An Optical Technique for Measuring Vibratory Motion in Rotating Machinery

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A method to measure the frequency and amplitude of vibration in a rotating element is presented. Using optical interferometric techniques, the flexure and torsion of a gas turbine compressor blade is shown to be measurable over the entire 360 deg of rotation. Vibrations are shown to be measurable independent of blade rotation speed; the effects of misalignment in system are shown to be small. Angular deflections from 0.5 to 500 mrad were measured in the test system.

I. Introduction

MEASUREMENTS of vibratory and otherwise oscillating motions in rotating machinery have always presented problems. The motion under study is usually buried with other motions of much greater magnitude. Instruments requiring physical contacts often prove impractical at high rotational speeds because of problems introduced during information transfer to stationary recording devices.[1] This paper introduces an optical technique for measuring the vibratory motions in the rotating machine. This technique is demonstrated in a simple laboratory setup.

A particular application of interest is in connection with the compressor blades of a gas turbine. Flutter in the compressor blades ultimately limits the blade speed and, thus, the maximum fluid dynamic throughput of the compressor.[2,3] In order to understand the fluid mechanics of blade flutter, the actual motion of each blade must be studied. Although vibrational motion of a blade can be studied using a variety of techniques when the blade is at rest, monitoring of blade vibration while the compressor is turning several thousand rpm proves a much more formidable problem.

Because of the rotational motion of the compressor blades, diagnostic instrumentation requiring physical contact is practically precluded. A number of systems have been designed using optical sensing techniques.[4,5] These techniques, however, have been limited to looking at one spot in the rest frame and studying the position of compressor rotor blades as they come by this point. Thus, the deflection of a particular blade may be studied only once per revolution. Motion that may occur as a multiple of the rotating frequency is not detectable using these techniques. Other techniques, such as holography, have been tried in studying blade flutter. Although these techniques have yielded valuable information as to flutter modes, they suffer from the same problems of not being able to produce continuous information on blade vibration.

An interferometric technique is described in this paper. Two retroreflectors are used to relay flutter information from a rotating machine through an optical link to a stationary demodulator. Although laser interferometry is by no means a new technique,[5,6] its use always has required two separate beams of light directed onto a relatively stationary position. The mixed signals from the two moving retroreflectors provide an interference pattern at the source. Since light reflected from retroreflectors always returns to the source, vibration can be analyzed through the entire 360 deg of rotation.

The theory of operation of this vibration detection technique is discussed in the next section. This theoretical analysis is followed by an optical layout and an analysis of the return signal from a vibrating member. Finally, laboratory measurements are presented using a known vibrating system.

Theory of Operation

The operating concept of this laser detection technique is illustrated in Fig. 1. This system is entirely analogous to the Young two-source experiment.[7] Coherent laser light is spread such that it illuminates two retroreflectors at the same time. Since the property of retroreflectors is that they return light back to source, the returns from the two retroreflectors mix to form a pattern of fringes at the source. A beamsplitter is used so that the return light can be directed to a more convenient location. The spacing of the maxima of the fringe pattern is given by

$$S=\lambda R/s \tag{1}$$

where R is the range from the retroreflectors to the mixing plane, s is the distance between retroreflector centers, and λ is the wavelength of the laser light. The fringes are always aligned perpendicular to the direction of s. The return beams from the two retroreflectors are as from two point sources a distance R behind the retroreflectors and separated by $2s$. If either retroreflector moves toward or away from the mixing plane by a distance $\lambda/4$, the return beam is shifted by $\lambda/2$. The fringe pattern will shift by ½ the fringe separation, changing maxima to minima. Relative motion of one retroreflector with respect to the other retroreflector in the direction of the beam produces a moving fringe pattern at the mixing plane. An aperture is placed at the mixing plane that passes only a portion of one fringe through. Light passing through this aperture exhibits an intensity modulation as the fringe pattern moves across the mixing plane. As long as there is no relative motion between retroreflectors, the fringe pattern does not shift. Rotation of the system, along an axis that does not change the relative range, rotates the fringe pattern at the mixing plane but does not affect the fringe spacing or the intensity at the central fringe. By placing the aperture on the axis of rotation, only relative changes in distance of retroreflectors along the line of sight would cause an intensity modulation.

