Mechanical Systems and Signal Processing 25 (2011) 344–359

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/jnlabr/ymssp

# Eulerian laser Doppler vibrometry: Online blade damage identification on a multi-blade test rotor

A.J. Oberholster, P.S. Heyns *

*Dynamic Systems Group, Department of Mechanical and Aeronautical Engineering, University of Pretoria, Pretoria 0002, South Africa*

ARTICLE INFO

*Article history:*
Received 20 June 2009
Received in revised form
10 March 2010
Accepted 13 March 2010
Available online 18 March 2010

*Keywords:*
Online blade condition monitoring
Eulerian laser Doppler vibrometry
Multi-blade rotor
Non-harmonic Fourier analysis
Time domain analysis
Artificial neural networks

ABSTRACT

Laser Doppler vibrometry enables the telemetry-free measurement of online turbomachinery blade vibration. Specifically, the Eulerian or fixed reference frame implementation of laser vibrometry provides a practical solution to the condition monitoring of rotating blades. The short data samples that are characteristic of this measurement approach do however negate the use of traditional frequency domain signal processing techniques. It is therefore necessary to employ techniques such as time domain analysis and non-harmonic Fourier analysis to obtain useful information from the blade vibration signatures. The latter analysis technique allows the calculation of phase angle trends which can be used as indicators of blade health deterioration, as has been shown in previous work for a single-blade rotor.

This article presents the results from tests conducted on a five-blade axial-flow test rotor at different rotor speeds and measurement positions. With the aid of artificial neural networks, it is demonstrated that the parameters obtained from non-harmonic Fourier analysis and time domain signal processing on Eulerian laser Doppler vibrometry signals can successfully be used to identify and quantify blade damage from among healthy blades. It is also shown that the natural frequencies of individual blades can be approximated from the Eulerian signatures recorded during rotor run-up and run-down.



## 1. Introduction

Laser Doppler vibrometry allows the measurement of vibration on rotating blades in a non-contact fashion, thus eliminating the need for telemetry. Blade vibration data can be measured in a rotating (i.e. Lagrangian) reference frame or a stationary (i.e. Eulerian) reference frame. The first approach is better known as tracking laser Doppler vibrometry (TLDV) and involves controlling the laser beam orientation in order to follow a specific point on a blade during rotation. This technique requires line-of-sight with the blade over a significant rotation angle, making it impractical for use on most industrial rotors because of the presence of stator vanes and rotor casings. Eulerian laser Doppler vibrometry (ELDV) is a more practical approach since the laser beam is focused at a fixed point in space while the blades under consideration sweep through the laser beam. Vibration data is therefore available for the short periods during which each blade is exposed to the laser beam. It is the short duration of these signals that poses the main challenge associated with their signal processing, as useful results are not obtainable with the traditional frequency domain techniques.

Although there is little literature available on this subject, the application of ELDV to rotating blades has been studied since the late 1960s. Kulczyk and Davis [1] developed a laser vibrometer for this application and also noted the challenges

* Corresponding author. Tel.: +27 12 420 2432; fax: +27 12 362 5087.
*E-mail address:* stephan.heyns@up.ac.za (P.S. Heyns).

0888-3270/$ - see front matter 
doi:10.1016/j.ymssp.2010.03.007

**Nomenclature**

| | |
|---|---|
| $A$, $B$ | ELDV measurement position |
| $b$ | Blade number |
| $D$ | Damage level |
| $F$ | Simulated nozzle impulse force |
| $f$ | MAUPAT reference frequency |
| $k$ | Pressure waveform normalization factor |
| max | Maximum |
| $P$ | Pressure pulse waveform |
| $q$ | Peak number index |
| $R$ | MAUPAT reference frequency index |
| $t$ | Time |
| $v_L$ | TLDV velocity signature |
| $\delta$ | Rotor order number offset constant |
| $\overline{\varepsilon}$ | Vector of rotor order numbers at RMS peaks |
| $\overline{\lambda}$ | $\overline{\varpi}$ correction vector |
| $\theta$ | Rotor angle |
| $\sigma_{CORR}$ | Correlation coefficient standard deviation |
| $\sigma_{MAUPAT}$ | MAUPAT standard deviation |
| $\tilde{\sigma}_{MAUPAT}$ | Average of $\sigma_{MAUPAT}$ trends over different $f_R$s |
| $\sigma_{RMS}$ | RMS standard deviation |
| $\Omega$ | Rotational frequency |
| $\overline{\varpi}$ | Estimate $\omega_1$ vector |
| $\omega_1$ | First blade bending mode natural frequency |
| $\omega_{1,est}$ | $\omega_1$ estimate |
| $\overline{\psi}$ | Rotational frequency vector |

