Measurement of 2D dynamic stress distributions with a 3D-Scanning Laser Doppler Vibrometer

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ABSTRACT

Recently a method has been developed to measure surface dynamic strain and stress fields by using a contactless 3D scanning laser Doppler vibrometer. Assuming a free visible surface of the test specimen this method, a combination of advanced measurement technique and a post-processing algorithm, enables the assessment of high resolution dynamic surface loadings including quantity and direction of strain/stress distributions.

The first part of the article describes the basic principles of the method. The second part informs about the validation work of the measurement results. Different steps were performed in order to measure real structures. A numerical model was the base for correlation with measured deflection-shapes, strain- and stress-fields. During this analysis, the different influencing parameters for measuring the strain information could be analyzed systematically. The third part presents a comparison of vibrometer measurements to strain gauge values.

The validation of the method shows a high level of agreement between measured values compared to numerical strain and stress results. The correctness of the absolute strain values could be validated by the comparison with strain gauges. Further research will be done to close the gap between simulation and measurement.

1. INTRODUCTION

For a safe and reliable design of structures the knowledge of mechanical stresses under structural usage is inevitable. Especially for dynamically loaded structures precise information about maximum stresses is important in order to design robust components.

A newly developed technique based on a 3D-Scanning Laser Doppler Vibrometer (3D-SLDV) enables the contactless measurement of surface stresses of a vibrating structure. The primarily measured information is the 3D deflections at all surface grid points of the measured structure. The 3D deflection components are used to calculate strain and stress distributions in a post-processing routine. This procedure has first been proposed by Mitchell et al. [1]. The basic principles of the method and details on the post-processing routine have been published by Meitzner [2] and Cazzolato et al. [3].

In this work, the focus is on the validation of the method.

2. THEORETICAL BASICS

The 3D-SLDV (see fig. 1) measures the three-dimensional vibration vectors at all specified surface points. It consists of three 1D-SLDVs. For the measurement three lasers are directed simultaneously to one point. Each vibrometer measures the vibration vector in the direction of its laser beam. The three vibration vectors are then transformed into a global orthogonal coordinate system. All points are measured sequentially; therefore, the object vibration must be repeated for the measurement of each point. The method has been described by Bendel et al. [4].

Fig. 1: Test setup comprising the three scanning heads and a digital camera (left) and a test specimen, mounted on an electromagnetic shaker (right)

Fig. 2 shows the basic principle of the strain measurement with the 3D-SLDV. To position the lasers, the geometry data of the object is imported from the FE-model. For the measurement a routine called VideoTriangulation has been developed; this routine uses image processing of a high resolution video camera to ensure that the three lasers are on the same spot. From the updated laser angles, the geometry data of the real object can be obtained.

Once the three lasers are on the same spot, the three vibrometers acquire data simultaneously. The raw data is transformed into the global coordinate system of the object.

The next step is an optional smoothing. As the following strain calculation requires a spatial differentiation of the data, it is very sensitive to noise. Sophisticated smoothing algorithms reduce the noise prior to strain calculation.

The raw data for the strain calculation is the 3D displacement vectors. These vectors are transformed into a local coordinate system which is aligned with the local geometry of the object's surface. From the local in-plane displacement and the geometry, strain is calculated for each surface triangle.

The final step is the transformation of the strain data into the object's global coordinate system, this allows for displaying and analyzing the data. The results can be directly compared to the results of the FE calculation.

