Optoelectronic-Strain-Measurement System
for Rotating Disks

by M.L. Simpson and D.E. Welch

ABSTRACT—A recently developed optical technique is presented in the following paper for measuring in-plane deformations and strains of rotating hardware. The technique is fully described. Data are presented which were obtained in preliminary tests using the system on a rotating disk. The experiments show that the system is capable of making radial-deformation measurements to within 9.5 μm over a 10-mm range.

Introduction

A technique is described in the following report for measuring dynamically and in real time, radial growth and strain due to the centrifugal stresses generated in rotating hardware. An accurate measurement of in-plane deformation and strains in high-speed rotating equipment, such as flywheels and turbomachinery, is essential for ensuring the hardware integrity and reliability. Alternative optical techniques for measuring in-plane deformations, such as speckle or holographic interferometry, involve complex alignment techniques and are highly sensitive to out-of-plane rigid-body translations (on the order of wavelengths). Therefore, these methods are difficult to apply to high-speed rotating equipment in real time. Strain-gage telemetry systems, on the other hand, are difficult to maintain in high-acceleration fields and tend to be extremely sensitive to the surrounding environment. The optoelectronic-strain-measurement system (OESM) described here has the advantages of using a noncontacting optical system without complex alignment and yet, like the telemetry system, provides a real-time electronic output, which may be recorded and processed using conventional data-processing techniques.

A block diagram of the experimental arrangement is shown in Fig. 1. The technique involves photoetching or painting a pattern (see Fig. 2) on the test hardware and monitoring changes in the pattern with a retroreflective optical probe whose sensor axis is perpendicular to the pattern. As the test piece rotates, the output of the optical probe fluctuates from a logic level '1' when the probe is positioned over the dark portion of the pattern to a logic level '0' when the probe is positioned over the light portion of the pattern, thus producing a series of pulses. As the part is subjected to higher centrifugal stresses, it begins to deform. The resulting deformation displaces the pattern. Because the optical probe is fixed, these deformations result in a change in the width of the pulses (duty cycle) generated by the probe. The pattern itself is designed such that the radial deformation is a linear function of changes in duty cycle.

The following paper describes the theory and application of the OESM system. A set of preliminary experiments is described in detail, in which the system was used to make measurements on a rotating disk. Finally, a discussion is presented which elaborates the potential development of this system.

Theory

Pattern Type

For a linear response, the angular width of the pattern should be linearly related to radial position. This shape is an Archimedean spiral of the form:

\[ \theta = a_r b \quad \text{or} \quad r = a' \theta + b' \]  

(1)

For sensing pattern width of a rotating part, two such spirals joined at a common point and of opposite sense are required, as shown in Fig. 2. As this pattern rotates past a fixed probe viewing normal to the plane and sensing the presence or absence of the pattern area, the angular width of the pattern sensed by the probe (duty cycle) is a direct indication of the radial position of the pattern relative to the probe.

Optimization of Pattern Parameters

Preliminary inspection shows that, with a single pattern or 'lobe', an offset between the center of the pattern and the center of rotation creates nonlinearities in the radial position versus observed duty cycle. The extent of this nonlinearity was investigated parametrically as a function of the pattern radial width/radius ratio, \( D/R \), the number of pattern lobes, and the extent and direction of the offset. Figure 2 represents a two-lobed spiral pattern which has been offset from the center of rotation by an amount, \( \phi \), and at an angle, \( \phi \), referred to the pattern axis. Using the terminology from this figure, the duty cycle observed by a fixed probe at a distance \( r' \) from the center of rotation viewing the offset pattern can be found by:

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\[ r'^2 = r'^2 + q^2 - 2qr \cos (\theta, -\phi) \]

which is the law of cosines and

\[ \theta'_1 = \frac{\pi}{2} \left[ 1 - \left( \frac{1 - r'/R}{D/R} \right) \right] \]

or the pattern equation. Then

\[ \left( \frac{r'_1}{R} \right)^2 - 2 \left( \frac{q'r'_1}{R} \right) \cos \left\{ \frac{\pi}{2} \left[ 1 - \left( \frac{1 - r'/D}{D/R} \right) \right] - \phi \right\} + \left( \frac{q}{R} \right)^2 - \left( \frac{r'_1}{R} \right) = 0 \]

Fig. 1—Block diagram of OESM experimental arrangement

Fig. 2—Two-lobed spiral pattern offset from the center of rotation

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