involved with the short sample periods. They showed that ELDV samples could be analyzed for individual blade vibration frequencies above the signal fundamental frequency, and concluded that lower frequency information was more likely to represent the global response of the blades. Kulczyk and Davis [2] subsequently performed ELDV measurements on rotor blades spinning at 13,000 rpm, proving the high-speed implementation capabilities of the technique. Further work ([3,4]) was aimed at performing signal processing on individual ELDV signatures, focusing on analytically estimating low-order blade vibration frequencies. Both approaches considered pure sinusoidal blade excitation only.

Using non-harmonic Fourier analysis (NHFA), Oberholster and Heyns [5] showed that a change in the NHFA phase angle at a reference frequency is indicative of a signal frequency shift and/or a signal phase shift. Based on these findings, Oberholster and Heyns [6] implemented NHFA on a single-blade axial-flow test rotor at 720 rpm, using impulse excitation. By monitoring the phase angle trends at various blade natural frequencies, they were able to observe deterioration in blade health from ELDV measurements. In particular they showed that maximum absolute unwrapped phase angle trends (MAUPATs) over bands around the various reference frequencies provide robust indicators of blade health deterioration. They noted however that they did not isolate the signal components as suggested by Hirata [7] because the signals were too short to accomplish this [8]. Therefore the blade health deterioration indicators they obtained were influenced by signal changes over the entire frequency bandwidth of their measurements.

This article extends the work of Oberholster and Heyns [6] to a multi-blade test rotor to verify the ability of their technique to identify damaged blades from among healthy blades. When considering a multi-blade rotor, it becomes necessary to take into account the effects of global blade vibration modes since damage on one blade affects the dynamics of the remaining blades and *vice versa*. As a result, trends may be identified from the undamaged blades which in turn may lead to the erroneous identification of damaged blades. A robust signal processing approach that accurately indicates blade damage is therefore required.

The first section of this article focuses on the experimental test setup and testing procedure. The procedure was done in two separate phases to consider damage on a single blade and damage on multiple blades consecutively. The effects on the blade-forcing frequency spectrum by blade-spacing variation due to manufacturing tolerances are studied and it is shown that these effects have to be taken into account during simulations using a finite element model (FEM).

During experimental testing, high response levels were observed in both TLDV and ELDV measurements at certain damage cases and rotor speeds, similar to those reported by Oberholster and Heyns [6]. To investigate this phenomenon, an FEM of the test rotor was constructed and subsequently the root-mean-square (RMS) values of the measurements were shown to be promising indicators of blade health.

The results obtained from signal processing on the experimental ELDV measurements at various rotor speeds ranging from 720 to 1440 rpm, are discussed in the next section. It is shown that the statistical trend properties of MAUPATs as well as RMS and correlation coefficient trends are useful parameters for identifying damaged blades and monitoring the degradation in these blades. In addition, multiple ELDV measurement positions are demonstrated to be advantageous to achieving robust results. After the training of artificial neural networks (ANNs) with these parameters, it is proven that ELDV measurements can be used to accurately identify and quantify blade damage from among healthy blades.

Finally, it is verified experimentally that the first natural frequency of the individual blades can be accurately estimated from the run-up and run-down ELDV measurements.

## 2. Test setup

Fig. 1 shows the axial-flow test rotor considered in this article. The test rotor consisted of five straight, flat blades and was driven directly by a speed-controlled motor at speeds of 720, 960, 1200 and 1440 rpm during testing. The 2 mm thick blades were attached to the rotor hub by means of clamps and had lengths and widths of 110 and 25 mm, respectively. Due