{mm}$) to the plate, see Fig. 1. The pressure data (measuring time of $16\,\mathrm{s}$, sampling rate $48\,\mathrm{kHz}$) were recorded by a data acquisition system (mcdRec 721B, gfai tech GmbH). The software NoiseImage was used to evaluate the particle velocity on the surface of the plate. As a reference to the acoustic data, the surface vibrations were also measured using an LDV measurement system (PSV-500 Scanning Vibrometer Full-Field Vibration Measurement System, Polytec). 377 measuring points distributed equidistantly over the whole surface of the plate were scanned.

4. Results

The mode shapes from the FEM (left) and the EMA based on the LDV (middle) and SONAH (right) measurement data are shown in Fig. 2 to 11. The first 10 modes that occur at excitation frequencies above $100\,\mathrm{Hz}$ are displayed. To ensure comparability, all pictures show the same centered plate section ($50\,\mathrm{cm}$ x $50\,\mathrm{cm}$) with the same color scale. The upper image series shows the normalized vibration amplitude, while the lower image series shows the corresponding phase. Regardless of the chosen method, the mode shapes calculated by the FEM could be found. Only the 11th mode (see Fig. 7) could not be determined from the acoustic data. It is noticeable, however, that the amplitudes in the middle of the plate are generally slightly overestimated using SONAH. This is probably caused due to the low density of the microphones in the middle of the microphone array, where two optical cameras (fisheye optic for SONAH and wide angle optic for beamforming) are located. The relative phase distribution of the corresponding mode shapes determined in the comparison of the three methods shows only minor differences. At this point it should be noted that inverted phases occur due to the normalized visualization of the eigenvector in the representation (see e.g. Fig.5 and Fig.6). Since the relative phase relations to the different points on the surface remain the same, this has no influence on the quality of the results.

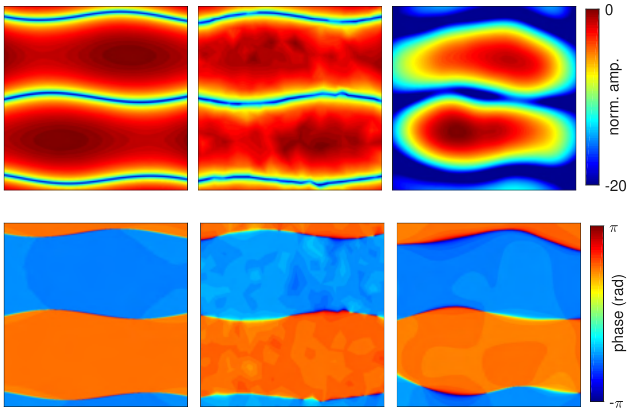


Figure 2: Amplitude (top) and phase (bottom) of mode No 6; FEM (left), LDV 161 Hz (middle), SONAH 163 Hz (right)

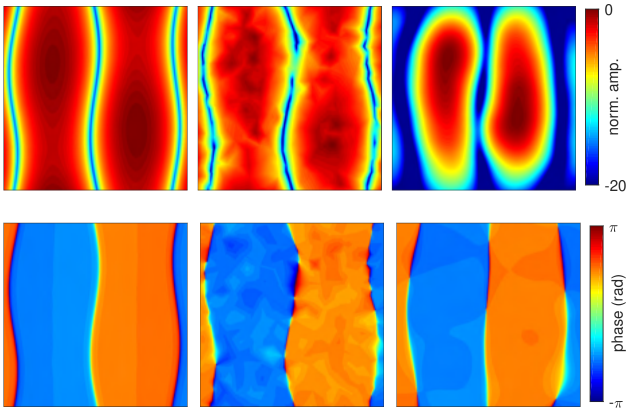


Figure 3: Amplitude (top) and phase (bottom) of mode No 7; FEM (left), LDV 164 Hz (middle), SONAH 165 Hz (right)

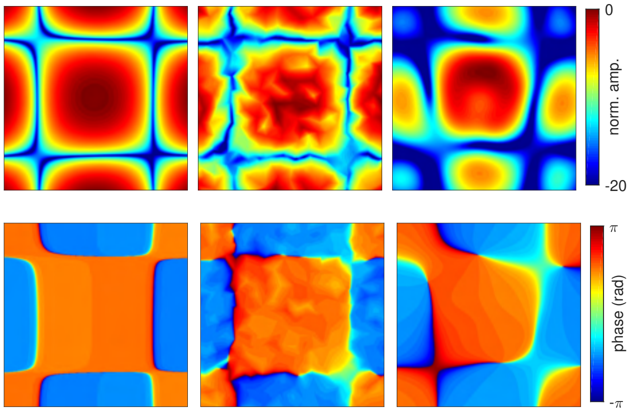


Figure 4: Amplitude (top) and phase (bottom) of mode No 8; FEM (left), LDV 170 Hz (middle), SONAH 172 Hz (right)