The fringe shift across the aperture in Fig. 1 can be analyzed as a deflection in the object carrying the two retroreflectors along an axis perpendicular to the line separating their centers. In fact, the velocity of the fringe

Received April 8, 1977.
Index categories: Testing, Flight and Ground; Research Facilities and Instrumentation.
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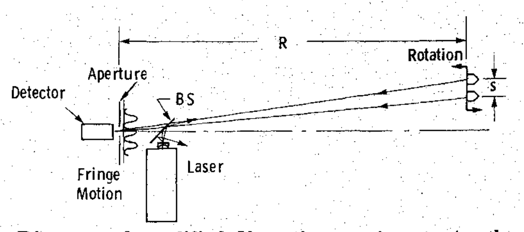

Fig. 1 Diagram of modified Young's experiment. As the plane carrying the retroreflectors is rotated in the direction shown, the fringe pattern must move downward, giving a varying intensity at the detector.

pattern across the mixing plane is equal to

$$v_M = 2R\dot{\theta} \tag{2}$$

where $\dot{\theta}$ is the angular velocity of the object holding the two retroreflectors. This fringe motion is equivalent to the motion of the two virtual sources located at 2 R. Combining Eq. (2) with Eq. (1), the frequency of intensity maxima passing through the aperture is

$$f = v_M / S = (2s\dot{\theta}/\lambda) \tag{3}$$

Thus, the frequency of light seen by a detector behind the aperture is a function only of the retroreflector separation and the angular rate of change along the axis separating the two retroreflectors. Although the frequency is independent of range, the fringe spacing at the mixing plane is proportional to range. It may be seen from Eq. (3) that the distance s is of particular importance in determining $\dot{\theta}$ for a measured frequency.

The intensity of the retroreflector returns at the detector is important in determining the size of laser needed. This intensity is limited to light contained in the area of the aperture. From Eq. (1), it may be seen that the diameter of the aperture, which has to be smaller than the fringe spacing S is proportional directly to the range and inversely to the retroreflector separation. It is, of course, assumed that this spacing is smaller than the diameter of the returned spot. This spot size is approximately twice the diameter of each retroreflector. Note that, provided that the diameter of each retroreflector is larger than one-half the fringe spacing at the mixing plane, further increases in reflector diameter only increase the number of fringes on the mixing plane and not the intensity within each fringe.

Optical Arrangement

The actual optical arrangement of the optical motion detector is shown in Fig. 2. A continuous wave argon ion laser is used to illuminate the entire face of the rotating machine, such as a compressor fan, to be studied. This is done by using a lens expander system, L_1 and L_2, to diverge the laser beam to approximately 60-cm diam, 5 m away. A pair of retroreflectors are placed on the rotating machine, either radially or tangentially, to measure the flexural or torsional modes of vibration, respectively. The retroreflected returns are brought back through lens L_2 and redirected through a beamsplitter (BS) onto aperture A. The aperture A is placed on the redirected optical axis at the location where the centerlines of the return beams, from both retroreflectors, cross.

The aperture A allows light from only the center fringe of the interference pattern formed on the face of the aperture to fall on the photomultiplier (PMT). In front of the PMT is placed a narrow band filter to allow only the light from one laser line to get into the PMT. Note that by filtering both at the retroreflectors and in front of the PMT, several pairs of retroreflectors, color coded to different colors of laser light, may be used at the same time. Thus, different modes of vibration on several blades of a compressor may be monitored simultaneously.

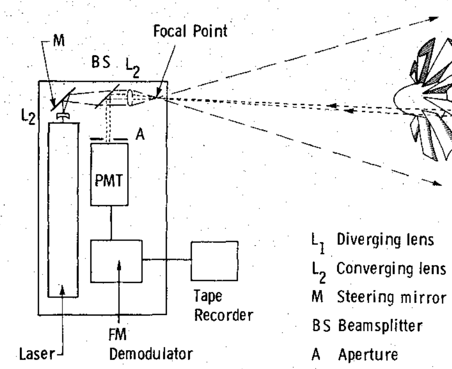

Fig. 2 Diagram of optical arrangement used to measure compressor blade flutter.