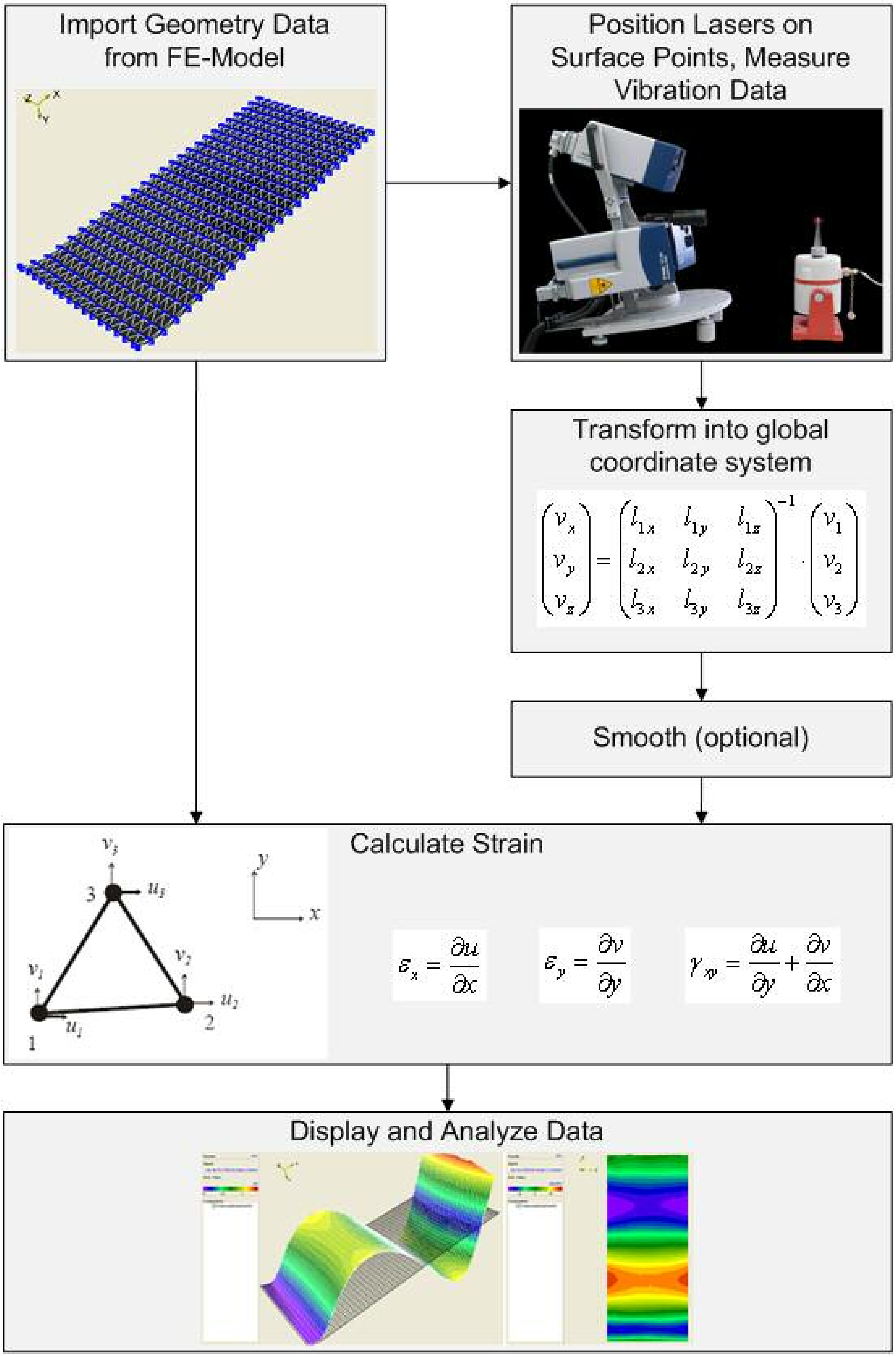


Fig. 2: Basic principle of the strain measurement with a 3D-SLDV

An example for the measurement is shown in fig 3. It shows the third bending mode (mode 6) of the hereafter described test specimen at 7.8 kHz.