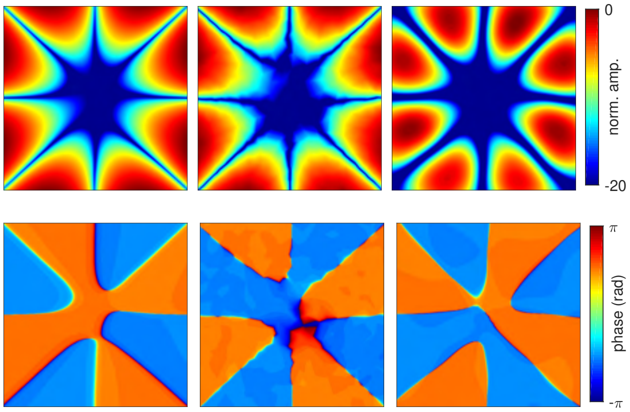


Figure 5: Amplitude (top) and phase (bottom) of mode No 9; FEM (left), LDV 187 Hz (middle), SONAH 186 Hz (right)

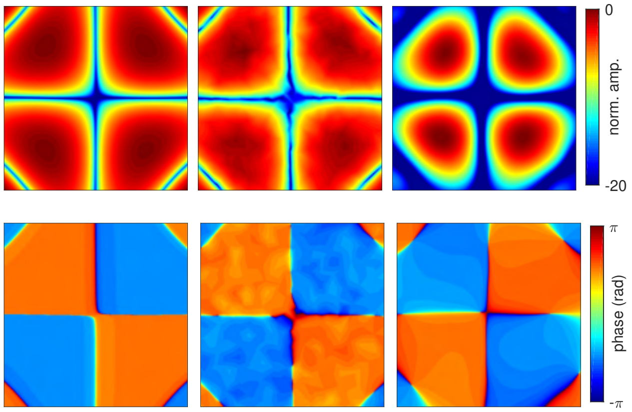


Figure 6: Amplitude (top) and phase (bottom) of mode No 10; FEM (left), LDV 203 Hz (middle), SONAH 206 Hz (right)

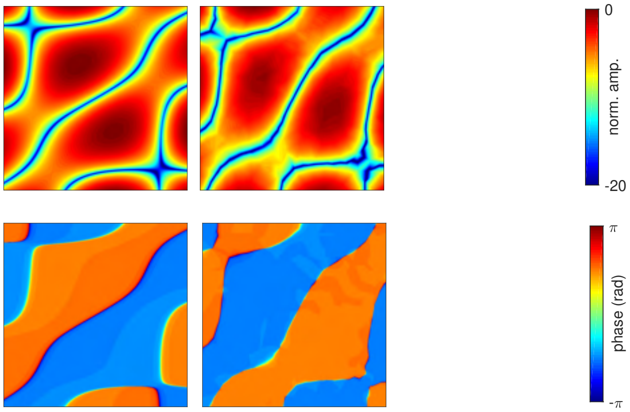


Figure 7: Amplitude (top) and phase (bottom) of mode No 11; FEM (left), LDV 265 Hz (middle), SONAH not found

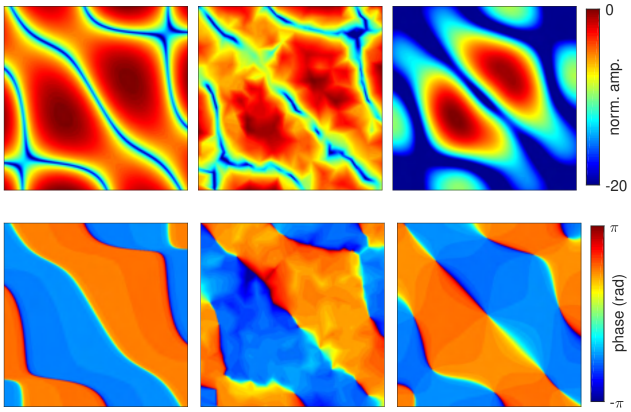


Figure 8: Amplitude (top) and phase (bottom) of mode No 12; FEM (left), LDV 281 Hz (middle), SONAH 280 Hz (right)

