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Low-coherence interferometry based roughness measurement on turbine blade surfaces using wavelet analysis

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ABSTRACT

In this paper, a non-contact optical system, a low-coherence interferometer (LCI), is introduced for the purpose of measuring the surface roughness of turbine blades. The designed system not only possesses a high vertical resolution and is able to acquire the roughness topography, but also it has a large vertical scanning range compared to other commonly used optical systems. The latter characteristic allows us to measure turbine blades surfaces with large curvature without collisions between the lens and the measurement object. After obtaining the surface topography, wavelet analysis is applied to decompose the original surface into multiple bandwidths to conduct a multiscale analysis. The results show that the developed LCI system proofs a good performance not only in obtaining the surface topography in the roughness scale but also in being able to measure surfaces of objects that possess a complex geometry in a large vertical range. Furthermore, the applied biorthogonal wavelet in this study has performed good amplitude and phase properties in extracting the roughness microstructures from the whole surface. Finally, the traditional roughness parameters, such as the mean surface roughness S_a and the Root Mean Square (RMS) roughness S_q, are evaluated in each decomposed subband and their correlations with the scale of each subband are analyzed.

1. Introduction

Roughness measurement plays an essential role in today's aerospace industry. The assessment of the surface roughness of jet engines components is a prerequisite for Computational Fluid Dynamics (CFD) and for the optimization of the aerodynamic performance. Many previous studies and experiments have been reported relating to the various functions of surface roughness in turbine machines. Mulleners investigated the impact of surface roughness on a turbulent blade wake [1]. Hohenstein studied the relationship between the surface roughness and its influence of the turbine efficiency [2]. Zhang simulated the aerodynamic losses by the suction surface of a turbine airfoil to research the effects of surface roughness [3]. Bons gave a review of surface roughness effects in gas turbines based on publications in the open literature over the past 60 years [4]. In order to acquire the microscopic surface topography precisely, optical non-contact measurement systems are usually applied, such as confocal laser scanning microscopes, focus variation instruments and vertical scanning interferometry (VSI) [5–8]. However, jet engines' components like turbine blades and blisks (blade integrated disks), as shown in Fig. 1, often have a complex geometry and small structure space, where common optical microscopes have difficulties to reach into them (e.g. between two blades components in Fig. 1) and obtain a large spatial range. For this reason, a compact low coherence Michelson interferometer (LCI) with a long working distance is developed specifically for measuring the surface roughness on complex turbine blades.

Furthermore, a comprehensive and accurate evaluation of roughness after obtaining the surface topography is crucial to functional performance and quality control. The turbine blade's surface has multi-scalar characteristics and consists of three different scales: roughness, waviness and form. Roughness refers to the short-wavelength component with high spatial frequency, which is inevitably produced by machining process or cutting tool in a form of irregular marks; waviness is usually caused by undesired machining process e.g. by an unbalanced grinding wheel, where medium long wavelength marks are generated in a periodic form. Form is the general geometry of the object with the largest wavelength, ignoring variations due to roughness and waviness. Normally, the three scales are superimposed together on the turbine blades surface. A careful separation is important for the further characterization. In last decades, a number of works haven been done relating to this topic. In earlier days, analog 2RC filters [9–11] were applied to decompose a signal to multiple scales. However, the 2RC filter suffers from phase distortion, and it

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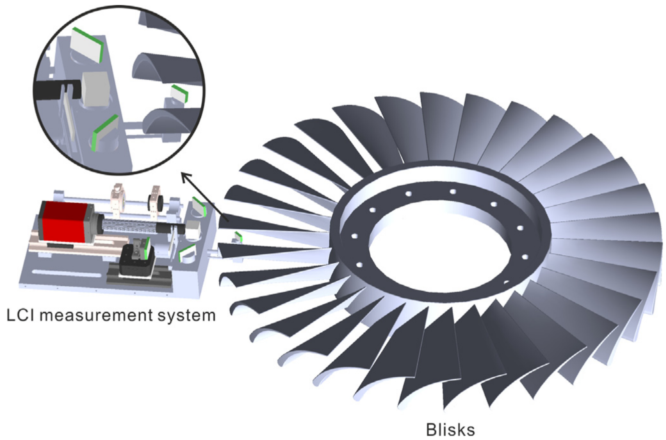

Fig. 1. Surface measurement of a compressor blisk between blades using the LCI system.

was later replaced by Gaussian filters. The most important properties of the Gaussian filter are the linear phase characteristics and the 50% transmission at the cutoff wavelength. As a result, it has been widespread in the practical implementation until today because of its easier applicability. However, Gaussian filters also suffer from some limitations, such as the edge distortion and inability to deal with large pits and peaks [12,13]. Moreover, the spatial information or the location is lost when Gaussian filter is applied in frequency domain by using Fourier transform. Although short-time Fourier transform was introduce to attempt to give both spatial and frequency information, the decomposed resolution, however, depends on the window size.