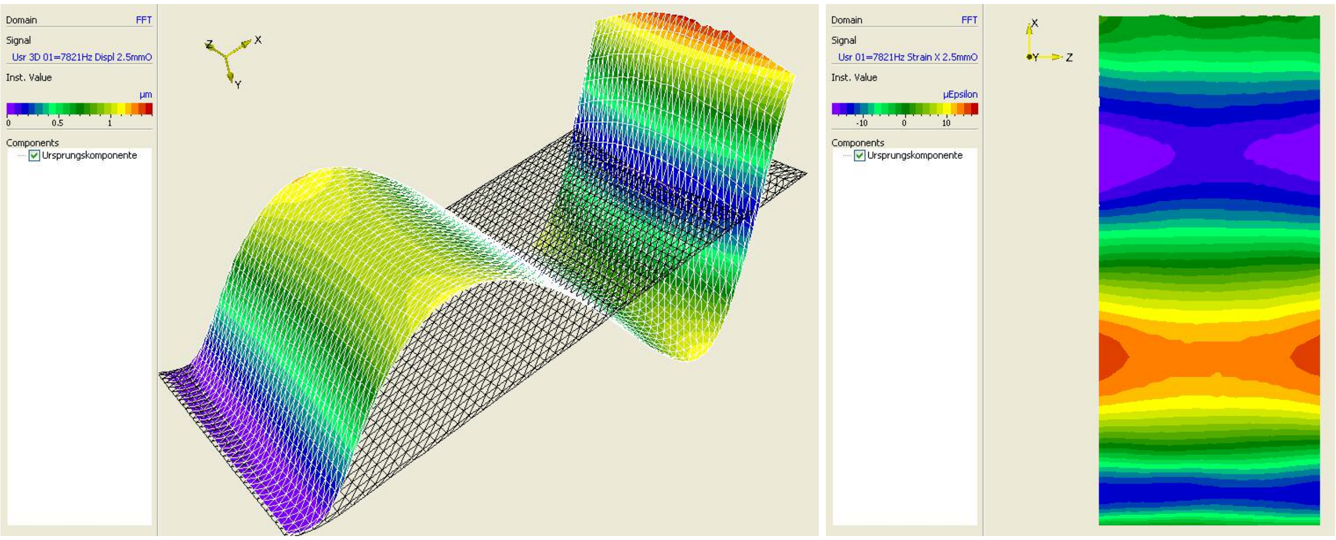


Fig. 3: Deflection shape and strain distribution of test specimen at 7.8 kHz

3. VALIDATION OF THE STRAIN AND STRESS MEASUREMENT

In order to determine the validity and the limits of the method for structural measurements, extensive validation work has been performed.

The validation work has been performed in three main steps:

1. Validation of the post-processing routine
2. Correlation of the Vibrometer measurement with FE-simulation
3. Correlation of the Vibrometer measurement with a strain gauge

The validation has been performed on a symmetric cantilever test structure (Fig. 4). A 3 mm thin rectangular plate was used to identify and validate modal strain distributions. To achieve well defined boundary conditions the test specimen contains a 15 mm thick base. A fillet radius of 9.4 mm helps pushing the maximum strains away from the fixed base.

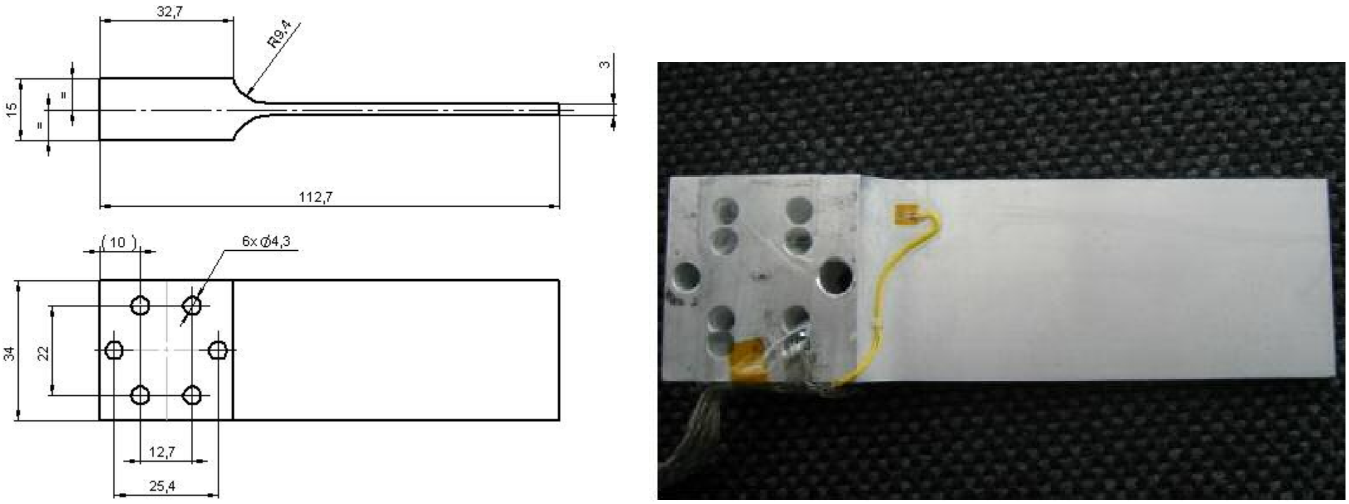


Fig. 4: Drawing and photograph of the test specimen, the applied strain gauge can be seen in the photograph

3.1 Validation of the post-processing routine

The first step in validation work was to validate the strain calculation post-processing routine. For this purpose a 3D numerical simulation model of the test specimen has been build, using the FE-Software CalculiX [6] (Fig. 5).

After performing a numerical modal analysis [5], the calculated mode shapes and the strain and stress distributions have been available directly from Calculix. Those calculated mode shapes have been used to validate the post-processing routine which calculates surface strains from the measured surface displacement values (Fig. 6).

The post-processing routine has been validated by a calculation of the Modal Assurance Criterion (MAC) with the strain values calculated by CalculiX.

The obtained MAC-values are shown in Fig. 7. All linear strain values are 0.999 which proofs the post-processing routine to be correctly implemented. Some shear strain values are below 0.99, this fact can be attributed to very high gradients at the edges of the structure which can be better resolved by the FE simulation due to a higher point density.

