Gain Control of Strain

Optical Measurement of the Dynamic Strain Field of a Fan Blade Using a 3-D Scanning Vibrometer

“The 3-D Scanning Vibrometer certainly has the potential to accurately measure small (full-field) normal and shear strains at both low and high frequencies, where other optical techniques would definitely fail. Compared to strain gages, strains can be measured up to one order of magnitude smaller.”

Introduction

A primary goal in many studies of structural dynamics is to identify the locations on a structure at which failures are most likely to occur. Fatigue damage is caused by fluctuating strain. It is therefore very desirable to identify the locations of maximum strain. To ensure dynamic and fatigue strength, it’s also necessary to measure the distribution of dynamic strain on these structures. Furthermore, it is essential to obtain an accurate and full-field strain distribution when using experimental data to verify and update a finite element (FE) model.

One of most basic methods to measure strain is using strain gages. There are a lot of drawbacks to this method. The strain gage is fixed to one location, and in small, lightweight structures the strain gages and their connecting cables create an additional mass-loading effect and added damping. Determining the exact position of the strain gage on the test surface can be another difficulty, since the strain maxima in real components can deviate from the model-predicted locations due to, for example, manufacturing variations and tolerances. Without the guidance of an FE model it is very difficult to ensure that you have identified the precise location of maximum strain because it is not practical to use a large number of strain gages.

Many optical methods were developed in the search for a better strain measurement technique. Scanning Laser Doppler Vibrometry (SLDV), a non-contact optical method with high spatial and vibration resolution that has been in use since the 1990s, was recently enhanced for 3-D measurements, resolving the vibration into the out-of-plane and in-plane components.

Theoretical Background

Using one SLDV, only the transverse displacement w of a vibrating plate can be measured correctly. According to small deformation theory, the strain components in a plate due to bending are given by

$$\epsilon_{xx}(x, y, t) = -z\,\frac{\partial^2 w(x, y, t)}{\partial x^2}$$

$$\epsilon_{xy}(x, y, t) = -z\,\frac{\partial^2 w(x, y, t)}{\partial x \partial y}$$

$$\epsilon_{yy}(x, y, t) = -z\,\frac{\partial^2 w(x, y, t)}{\partial y^2}$$

with z the transverse distance relative to the center of the plate, $w(x, y, t)$ the transverse displacement, x and y the coordinates of a point along the surface of the plate and t the time.

On the other hand, strain at the surface of a structure is equal to the spatial derivative of the in-plane surface displacement. Surface strains are often of major concern because they are typically greater than internal strains and thus are more likely to lead to failures. The in-plane displacements can only be measured using the 3-D Scanning Vibrometer.

Experimental Setup and Measurement

An aluminum fan blade was selected as a test component, which came from the fan assembly shown in Fig. 1. The part was particularly interesting because of its 3-D curvatures, small size, low weight, high resonant frequencies and expected small strains. A second fan blade was equipped with strain gages, and both blades were mounted on a shaker and placed in front of the PSV-400-3D Scanning Vibrometer (Fig. 2).

The measurement grid was created using Polytec's PSV software. Alternatively it could also be imported from an FE model. The coordinates of three points from the FE model were used in the PSV software to compare the results from the measurement and the FE model (same global coordinate system). The next step was to perform a precise measurement of the coordinates of all grid points using the Geometry Scan Unit and Video Triangulation feature of the PSV software.

During the measurement with the Scanning Vibrometer, a frequency sweep was executed in order to obtain a frequency spectrum of the fan blade without strain gages, as shown in Fig. 3. The resonant frequencies were identified by selecting the peaks in the frequency spectrum, visualizing the corresponding mode shapes and comparing them with the FE model.

The strain measurements were then executed at these resonant frequencies using a sine excitation at different vibration levels. The signals were generated using Polytec's on-board waveform generator and externally amplified. Using the attenuator button it was very easy to obtain vibration levels of 0 dB (10 V), -20 dB and -40 dB.

The effect of these strain gages can clearly be seen in Fig. 4, which shows the frequency sweep measurement of the fan blade with strain gages attached. It is clear that some resonant frequencies are shifted and that the amplitude of the associated peaks is reduced due to the added damping. In particular, the peak round 2 kHz has almost completely disappeared. This shows how important a non-contact (optical) method can be for small size structures. Using only strain gages it would be almost impossible to find all of the resonant frequencies and the correct (maximum) strains.