The signal at the PMT is an intensity-varying signal, which is a function of retroreflector motion along the line of sight. Since all of the desirable information is contained in the frequency modulation of the signal, intensity changes due to obstructions such as aerosols, temperature gradients, and laser power are of negligible effect on the information. The frequency information in the form of an alternating current from the PMT is converted by a frequency-to-voltage converter to give a vibration amplitude history of the vibrating blade. The frequency-to-voltage converter consists of a signal squaring circuit to remove amplitude modulation from the PMT signal, a monostable multivibrator to give a uniform voltage pulse for each zero crossing of the ac signal, and an op-amp integrator to convert the rate of zero crossings into a voltage.

Although the direction of the fringe pattern motion is proportional to the direction of rotation of the retroreflectors across s, this direction was not detected through the aperture. The directionality of the rotor blade flutter is, therefore, lost. Only the magnitude of the angular velocity along the line of sight is then measured using this technique.

The laser system is aligned carefully along the axis of the rotary machinery so that the plane of rotation is perpendicular to the optical axis. Angular misalignments would introduce a twice-per-revolution modulation to the return signal. A radial misalignment corresponds to a change in path length times the sine of the angle between the retroreflector return and the optical axis. Since both retroreflectors undergo the same distance change, the exact alignment of the laser system is not critical, and a misalignment of 1 cm would cause a 30-fringe shift, each revolution of the compressor blade. Since alignment can be made by rotating the blade slowly, the alignment error can be kept down to two or three fringes, corresponding to a few mils error.

Signal-to-Noise

The intensity of the interference fringe in Fig. 1 determines the size of the laser required. Even though the amplitude fluctuations in the return signal can be mostly filtered out in the demodulation electronics, it is important that sufficient photons are present on the face of the photomultiplier to show a clear fringe shift. The actual fringe pattern at aperture A in Fig. 2 is shown in Fig. 3. Light from the laser actually is allowed to focus at point F, a distance q from lens L_2, before spreading to illuminate the face of the compressor blade a distance R from point F. The return beams from the retroreflectors thus act like point sources, a distance $(2R+q)$ from lens L_2. The return spot size from each retroreflector is likewise $(2R+q)/R$ times the diameter of the retroreflectors. The centerlines of the return beams are separated by a distance $s(q/R)$ at lens L_2, and brought to coincide again at the mixing plane A. The return spot from each retroreflector, on the other hand, focuses at a distance f behind lens L_2, and rediverges to a spot approximately $2(p-f)/f$ times the retroreflector diameter.

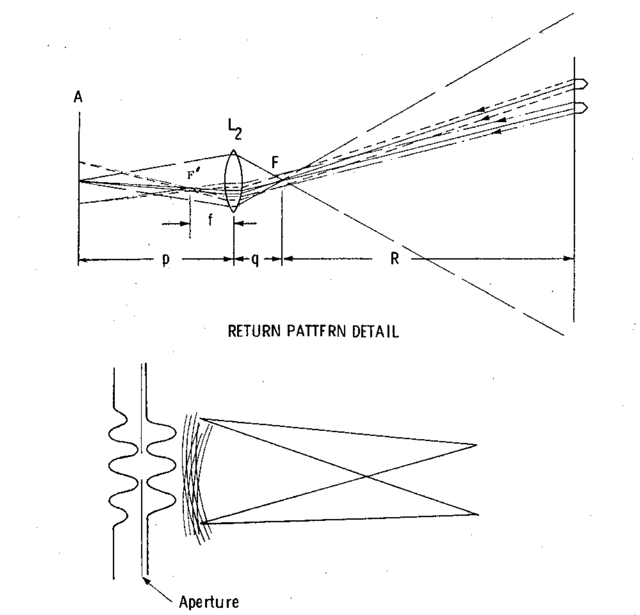

Fig. 3 Raytrace analysis of retroreflector return pattern at the aperture (mixing plane).

The fringe pattern at the mixing plane thus is due to two spherical waves, originating from point sources at location F'. The two point sources are separated by a distance fs/R. The fringe spacing at the mixing plane thus is given by the relation

$$S_A = [(p-f)/f][(q+2R)/2s]\lambda \qquad (4)$$

Note that this is the same relationship as Eq. (1), except for the factor $[(p-f)/f]$ $[(q+2R)/2R]$, to account for the focusing effects of lens L_2. The size of the spot formed by the return from each retroreflector also is modified by the lens. From Fig. 3, this diameter is

$$D_A = [(p-f)/f][(q+2R)/R]d_R \qquad (5)$$

where d_R is the diameter of the retroreflector. The diameter of the spot at the detector D_A again is modified by the focusing lens. In both Eqs. (4) and (5), the range R is assumed to be much larger than the focal point q.