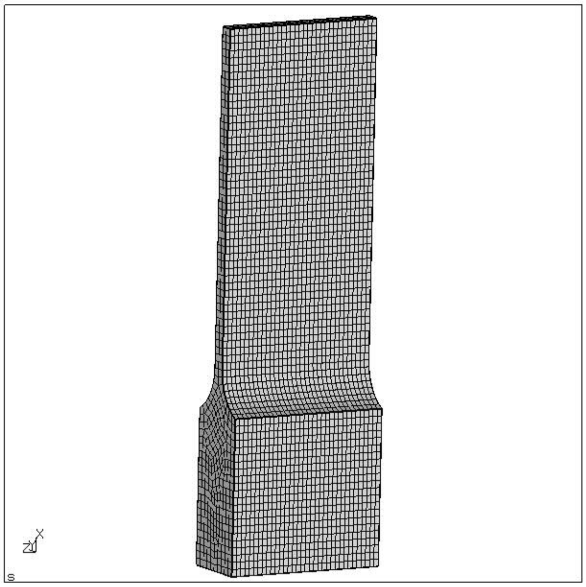


Fig. 5: Simulation model of the test specimen

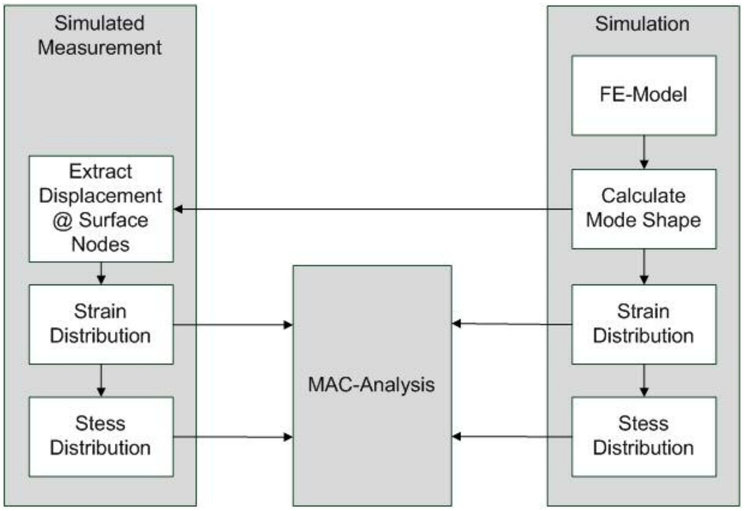


Fig. 6: Validation of the post-processing routine

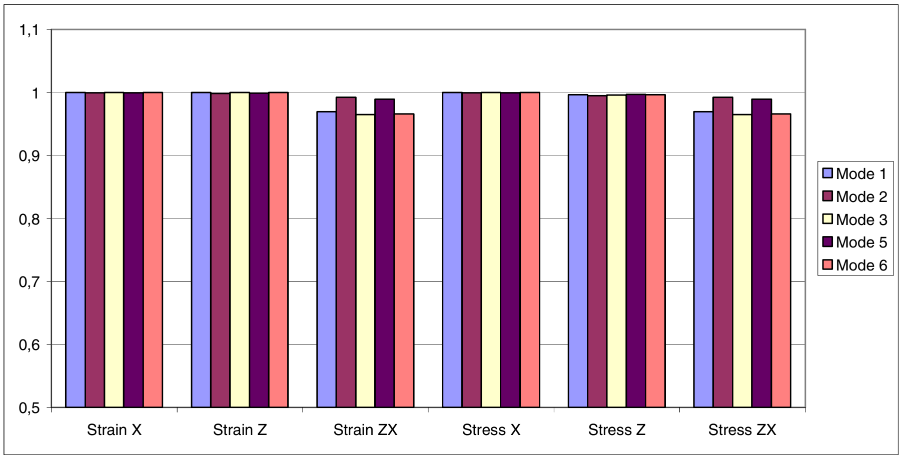


Fig. 7: MAC values between the post-processing routine and CalculiX

3.2 Correlation of the Vibrometer measurement with FE-simulation

In order to perform a measurement, the specimen has been mounted on an electromagnetic shaker, the principle of the setup is shown in Fig. 2. A measurement with broad-band excitation has been performed at a single point to find the exact resonance frequencies. At each resonance frequency, the deflection shape has been measured with sine excitation.

As described above, the deflection shapes have been post-processed to calculate strain and stress distributions. In the following, those post processed measurement values are referred to as measured strain and stress distributions.

The measured strain and stress distributions have been compared to those from simulation. The procedure is of this validation step is shown in Fig. 8. The results of the MAC analysis are shown in Fig. 9. The results of the visual comparison for one mode are displayed in Table 1.