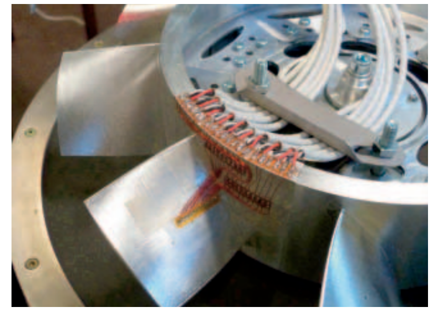

Fig. 1: Fan blade with strain gages in complete fan.

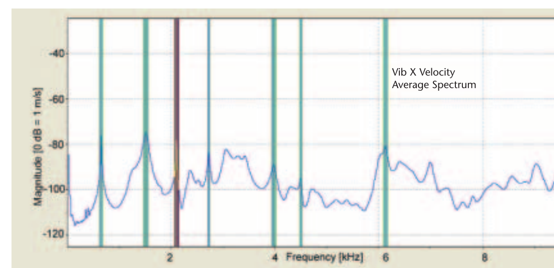

Fig. 3: Frequency spectrum of the fan blade without strain gages.

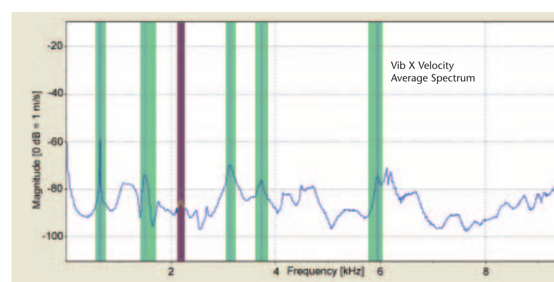

Fig. 4: Frequency spectrum of the fan blade with 10 strain gages.

Model Validation

In this section the experimental results of both the 3-D Scanning Vibrometer and strain gages are compared with an FE model.

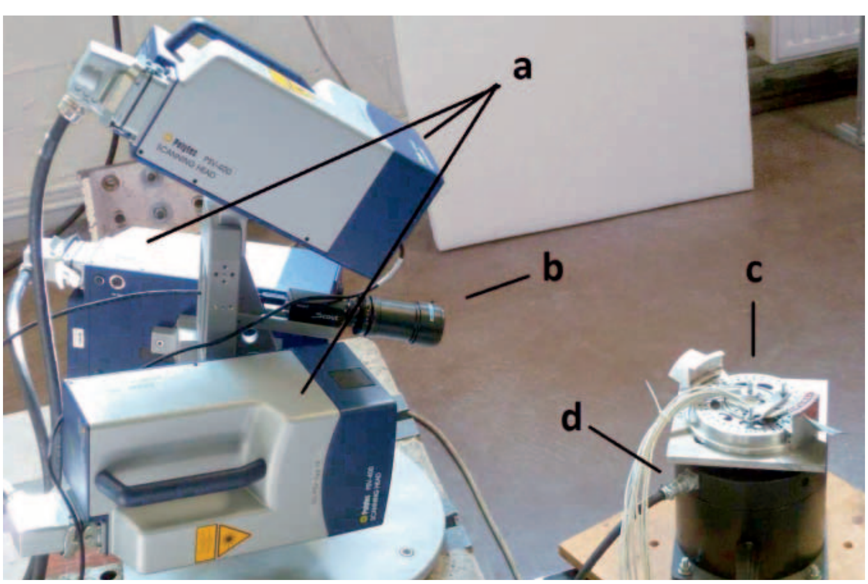

Fig. 2: Measurement setup: (a) PSV-400 scanning heads; (b) video camera; (c) fan blades mounted on (d) shaker.

After the measurements, the FE model was updated to obtain similar resonant frequencies. The resonant frequencies obtained by the FE model and 3D-SLDV are shown in Table 1. It's clear that attaching strain gages has a large influence on the (higher) resonant frequencies. Since the mode shapes of the FEM match the mode shapes measured with the Vibrometer, the differences between the resonant frequencies were not relevant, so no more effort was put into further updating (the boundary conditions of) the FE model.

Comparison of Strain Results

This section shows the strain distributions obtained from the 3-D Scanning Vibrometer measurements compared to the FEM results. In addition, the full paper features a comparison between the 3-D Scanning Vibrometer, FE model and strain gages using slices at the location of the strain gages (not shown here). As Fig. 5 shows, there is an excellent agreement in the normal strain between the FE model and the vibrometer. Only the measurement of the normal strain perpendicular to the curved surface (X-direction) shows more deviation. Additional investigations show that it is even possible to obtain satisfying results for the shear strain. The agreement for the shear strain in the XY-plane is slightly worse than for the other planes, but still satisfactory.

