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Rotating blade vibration analysis using photogrammetry and tracking laser Doppler vibrometry

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A B S T R A C T

Online structural dynamic analysis of turbomachinery blades is conventionally done using contact techniques such as strain gauges for the collection of data. To transfer the captured data from the sensor to the data logging system, installation of telemetry systems is required. This is usually complicated, time consuming and may introduce electrical noise into the data. In addition, contact techniques are intrusive by definition and can introduce significant local mass loading. This affects the integrity of the captured measurements.

Advances in technology now allow for the use of optical non-contact methods to analyse the dynamics of rotating structures. These include photogrammetry and tracking laser Doppler vibrometry (TLDV). Various investigations to establish the integrity of photogrammetry measurements for rotating structures involved a comparison to data captured using accelerometers. Discrepancies that were noticed were attributed to the intrusive nature of the contact measurement technique. As an extended investigation, the presented work focuses on the validation of photogrammetry applied to online turbomachinery blade measurements, using TLDV measurements.

Through a frequency based characterisation approach of the dynamics of the two scanning mirrors inside the scanning head of a scanning laser Doppler vibrometer (SLDV), TLDV is employed in developing a system that can be used to achieve a perfect circular scan with a Polytec SLDV, (PSV 300). Photogrammetry out-of-plane displacements of a laser dot focused on a specific point on a rotating blade are compared to displacements captured by the laser scanning system. It is shown that there is good correlation between the two measurement techniques when applied to rotating structures, both in the time and frequency domains. The presence of slight discrepancies between the two techniques after elimination of accelerometer based errors illustrated that the optical system noise floor of photogrammetry does contribute to inconsistencies between photogrammetry and other measurement techniques.

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Nomenclature

A	Area
C_c	Circularity constant
d_s	Scanning mirror separation distance
r_s	Scanning path radius
t	Time
T_{delay}	Time delay
T_{exp}	Exposure time
T_{int}	Inter-frame time
T_{trig}	Trigger time
$\theta_{sx}(t)$	X-mirror scanning angle
$\theta_{sy}(t)$	Y-mirror scanning angle
ϕ_s	Initial phase
φ_{sx}	X-mirror amplitude
φ_{sy}	Y-mirror amplitude
ω	Scanning rotational frequency
Ω_s	Target rotational frequency

Abbreviations

3DPT	3 Dimensional Point Tracking
DIC	Digital Image Correlation
FEA	Finite Element Analysis
FOV	Field Of View
FPS	Frames Per Second
LDV	Laser Doppler Vibrometry
MAC	Modal Assurance Criterion
ODS	Operational Deflection Shape
SNR	Signal-to-Noise Ratio
STLDV	Self Tracking Laser Doppler Vibrometry
TLDV	Tracking Laser Doppler Vibrometry

1. Introduction

1.1. Turbomachinery vibration measurement

Whilst various techniques such as monitoring the curing process of turbine blades [1] are being employed to improve the quality of manufactured blades, understanding online turbomachinery blade vibrations still remains a matter of great practical importance in the continuous assessment of the condition of rotating structures. This is essentially important for condition monitoring purposes and remaining useful life estimation.

Various measurement techniques can be employed to capture the blade vibration information. Conventionally, contact systems which involve the use of accelerometers and strain gauges are used. These are physically attached to the blades under investigation, and telemetry systems are then used to transfer the measured signals from the transducers to the data logging systems. Even though measurement procedures using these transducers are well established, contact techniques present a number of drawbacks especially when it comes to rotating structures. They are point-wise in nature and only specific blade locations, on a limited number of blades, can be instrumented [2]. Thus vibration response measurements on all blades cannot be captured simultaneously. Being contact in nature, the instrumentation also influences the dynamic behaviour of the system under investigation, leading to inaccurate measurements. Depending on the material properties of the turbomachine, mass loading effects and local stiffness alterations at the point of transducer attachment can both be sources of errors in captured measurements. The telemetry systems used with these contact techniques are not only costly and time consuming to install [2], but they can also contribute to the electrical noise in the signals from the transducers.

Blade tip timing [2–4] and casing pressure measurements [5] have been employed as non-contact techniques for blade vibration analysis. These techniques are more reliable than contact techniques in terms of life expectancy under the very hostile conditions of high temperatures and pressures under which turbine blades operate [2]. However, they are based on very limited information essentially obtained in the region of the blade tips only, and are subject to potentially large faults in the interpretation of the measured results.

Optical non-contact techniques that allow extraction of vibrational information over the entire blade surface have been proposed. These include laser Doppler vibrometry (LDV) and photogrammetry. In addition to being non-intrusive, these techniques are capable of simultaneously capturing full-field measurements in more than a single degree of freedom (photogrammetry in this case). These techniques are not as well established as the contact techniques, thus there is a need for detailed laboratory investigations to validate them. Superior approaches that can provide deeper physical insight into the nature of blade vibrations of online systems can then be developed for improved condition monitoring practices.

The work presented here uses LDV to validate a form of photogrammetry (3-dimensional point tracking, 3DPT). Good correlation between the two optical non-contact measurement techniques is demonstrated.

1.2. Optical non-contact vibration analysis techniques

1.2.1. Photogrammetry

Photogrammetry is a non-contact full-field measurement technique in which a pair of digital cameras is used to synchronously capture a series of images of the structure under examination. By positioning the two cameras at a known distance from each other, stereo photographs of the object can be obtained which, when viewed together, provide a 3D representation of the object. In the captured image sequence, correlation algorithms are used to track a specific pixel with a

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