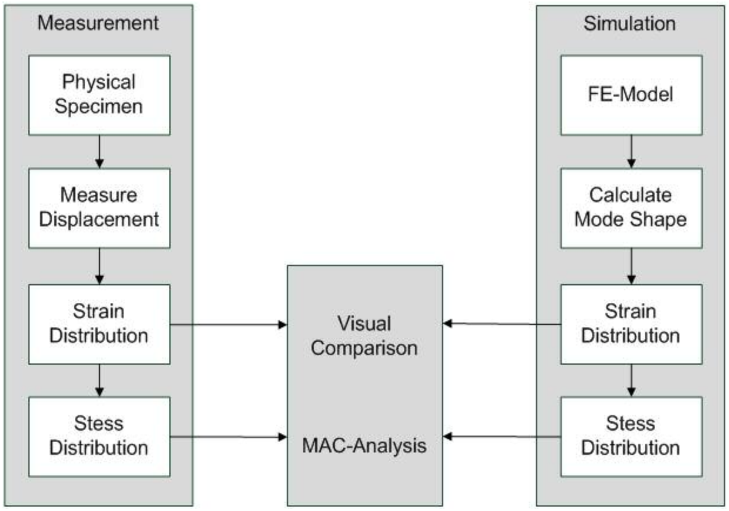


Fig. 8: Validation of the strain and stress measurement

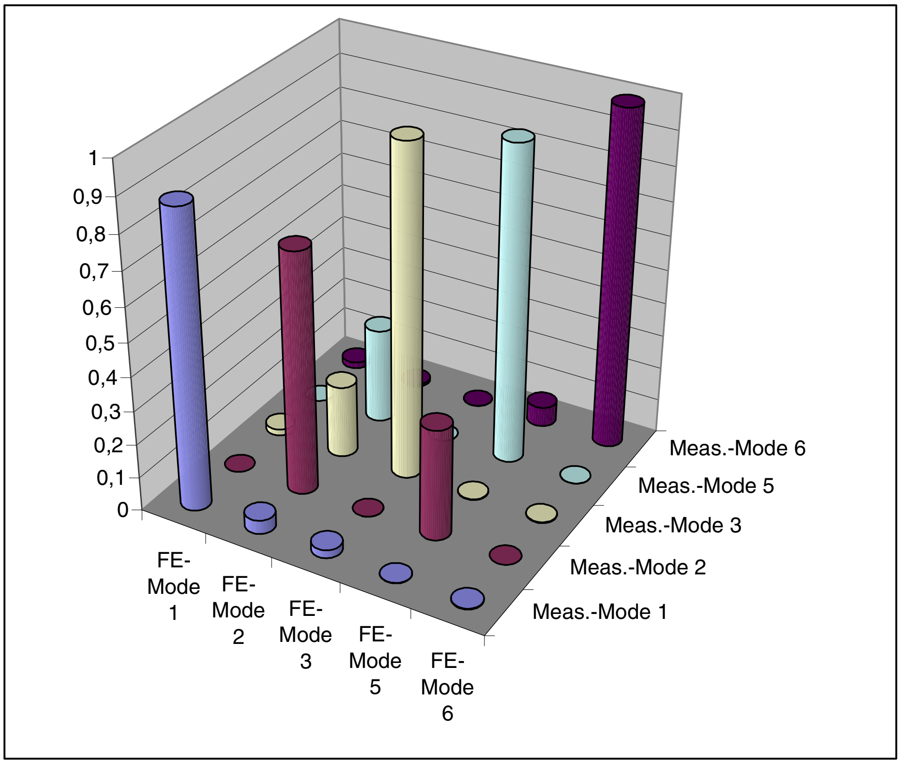


Fig. 9: MAC values between simulation and measurement

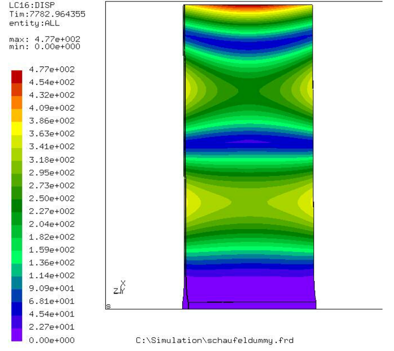
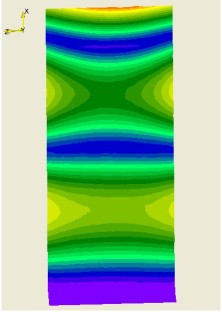
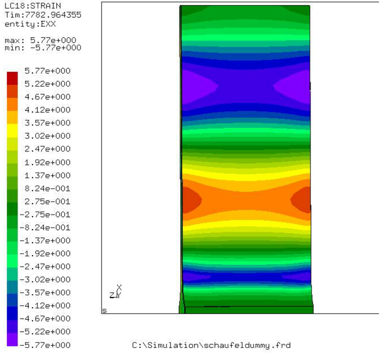
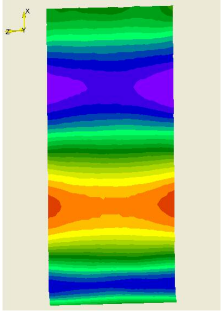
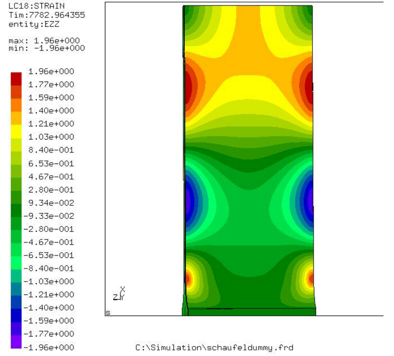
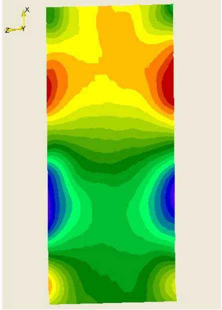
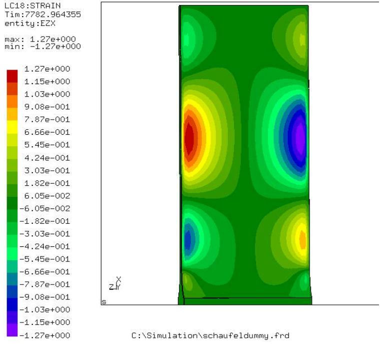
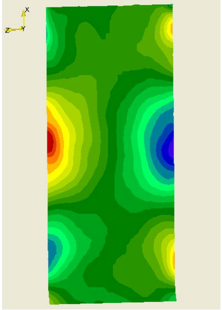
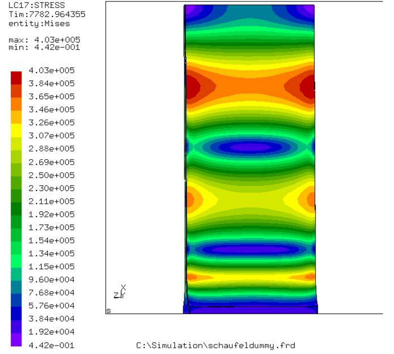
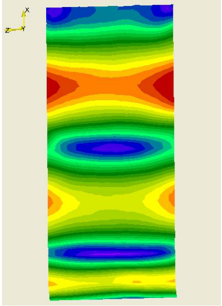
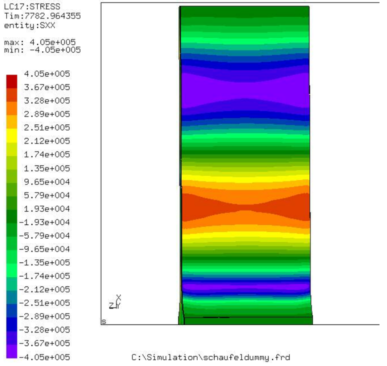
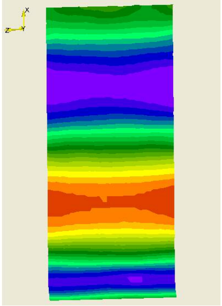
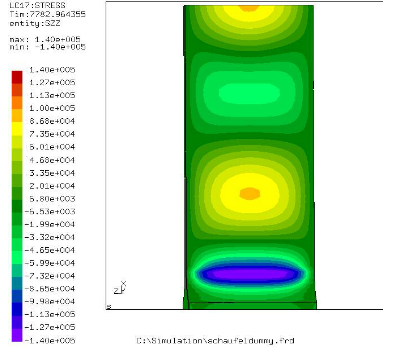
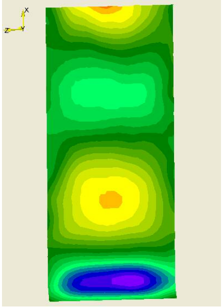
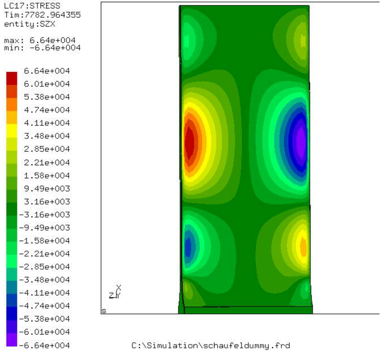
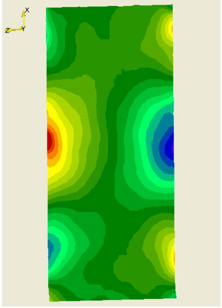
Simulation	Measurement	Simulation	Measurement
			
Displacement		Strain X (vertical)	
			
Strain Z (horizontal)		Strain ZX	
			
Von Mises Stress		Stress X (vertical)	
			
Stress Z (horizontal)		Stress ZX	

Table 1: Visual comparison between measurement and simulation for the third bending mode at 7.8 kHz

3.3 Comparison of the Vibrometer measurement with strain gauges

Strain gauge measurements are well established in durability testing. However, determining the absolute strain value with strain gauges means to get an integral value from the gauge's sensitive area. A single strain gauge provides furthermore only informations in its spatial validity. The newly developed technique based on 3D-deflection measurements provides the complete information about directions and quantitative strains.

