Surface Measurement of Dynamic Stress Distribution on Turbine Blades

To develop robust, high-performance turbines for industrial and commercial applications, the dynamic stress distribution within the associated structures must be understood. It is known that dynamic excitation forces within a component produce characteristic stress distributions that are dependent on the deflection shape. Furthermore, the service life of a new component can be approximated with simulation models but must be verified by appropriate testing to assure the accuracy of the modeling. To do this, the stress maxima of the individual modes of vibration are measured and compared to model values. To make measurements of vibration-induced stress, strain gauges are typically used. However, determining the correct position for the strain gauge on the test structure can be difficult since the stress maxima in real components can deviate from the model-predicted locations due to manufacturing variations and tolerances. Consequently, several strain gauge positions are required to capture data and correctly evaluate a vibration mode. To avoid this problem, there is great interest in capturing the strain on components using several modes of vibration - without mounting and moving individual strain gauges across the structure's surface.

In this article, using laser vibrometer measurements of the dynamic strains and stresses in turbine blades, we show how model verification can be carried out with considerably less effort and significantly increased accuracy. In the example application, the measurement values obtained in this way were compared to simulation values. This showed that a very high degree of consistency was attained. Asymmetries of the vibration stresses in the real component can be traced back to production tolerances and cannot be taken into consideration in the simulation.

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Minimizing Test Expense – Improving Quality

Fig. 1: Instrumented turbine blade with strain gauges.

The need to search for alternatives to strain gauges is obvious. Optical methods, such as image correlation or ESPI, considerably reduce the expense of instrumentation, but have their own limitations such as in resolving the amount of the structure's dynamic expansion. To overcome these limitations, MTU Aero Engines in Munich and Polytec in Waldbronn have cooperated on a study that measures dynamic expansion using three-dimensional scanning laser Doppler vibrometry. To compare the process with the numeric simulation, a model component was produced and characterized first with the finite element method and then experimentally. The results help determine whether it is possible to directly apply the method to turbines and compressor blades essential for MTU's business.

Non-contact Dynamic Strain and Stress Measurement

Key to the dynamic strain measurement is the PSV-400-3D Scanning Vibrometer that measures vibration in three dimensions, capturing the distribution of the surface vibration on a component using three laser sensors. The laser vibrometer can determine the three-dimensional vibration vector at every point on a previously-defined measurement grid.

A typical test configuration is seen in Fig. 2 with three sensor heads and a turbine blade excited by a shaker.

Fig. 2: 3-D Scanning Vibrometer testing a turbine blade.

The measurement grid can either be imported from a Finite Element Model and then aligned with the real specimen, or it can be defined manually with the geometry of the measurement points experimentally measured. At every point on the measurement grid, the three laser beams are aligned using so-called Video Triangulation. This allows a high precision measurement of both the geometry and also the three-dimensional dynamic motion vectors at the measurement points.

The strain is calculated from the difference in the displacements between neighboring points (Fig. 3). To do this, both the displacement data and also the geometry data of the measurement points must be known with high accuracy. The PSV-400-3D ensures that both geometry and displacement data are provided. With the aid of the material parameters Young's modulus and Poisson's ratio, the dynamic stress distribution is calculated from the strain distribution.

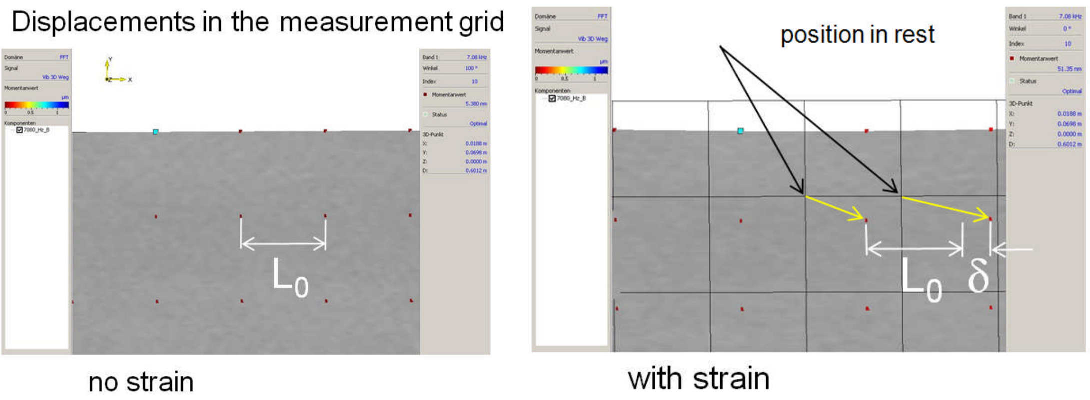

Fig. 3: Displacement of the measurement points through strain.