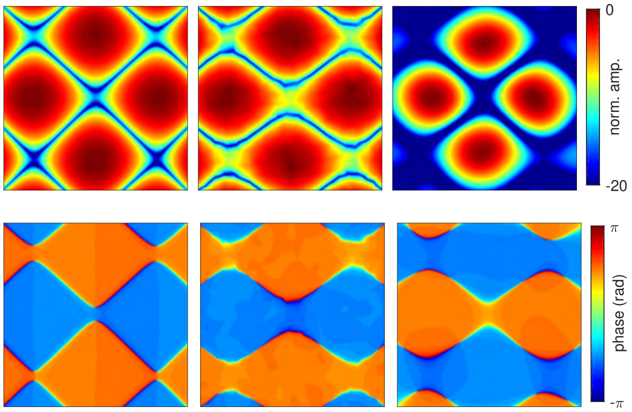


Figure 9: Amplitude (top) and phase (bottom) of mode No 13; FEM (left), LDV 313 Hz (middle), SONAH 313 Hz (right)

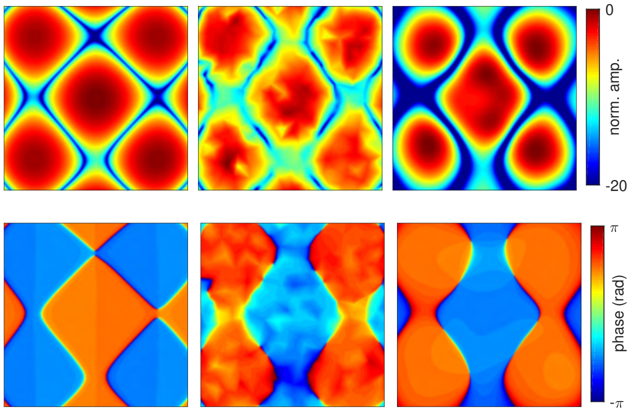


Figure 10: Amplitude (top) and phase (bottom) of mode No 14; FEM (left), LDV 324 Hz (middle), SONAH 324 Hz (right)

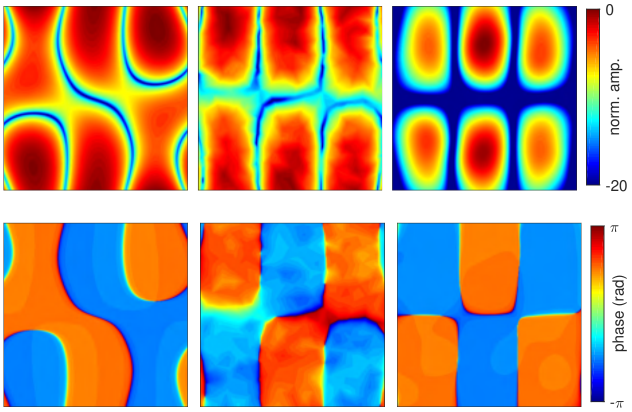
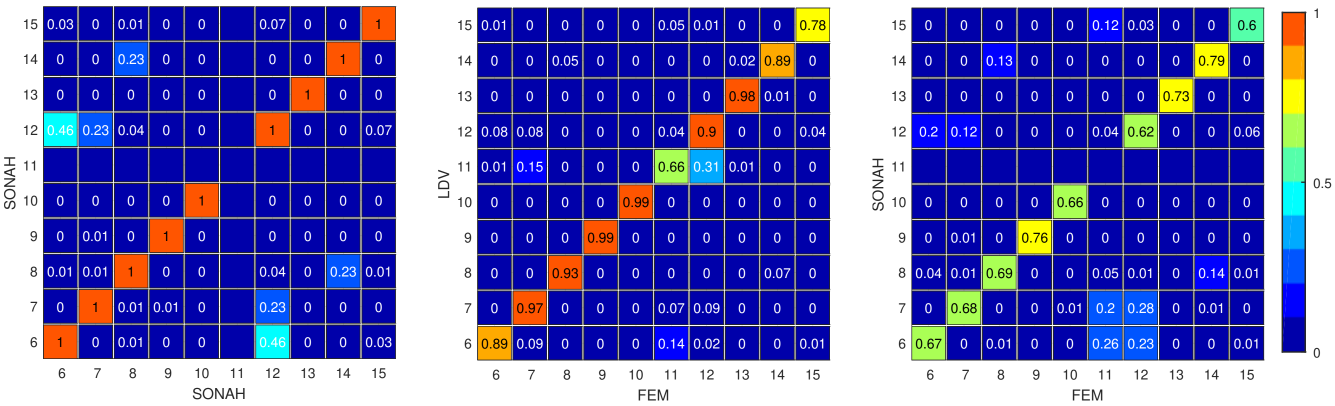


Figure 11: Amplitude (top) and phase (bottom) of mode No 15; FEM (left), LDV 350 Hz (middle), SONAH 350 Hz (right)