To confirm the validity of the absolute strain values, measured with the 3D-SLDV, a strain gauge has been applied on the back of the double symmetric test specimen (see fig. 3, left). The strain values have been measured simultaneously with the 3D-SLDV on the front of the test specimen. For the comparison, the point, opposite to the strain gauge has been analyzed together with the values from the strain gauge. Fig. 10 shows the measured values for the modes up to 10 kHz.

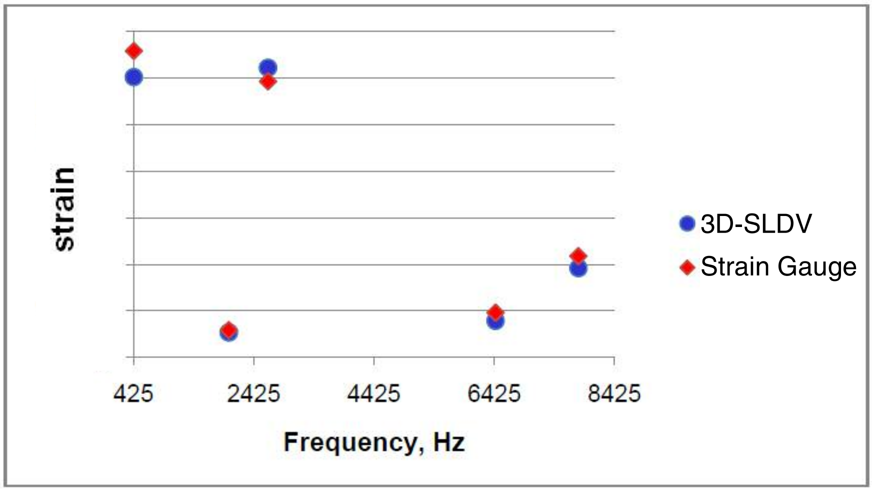


Fig. 10: Measured values from the strain gauge and the 3D-SLDV

Both methods show a very good agreement, it could not been analyzed if the differences stem from the measurement or from asymmetries of the test specimen.

4. INFLUENCE OF DATA SMOOTHING

As shown in Fig. 1, an optional smoothing of the measured vibration data is in the process of calculating strain and stress distributions from the measured vibration data. The purpose of the smoothing is to minimize measurement noise which becomes apparent in the strain data, as the post-processing routine is a numerical differentiation.

The smoothing has a great influence on the quality of the results. To adjust the strength of the smoothing a radius parameter must be specified in millimeters. Table 2 shows strain values with different filter settings for a sample measurement. It can be seen that for the chosen example, a filter radius of 2.5 mm is optimum. For a filter radius of 5 mm, the smoothing effects are better, but it can be seen that the maximum strain values are significantly reduced by the smoothing.

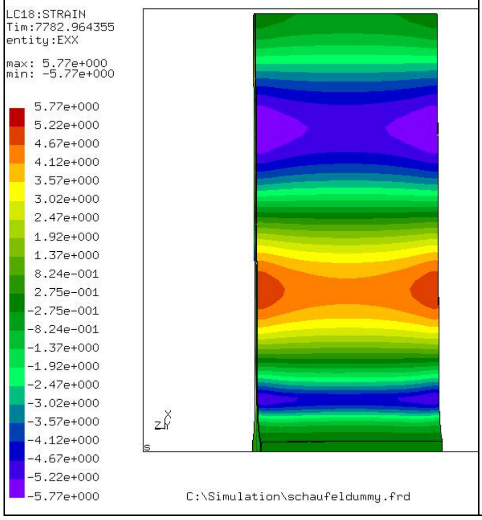
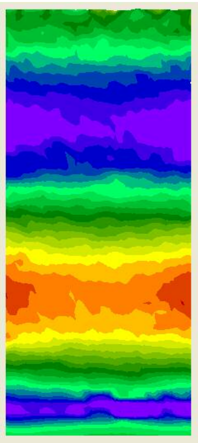
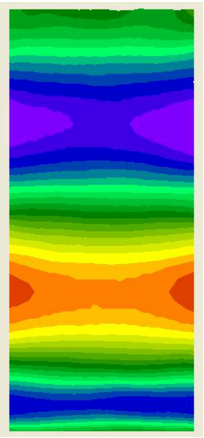
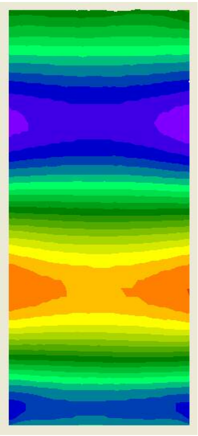
Simulation	No smoothing	1.5 mm	2.5 mm	5.0 mm
				