Since the measurement is performed with focused laser beams, almost any measurement point density can be attained, easily exceeding what is possible through contact strain gauges. This circumstance simplifies and improves verification of simulation results.

Apart from the increased quality of results, the quick response time of the scanning vibrometer also has a positive impact. Tests can be carried out quickly and the results of modifications can be verified without delay and avoid reinstrumenting the test structure.

Verification of the Simulation Results through Test Measurements on a Manufactured Plate

To validate the process, an aluminum test plate was made with the dimensions of 80 mm x 34 mm and a thickness of 3 mm. The plate is thickened at one end using a defined radius of 15 mm to transition from the thin to the thick section (Fig. 4), allowing the plate to be clamped under defined conditions.

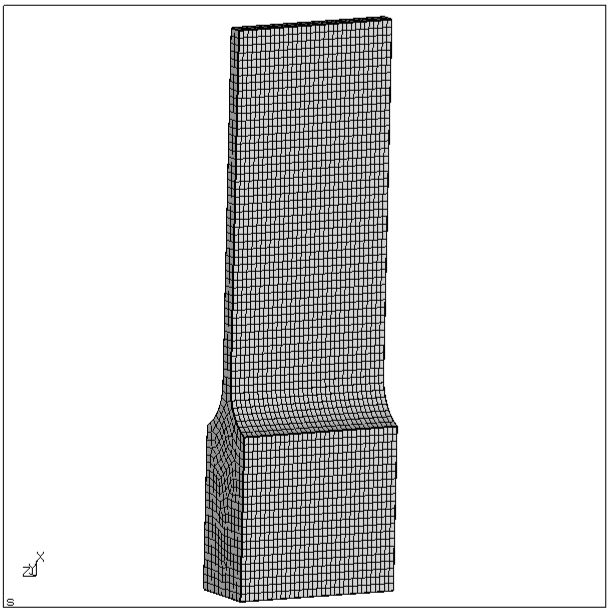

Fig. 4: Test item modeled in FE software.

The plate structure had been modeled and calculated with the aid of the FE simulation program Calculix. In the simulation, the eigenmodes up to 16 kHz were calculated with the associated deflection shapes and strain/stress distributions.

Measurement as well as evaluation and visualization was done by using the PSV Software. In an overview scan with broadband excitation, the simulated deflection shapes were identified and the associated frequencies were determined. After that, the individual deflection shapes were precisely measured with sinusoidal excitation. Automatic Video Triangulation during the measurement ensured that the three lasers converged precisely at each measurement point. At the same time, the actual 3-D geometry was captured with a resolution of 15 µm.

The primary measured quantity is the 3-D velocity vector at each measurement point on the structure. This can be converted within the frequency range into a 3-D displacement vector. On the basis of these displacements, the strains and stresses are calculated using the PSV Strain Processor software. The strain and stress distributions can then be visualized using the PSV software.

The PSV-400-3D Scanning Vibrometer makes it possible to freely define the coordinate system and to compare the measurement data with the simulation output in the coordinate system of the simulation. Thus a direct comparison of the strain and stress distributions between the measurement and simulation is simple. In Figures 5 – 7, a comparison of the displacements, strain distributions and stress distributions for a selected mode of vibration at 15 kHz is shown.

