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Research Paper

A system for accurate measuring of thermal-structure displacement on a high speed rotating turbine disk by using digital image correlation technology

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HIGHLIGHTS

- A noncontact rotational thermal-structure deformation measurement system is build.
- The digital image correlation (DIC-2D) technology is used.
- The synchronisation and rotational motion blur correction are key technologies.
- The system can accurately measure in-plane thermal-structure deformation.
- The influence from windage heating effect should be considered in test.

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ABSTRACT

A non-contact rotational thermal-structure deformation measurement system based on digital image correlation (DIC-2D) technology was proposed and established to measure in-plane thermal-structure deformation on a high speed rotating disk accurately. Digital images can be captured at a constant rotor azimuth by applying a precise synchronisation strategy to coordinate the operating frequency and internal delays of a camera and a stroboscope. The relationship between false radial displacement and rotational motion blur (*RMB*) was quantified through a series of baseline tests. Firstly, the deformation of a disk was investigated by theoretical analysis considering windage heating and transient thermal loading effects to obtain the baseline for verification. Then, a flat metal disk was tested with windage heating effect to analyse the accuracy at rotational speeds that range from 3000 rpm to 6000 rpm. The model was also tested with three different thermal loading conditions at a fixed rotational speed of 3800 rpm to validate the reliability of the model. The comparison results revealed that the proposed system can accurately and reliably measure in-plane thermal structure deformation of a rotating disk with a tangential velocity of up to 200 m/s, and the maximum deviation was less than 15% at 3800 rpm.

1. Introduction

As one of the core parts of a gas turbine engine, the turbine disk operates under severe and complex centrifugal and thermal loading conditions. Thus, materials progressively deteriorate because of the accumulation of fatigue and thermal creep damage, and, in general, turbine disk failure is likely to cause a hazardous engine effect [1]. In order to maintain the structural integrity of a turbine disk, various stress analysis techniques were developed to determine the stress–strain distribution of each life-limited component. However, these techniques must be initially validated by basic experiments [2] to identify effective approaches. Researchers employed strain gauges, which are adhered to the surface of a rotating test section, to measure surface deformation. The signals received from rotating sensors are transmitted to stationary facilities via slip rings [3] or by radio or wireless transmission [4]. However, this approach has limitations, i.e. time-consuming preparations, a poor signal-to-noise ratio and a low spatial resolution. Full-field non-contact optical methods [5] were recently developed to measure the motion or deformation of rotating objects and address the limitations of the previous approach.

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Nomenclature

a	substitution variable
b	substitution variable
C	a two-dimensional array
c_p	specific heat
E	Young's modulus of elasticity
E_n, F_n	coefficients of Eq. (7), $n = 1, 2, 3, \ldots$
f	working frequency of the rotor system
h	heat transfer coefficient
I	the image intensity of an interrogation window
J_0, J_1	zero-order and one-order Bessel function
k_d	thermal diffusivity
MOD_n	coefficient of Eq. (8), $n = 1, 2, 3, \ldots$
m	substitution variable
N_0, N_1	zero-order and one-order Neumann function
r	radial distance from the rotational axis
R	dimensionless radius
R_n	coefficient of Eq. (7), $n = 1, 2, 3, \ldots$
RMB	rotational motion blur
Re_Φ	rotational Reynolds number ($\rho_{\text{air}}\Omega r_{\text{outer}}^2/\mu_{\text{air}}$)
T	temperature
t	time
t_{exp}	exposure time
u	disk displacement
v	velocity
x	coordinate direction
y	coordinate direction
α	coefficient of thermal expansion
δ	thickness of disk
λ	thermal conductivity
μ	viscosity of the fluid
ρ	mass density
σ	stress
υ	Poisson's ratio
ω	angular speed
Ω	rotational speed

Subscripts

air	the fluid around a disk
eq	equivalent stress
exp	exposure
false	false
heat	windage heating effect
inner	station at the central hole of a disk
max	maximum
n	1, 2, 3, ...
origin	origin
outer	rim of a disk
thermal loading	thermal loading heating effect
r	radial direction
z	axial direction
θ	circumferential direction

1.1. Interferometric techniques

Pulsed digital holographic interferometry was applied to measure rotating objects dynamically by following two methods. The first method uses an on-axis illumination optical derotator to eliminate the rotation fringes of an object [6], whereas the second approach employs pulsed lasers to freeze the motion of an object between the acquisition of the two digital holograms [7]. Electronic speckle pattern interferometry (ESPI) was combined with a pulsed laser to measure the increase in in-plane temperature rise and/or centrifugal-force-induced displacements of a disk with tangential velocities, υ_θ, of up to 300 m/s [8,9]. This interferometry technique, which uses two laser pulses that illuminate the object along the rotating axis, was set to be sensitive to out-of-plane rigid-body displacement [10]. This approach was applied to measure rotating objects by separating rotating fringes from fringes that were solely related to vibration. Speckle shearing interferometry, which is regarded as an advanced approach, was adopted to measure surface strains from a test object that was rotating and thermally loaded [11]. This method measured the changes in the displacement gradient rather than displacement under an applied load [12]. Projection moiré interferometry (PMI) was employed to characterise the vibrations of a NASA active twist rotor blade [13]. PMI relies on the projection of an equally spaced grid on the model surface. The deformed grid images are supposed on the computer-generated reference grid so that the moiré fringe formation can be calculated.

1.2. Digital image correlation (DIC) method

In 1982, Peters and Ranson [14] proposed the DIC method at the University of South Carolina. And in the last decade, the DIC technique was employed to investigate the characteristics of rotating objects. Helfrick et al. [15] used a pair of digital cameras with a stroboscope to capture the out-of-plane motion of rotating blades. However, the accuracy of this technique was not indicated. Sirohi and Lawson [16] investigated the deflection characteristics of reduced-scale rotating helicopter blades by employing DIC-3D technique. The technique was validated on a vibrating cantilever beam, and all of the data were within the experimental error bounds, which were specified by a laser displacement sensor. After conducting non-rotating validation, the collective pitch angle, which was measured by DIC, was correlated with that obtained by an inclinometer with an error of less than 6%. Schmidt et al. [17] introduced two applications on high-speed rotating components. One application uses short-duration white light pulses to analyse the 3D deformation of an automobile tyre on a road wheel (υ_θ, max = 80 m/s). The other application was an initial work in which the in-plane deformation of a composite flywheel (rotational speed, Ω, up to 35,000 rpm) was investigated under a pulsed laser. These applications demonstrated that measuring deformations on high-speed rotating components was feasible by employing pulsed illumination with short exposure time. However, limited quantitative results were presented in previous studies.

Interferometric techniques can achieve excellent deformation resolutions. However, these techniques require complex experimental cameras and illumination systems. Sensitivity to vibration is another concern. The fibre bundles used in these techniques require vibration isolation to prevent the possibility of phase changes within the bundles from destroying the fringe patterns. Thus, applying these methods in industries is difficult because images must be recorded on sustained rotational motions. In contrast to the interferometric optical method, the DIC method has unique advantages [18], such as simple implementation, easy specimen preparation, and low requirements in measurement environments for rotating components. The DIC technique was developed further in terms of measuring the deformation of rotating components. However, two issues, which significantly influence the accuracy of deformation measurements under high rotational speeds, must be investigated and discussed comprehensively. These issues