Table 2: Influence of the smoothing filter radius for Strain_X of the third bending mode at 7.8 kHz

A qualitative research of the influence of the smoothing filter radius has been performed by MAC-analysis. After calculating the strain values by post-processing, the MAC-values with the simulated strain distributions have been calculated. For the chosen example, the optimum filter setting is at 2.5 mm (Fig. 11), which confirms the visual analysis above.

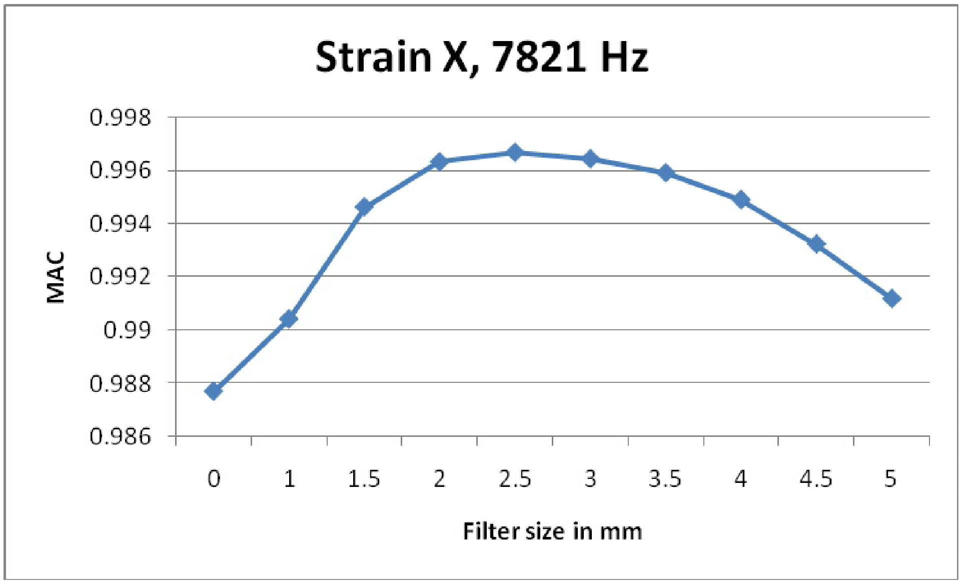


Fig. 11: Influence of the filter size on the MAC values for Strain_X of the third bending mode at 7.8 kHz

5. CONCLUSIONS

A method to optically measure strain and stress values has been presented. The validation of this method showed a high level of agreement between the measured values and the simulation results and the measured strain gauges. Based on the high sensitivity of the 3D-SLDV, high resolution surface dynamic strain measurements are able. An accurate structural validation between numerical simulations and high resolution measurement results is possible. This contactless measurement device helps to reduce costs concerning instrumentation work and leads to reliable data even under rough measurement conditions. The complete measurement can be performed within a few hours.

REFERENCES

[1] Mitchell, L.D., West, R.L. and Wicks, A.L. (1998), "An emerging trend in experimental dynamics: Merging of laser-based three-dimensional structural imaging and modal analysis", *Journal of Sound and Vibration, 211(3),323-333*.

[2] Meitzner, R.; MTU Aero Engines (2005); *patent applications DE 102005042820A1 and US20080249722A1*.

[3] Ben Cazzolato, Stuart Wildy, John Codrington, Andrei Kotousov and Matthias Schuessler (2008), "Scanning laser vibrometer for non-contact three-dimensional displacement and strain measurements", *Proceedings of the Australian Acoustical Society Conference, Geelong, Australia, Nov 24-26*.

[4] K. Bendel, M. Fischer, M. Schüssler (2004), "Vibrational analysis of power tools using a novel three dimensional scanning vibrometer", *6th International Conference on Vibration Measurements by Laser Techniques: Advances and Applications, ed. E. P. Tomasini, Proc. of SPIE Vol. 5503 pp. 177-184*.

[5] Dhondt, G. (2004), "The Finite Element Method for Three-Dimensional Thermomechanical Applications", *Wiley*

[6] www.calculix.de