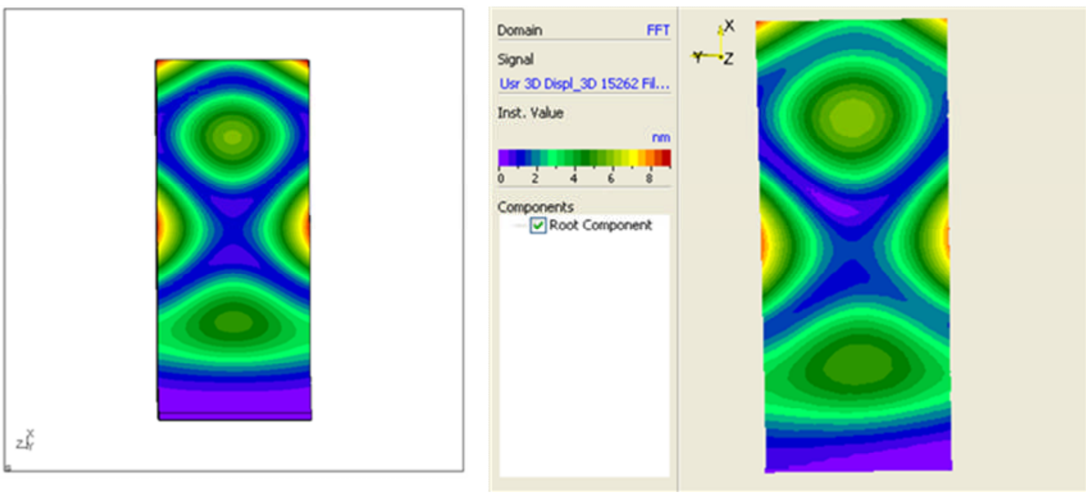

Fig. 5: 3-D displacement amplitudes show agreement between the simulation (on the left) and the measurement (on the right).

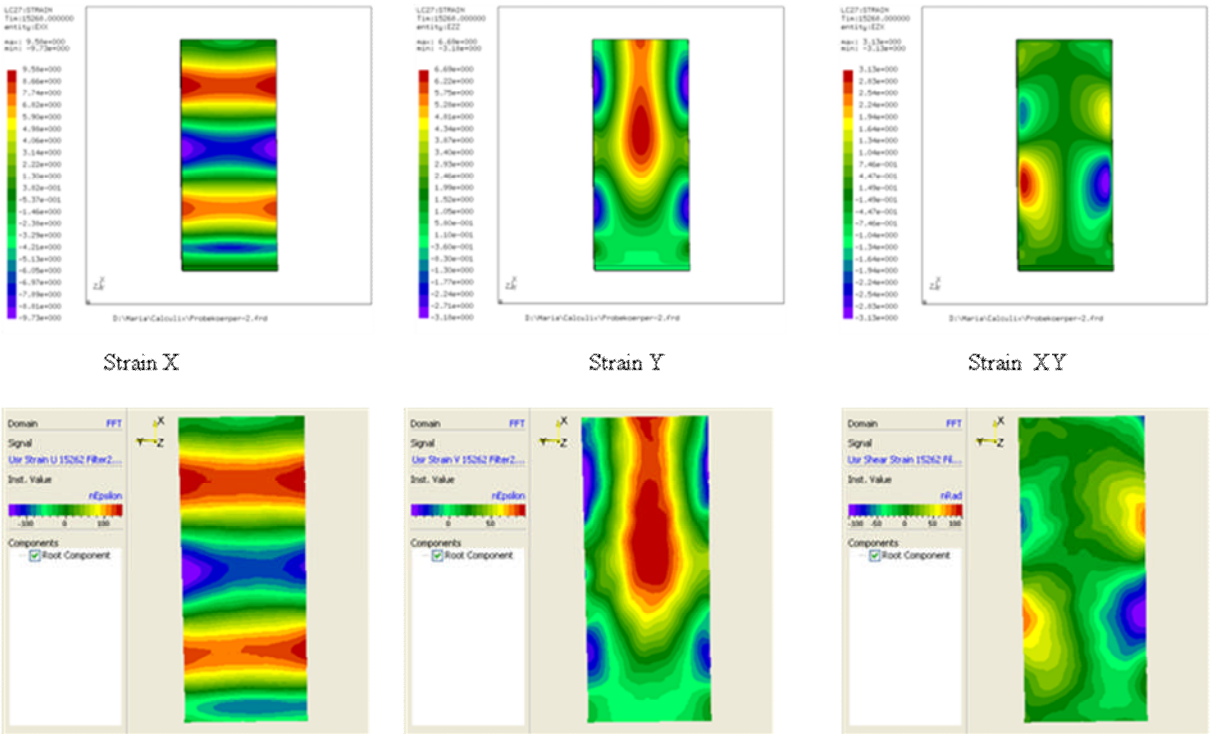

Fig. 6: Strain distributions show good agreement between the simulation (at the top) and the measurement (at the bottom).