The intensity of useful light at the detector plane is light contained in a circular spot, one fringe in diameter. The mean intensity in this region is given by

$$I = 2I_R\ \tau_0\ (S_A/D_A)^2 \qquad (6)$$

where I_R is the intensity flux from one retroreflector, and τ_0 transmission through the optical elements on the return pass. The intensity flux from each retroreflector is given by

$$I_R = (d_R/d_c)^2 P_L\ \tau_{\text{out}} R_R \qquad (7)$$

where P_L is the laser power, τ_{out} transmission fraction of the optical elements, R_R the reflectivity of the retroreflector whose diameter is d_R, and d_c is the diameter of the illuminated region. Combining Eqs. (4-7), the intensity on the photomultiplier is

$$I = (R^2\lambda^2\tau R_R/2d_c^2 s^2)P_L \qquad (8)$$

where τ is the transmission fraction both out and back through the lenses, beamsplitter, and narrow band optical filter.

In order to obtain frequency information from the return beam, sufficient photons must be present in each fringe to give contrast between intensity maxima and minima. Since frequencies as high as 10 MHz, corresponding to angular motions of 1000 rad/sec, must be detected, a minimum intensity criterion is given by

$$I_{\text{min}} = 2\pi\langle n\rangle h\nu f_{\text{max}} \qquad (9)$$

where f_{max} is the maximum frequency to be detected, $\langle n\rangle$ is the mean number of photoelectrons necessary to produce fringe contrast, and $h\nu$ is the energy of one photon. At the 5145A green line of the argon ion laser, the photoefficiency of an S-4 PMT is 0.05; thus, $\langle n\rangle \simeq 100$. The minimum detectable intensity to produce 10 MHz becomes

$$I_{\text{min}} = 2.4\times 10^{-9}\text{watts} \qquad (10)$$

Similarly, substituting representative numbers into Eq. (8), $s = 0.5$ cm, $\tau = 0.1$, $R_R = 0.8$, and $R = 5m$, the available intensity is a function of the illuminated portion of the compressor

$$I = 1.05\times 10^{-4} P_L/d_c^2 \quad \text{W/cm}^2 \qquad (11)$$

Thus, the diameter of the spot to be illuminated depends on the laser power is found by combining Eqs. (10) and (11):

$$d_c = 1.2P_L^{\ 1/2} \qquad (12)$$

where P_L is in watts, and the spot diameter d_c is in meters.

A further design consideration is the vibrational frequency. Because the compressor blade is oscillating, it must pass through zero angular velocity twice per cycle. In order to measure the excursion of the blade during one cycle, the motion must cause as many fringe crossings per cycle as possible. Thus, it is desirable to maximize the retroreflector spacing s without overly reducing the return intensity I. Since information theory states that at least two cycles are required to establish a modulation frequency, the minimum measurable angular motion is given by

$$\theta_{\text{min}} \sim \lambda/s \qquad (13)$$

Thus, for a 0.5-cm retroreflector separation, the minimum measurable rotation is 0.1 mrad. This is equivalent to 1-mil motion on a 10-in. blade. Since the usable return intensity goes inversely as the square of the retroreflector separation, retroreflectors further than a few centimeters apart would prove impractical using this design scheme.

Experimental Results

The system described by Fig. 2 was first tested out using a 0.5-mW HeNe laser to illuminate the face of a rotating 5-in. loudspeaker. A retroreflector, 3.5 mm in diam, was pasted on the speaker cone 2 in. from the center. A second retroreflector of the same diameter was pasted on a rigid arm such that the

a)

b)

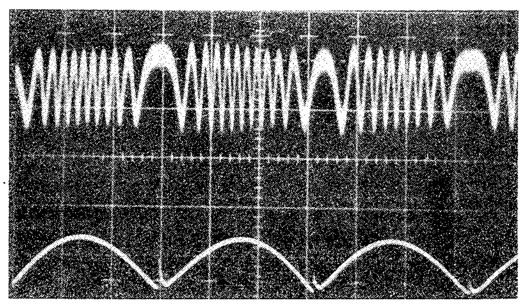

Fig. 4 Oscillogram of photomultiplier output signal from frequency demodulator. Upper trace a shows speaker at 300 Hz with a total excursion of 3 μm. Lower trace b shows demodulated signal for motion of $\pm$1 mm at 300 Hz.

separation of the two reflectors was approximately 0.6 cm. The entire speaker was rotated using a dc motor and drive. The rotation speed was continuously variable up to 5000 rpm. The speaker cone was driven by a frequency generator, which feeds a frequency and amplitude signal through two brush contacts, allowing the speaker to be driven to deflections as high as 3 mm peak-to-peak deflection, corresponding to a blade rotation of as high as 28 deg. This deflection would, of course, never occur in the actual compressor without catastrophic failure.