In recent years, wavelet analysis is developed to overcome the problems mentioned above, aiming to provide not only the frequency information but also the spatial information. In addition, it also offers the possibility to reconstruct the surface features, such as larger peaks, pits, valleys, more accurately and more naturally. Considering these merits, wavelet analysis has been gradually developed and applied to surface characterization [14–19]. In more practical terms, Liao applied biorthogonal wavelets to conduct a fast defect detection, such as dirt, scratch or 2D blemish on the surface [20]; Yuan et al. utilized orthogonal Daubechies wavelets to extract the surface roughness of wear particles [21]; Jiang et al. proposed the lifting wavelet representation in order to extract surface morphological features more precisely [22,23]. However, only few studies and applications of wavelet analysis on turbine blade surfaces have been reported in the literature. As already stated at the beginning, the short-wavelength features (roughness) of turbine blade surfaces play an important role in many functional performances. For this reason, an accurate extraction of roughness from the complex turbine blade surface is necessary and essential to the further assessment of numerical parameters.

The motivation of this study is to develop a LCI measurement system, which is able to measure the roughness of the turbine surface precisely. Afterwards, the wavelet analysis is introduced to process with the obtained measurement data for the purpose of decomposing the complex surface into multiple scales. Meanwhile, the numerical roughness parameters are evaluated based on multiscale analysis.

2. Development of a low-coherence interferometer

VSIs can be often divided into two categories: white light interferometers (WLIs), using white light source and low coherence interferometers (LCIs), using low coherence light source. Both of them are established techniques for the inspection and characterization of surface features [24]. As previously stated, the LCIs have the advantage of long working distance and are able to measure the complex surface geometry. The design and development of such a LCI measurement system in our work is based on a Michelson configuration, which utilizes a low-coherence deep red power LED as the light source, as shown in Fig. 2.

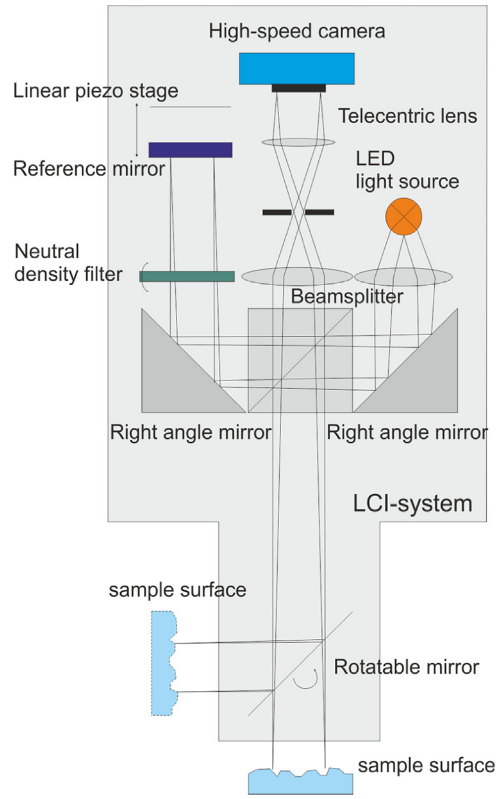

Fig. 2. The experimental setup of a LCI based on a conventional Michelson configuration.

The light source has a mean wavelength of 640 nm and a spectral bandwidth of 25 nm. The beam emitted by the light source is split into two beams using a 50/50 beam splitter. 50% of the beam is transmitted to a planar mirror at the reference arm (RA), and the other 50% of the beam is reflected to the measured sample at the measurement arm (MA). Because the intensity of the reflected beam from the RA is much higher than the beam from the MA, a variable neutral density filter positioned in front of the reference mirror is used to increase the contrast of the interference pattern. At the MA, a spring-damping arm carries a rotatable mirror to allow parallel or orthogonal measurement to the optical axis. Moreover, the spring-damping system can prevent damages from collision. The two 45° mirrors at the optical paths of the RA and the MA are used to decrease the width of the LCI. Consequently, it is well suited to measure in the small space between the neighboring blades.

The length of the RA is linearly changed by a piezo stage during scanning, which drives the RA in a nanometer-level step. Thus, interference patterns are produced by the changing the optical path difference (OPD) between the RA and the MA. These are later recorded by a high-speed CCD camera with telecentric lens in a data stack. Each pixel of the camera in the data stack corresponds to an interferogram (see Fig. 3). The discrete sampled intensity value of the interferogram is evaluated with the Hilbert transform (HT) to identify the central fringe position of these interferograms as shown in Fig. 4. Afterwards, the relative surface height of each pixel can be determined by using the obtained position.