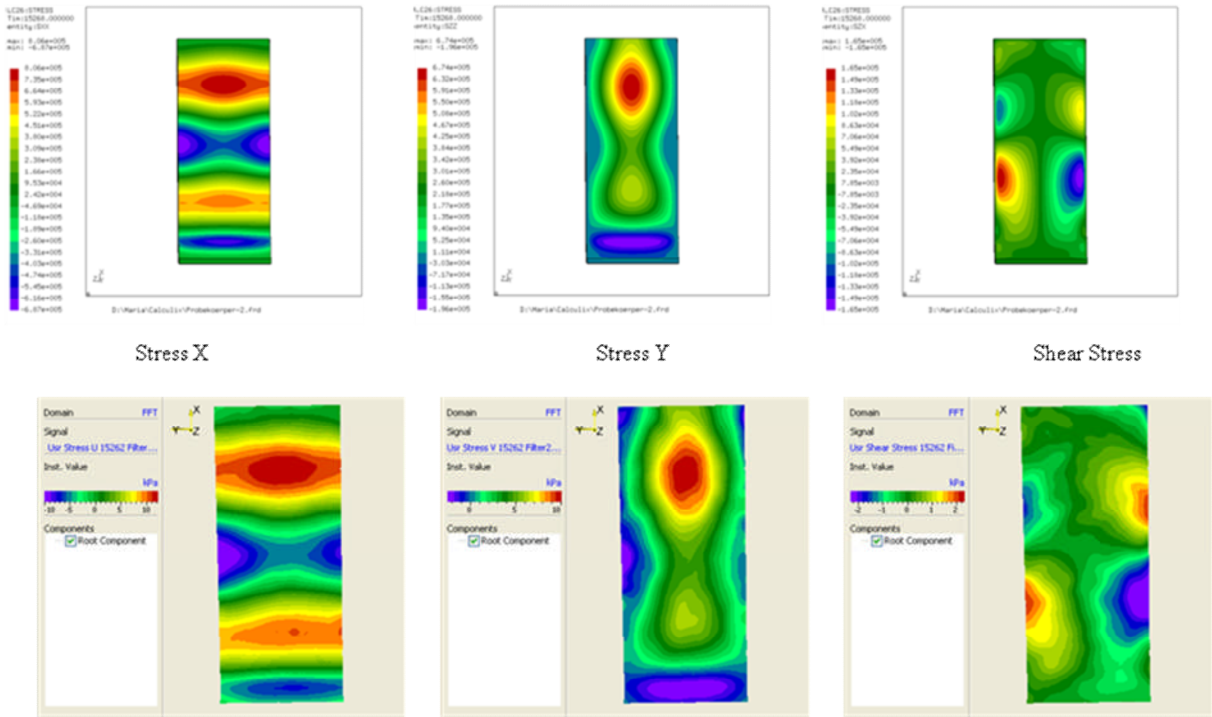

Fig. 7: Stress distributions can be calculated and compared between the simulation (at the top) and the measurement (at the bottom).

Summary

The approach of verifying the functionality of the dynamic strain measurement using the PSV-400-3D Scanning Vibrometer by carrying out tests on a simplified but still realistic model has proven to be extremely effective. The deflection shapes and the strain and stress distribution can be measured quickly and precisely using the model.

The results for the strain and stress distributions show excellent agreement with the simulation, both qualitatively and quantitatively.

Due to its very high sensitivity and ability to measure the strains in high resolution in all spatial directions, the non-contact PSV-400-3D Scanning Vibrometer is ideally suited for comparing the simulation results with the strain and stress distributions that occur in real components. In examining the integrity of the process, the benefits - apart from the above mentioned properties - are not only the reduction of the instrumentation times and costs, but the increased measurement accuracy. Because of the non-contact measurement procedure, the impact of the measurement on the vibration behavior of the component can be ruled out and the entire measurement sequence can be completed quickly in a few hours.

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