A typical oscillogram of the PMT output is shown in Fig. 4a. The signal shown is from the speaker driven at 300 Hz. Each peak in the alternating current shown represents a speaker motion of $\lambda/2$, or 316 nm. Thus, the total peak-to-peak excursion of the speaker is seen to be 3 μm.

The signal from the PMT is seen to be a typical FM signal with no carrier frequency. The ac portion of this signal is represented by the expression

$$I(t) = \sin[(2\pi A/\lambda)\sin(\omega_v t)] \tag{14}$$

where A is the amplitude of the moving retroreflector, which is driven at the frequency ω_v. The roots of this expression give the zero crossing when $2A\sin\omega_v t = n\lambda$, where n is an integer. By triggering a constant area pulse every zero crossing, then integrating these pulses in a time much shorter than π/ω_v, the integral signal vs time is given by the relation

$$V_{\text{out}} = A\omega_v/\lambda \, |\sin\omega_v^t| \tag{15}$$

Note that this scheme requires $A \gg \lambda$, that is, $\theta \gg \lambda/s$. A typical trace of the demodulated output is shown in Fig. 4b.

The absolute value signs around the modulating frequency in Eq. (15) may be looked at in two ways. If we consider the signal in the photomultiplier as from fringes moving across the aperture, only a change in intensity is measured, not the direction of the fringe motion. Completely analogous to this, consider the wavefronts from the two retroreflectors as being Doppler shifted. The frequency of the laser light from the retroflector moving towards the detector is upshifted, while the frequency of laser light moving away from the detector is downshifted. Since it is the beat signal that is detected, Doppler information containing the direction of motion is lost. For simple oscillatory motion, this directional information is not important. However, if more complex motion occurs, the magnitude as well as the sense of the motion would become important.

Conclusions and Future Work

An optical technique has demonstrated the ability to measure flexure and torsion of rotor blades to within a milliradian of deflection. This system has the particular advantage of following the vibratory motion over the entire rotational travel of compressor blade. Because of the very high frequency of laser light, the detectable velocity of vibration is limited only by the laser intensity. A commercial 0.1-W laser is sufficient to measure vibration of a compressor rotor blade up to 1-m diam using a simple lens system. The only modifications to existing compressor systems would be the addition of small retroreflectors, each typically 3 mm in diameter.

Outlined in this paper is only the very basic technique for measuring flutter in rotating machinery. The design parameters have by no means been optimized. For instance, if only very small motions are of interest, the FM signal may be doubled, quadrupled, or multiplied several orders of magnitude without destroying the modulating frequency in Eq. (14). Thus, the same demodulator would be able to measure displacements of as little as 1/10 mrad in torsion, the theoretical limit of FM demodulation. This deflection could be improved another factor of three by increasing the range from the vibration sensor to the compressor through a folded light path.

The system as described above is currently being adapted to the Massachusetts Institute of Technology Blowdown Compressor facility. Work will be carried out at the MIT Gas Turbine Laboratory, using this technique to measure the aerodynamic damping coefficient as a function of interblade phase angle, tip Mach number, and pressure ratio.

Work also is being carried out currently to allow much larger retroreflector separations than the present 1 cm. This is done by directing two beams of light and mixing the return signals through more complex optics. These systems work well for retroreflectors placed radially on the rotating machine. However, the torsional modes are limited to the very close retroreflector separations. Fortunately, complex vibrational modes are more likely to be developed in the flexure mode.

Although the discussion in this paper has been directed toward studying flutter in turbine compressor blades, this scheme is by no means limited to that application. The problem of wobble in rotating machines of all types has been one of the most difficult to measure. This system, as described, should be applicable to most of these systems.

Acknowledgment

The authors wish to thank Jack Kerrebrock of MIT for his many useful discussions and support. This work was sponsored by Aerodyne Research, Inc., internal funds.

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