	FE Model	3-D Scanning Vibrometer			
		Blade without gages		Blade with gages	
#	f [Hz]	f [Hz]	Rel. diff. [%]	f [Hz]	Rel. diff. [%]
1	650	650	0	650	0
2	2,015	2100	4	2188	9
3	3,082	2725	–12	2725	–12
4	4,183	3975	–5	3725	–11
5	5,865	6138	5	5950	1

Table 1: Comparison of the resonant frequencies.

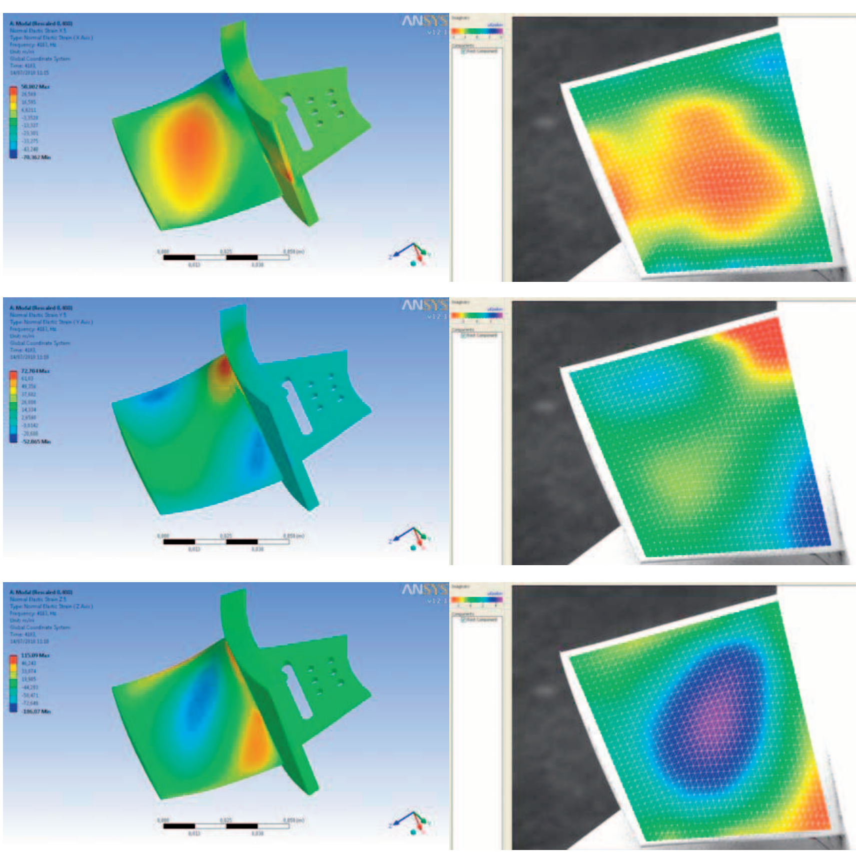

Fig. 5: Normal strain at 3975 Hz. Left: FE model; right: vibrometer results; top: X-axis; middle: Y-axis; bottom: Z-axis.

Conclusions

This investigation demonstrates that it is possible to obtain reliable dynamic surface strains from 3-D displacement data obtained with a 3-D Scanning Vibrometer. Shear strains as well as the normal strains can be measured accurately, as shown, by comparing the vibrometer measurement results with both a finite element model and strain gage measurements. It was proven that the dynamic behavior of the structure is changed by attaching strain gages to a fan blade. Some resonant frequencies were shifted and the peaks were greatly reduced at certain resonant frequencies. Non-contact measurements clearly do not exhibit these disadvantages. Moreover it was shown that the sensitivity of the vibrometer is much higher than strain gages. Strains can be measured up to one order of magnitude smaller compared to strain gages. The 3-D Scanning Vibrometer certainly has the potential to accurately measure small (full-field) normal and shear strains at both low and high frequencies, where other optical techniques would definitely fail.

Authors · Contact
Ing. Cedric Vuye[1,2],
cedric.vuye@artesis.be,
Prof. Dr. Steve Vanlanduit[2]
steve.vanlanduit@vub.ac.be,
Dr. Ir. Flavio Presezniak[2],
Prof. Dr. Ir. Gunter Steenackers[2] and
Prof. Dr. Ir. Patrick Guillaume[2]

[1] Artesis Hogeschool Antwerpen,
[2] Acoustics and Vibration Research Group, Dept. of Mechanical Engineering, Vrije Universiteit Brussels, Belgium

Reprinted from Optics and Lasers in Engineering, C. Vuye, S. Vanlanduit, F. Presezniak, G. Steenackers and P. Guillaume, Optical measurement of the dynamic strain field of a fan blade using a 3-D scanning vibrometer, 2011 **http://dx.doi.org/10.1016/j.optlaseng.2011.01.021** with permission from Elsevier.