In order to compare the mode shapes determined by LDV and SONAH with the numerically calculated mode shapes, the corresponding MAC matrices using Eq. (1) were created. Figure 12 shows the MAC matrix of the following combinations: (a): mode shapes of SONAH only (auto-MAC); (b): mode shapes of FEM and LDV; (c): mode shapes of FEM and SONAH. The results of the auto-MAC (Fig. 12a) show almost exclusively high values only on the diagonal, whereby a strong linear independence of the determined modes can be assumed. Only a comparison of the 6th with the 12th mode shows a relevant high MAC values of 0.46. When using a microphone array it should be noted that the spatial resolution of the measured eigenmodes depends on (analogous to the measuring point density when using a LDV). Thus, further investigations must show whether the insufficient separation of the mode shapes observed here can be improved by a higher measuring point density (more microphones) or a different positioning of the microphone array. The coss-MAC matrices compare the numerically determined mode shapes with those from the LDV measurements (Fig. 12b) and with those from the modes determined by SONAH (Fig. 12c), respectively. It is worth mentioning that the 11th mode, which could not be extracted from the acoustic data, could also only be determined poorly with LDV. The reason for this may be that the force introduction is at a position that is disadvantageous for this mode (node of the mode). A comparison of the two cross-MAC matrices shows that all modes determined by LDV measurements correspond very



(a) auto-MAC: SONAH

SONAH	6	7	8	9	10	11	12	13	14	15
15	0.03	0	0.01	0	0		0.07	0	0	1
14	0	0	0.23	0	0		0	0	1	0
13	0	0	0	0	0		0	1	0	0
12	0.46	0.23	0.04	0	0		1	0	0	0.07
11										
10	0	0	0	0	1		0	0	0	0
9	0	0.01	0	1	0		0	0	0	0
8	0.01	0.01	1	0	0		0.04	0	0.23	0.01
7	0	1	0.01	0.01	0		0.23	0	0	0
6	1	0	0.01	0	0		0.46	0	0	0.03

(b) cross-MAC: FEM vs LDV

LDV	6	7	8	9	10	11	12	13	14	15
15	0.01	0	0	0	0	0.05	0.01	0	0	0.78
14	0	0	0.05	0	0	0	0	0.02	0.89	0
13	0	0	0	0	0	0	0	0.98	0.01	0
12	0.08	0.08	0	0	0	0.04	0.9	0	0	0.04
11	0.01	0.15	0	0	0	0.66	0.31	0.01	0	0
10	0	0	0	0	0.99	0	0	0	0	0
9	0	0	0	0.99	0	0	0	0	0	0
8	0	0	0.93	0	0	0	0	0	0.07	0
7	0	0.97	0	0	0	0.07	0.09	0	0	0
6	0.89	0.09	0	0	0	0.14	0.02	0	0	0.01

(c) cross-MAC: FEM vs SONAH

SONAH	6	7	8	9	10	11	12	13	14	15
15	0	0	0	0	0	0.12	0.03	0	0	0.6
14	0	0	0.13	0	0	0	0	0	0.79	0
13	0	0	0	0	0	0	0	0.73	0	0
12	0.2	0.12	0	0	0	0.04	0.62	0	0	0.06
11										
10	0	0	0	0	0.66	0	0	0	0	0
9	0	0.01	0	0.76	0	0	0	0	0	0
8	0.04	0.01	0.69	0	0	0.05	0.01	0	0.14	0.01
7	0	0.68	0	0	0.01	0.2	0.28	0	0.01	0
6	0.67	0	0.01	0	0	0.26	0.23	0	0	0.01

Figure 12: Calculated MAC values by Eq. (1).

well with the numerical modes. Although the MAC values based on SONAH result in lower values, it is also possible to clearly assign them to the numerically ideal values.

5. Conclusion

In this work it could be shown that beside the complex mode shapes also the corresponding resonance frequencies can be determined. When using an LDV scanning system, approximately $5 - 30$ s are required to capture the surface vibrations at one point. However, during the same measurement time, the overall vibration behaviour of the surface of the plate can be estimated using a microphone array. The advantage of the commercial microphone array used here is its flexibility. It can not only be used for SONAH, but is also very well suited for localizing sound sources by means of acoustic beamforming due to the spiral arrangement of the microphones. However, the microphone arrangement is a compromise between these two measurement methods, which leads to inaccuracies in the vibration amplitude when comparing the LDV-determined mode shapes, especially in the outer area of the plate. The phase distribution, however, can be determined correctly for each mode number examined here. This shows that one EMA, based on the measurement using an acoustic array, is particularly relevant for comparison measurements, e.g. end-of-line quality control.

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