Journal of Sound and Vibration (2001) **240**(3), 581–586
doi:10.1006/jsvi.2000.3131, available online at http://www.idealibrary.com on IDEAL®

LETTERS TO THE EDITOR

ULTRASONIC DIAGNOSTIC SYSTEM FOR ROTATING BODIES

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(*Received* 30 *June* 1999, *and in final form* 6 *June* 2000)

1. INTRODUCTION

The aim of the study was to analyze the possible application of an active ultrasonic non-destructive inspection (UNDI) system for testing rotating bodies. Such a system will make it possible to carry out ultrasonic non-destructive testing of different components in real time and to monitor flaw development under the influence of both vibration and centrifugal forces. Turbines, flywheels and rotors of generators and electric motors and other rotating components can be tested for flaws such as cracks and welded-joint failures.

The eddy current method is commonly used [1] to detect internal defects in a dynamical regime. The method only enables one to detect flaws located close to the surface of a rotating body and cannot be used for components of complex shape. Vibration and acoustic noise techniques [2, 3], that have a number of limitations, are also used to inspect rotating bodies. For active ultrasound diagnostics current systems employ acoustic coupling between transducers and the part under test either through oil immersion or through air [4, 5]. When oil immersion is used, it is not possible to examine the body when it is in rotation. When air is used as the coupling medium, the acoustic bandwidth is limited to below 100 kHz due to high absorption, and the viability of the test is consequently reduced. Optical techniques for the excitation of ultrasonic waves [6] also has drawbacks which are due to difficulties in controlling the temporal and field parameters of generated elastic pulses. In reference [7] the non-destructive testing of railway wheels is proposed, but the method does not allow monitoring of flaw development when the wheels are rotating at a high speed.

There are many problems in using ultrasonic techniques to inspect the interior of a rotating body. Firstly, acoustic noise arises due to a combination of bearing rotation and vibration of the supporting structure. The noise level can greatly exceed the amplitude of diagnostically significant signals. The highest frequency of the rotating components is $f_m = f \times n$, where f is the rotation frequency and n is the number of balls in the bearings. When $f = 500$ (30 000 rev/min) and $n = 10$, then $f_m = 5$ kHz. Even if one assumes the frequency of the upper harmonics to be one order of magnitude higher ($f_m = 50$ kHz) then the operating band for the diagnostic system will have to commence at a frequency greater than 50 kHz. Secondly, there are difficulties associated with coupling between a rotating body and a stationary platform. Thirdly, problems of access and coupling to rotating bodies prevent the majority of conventional UNDI methods from being used. As the test system reported here is designed to test for defects when bodies are rotating, then identification of defects must be carried out by analyzing the changes in ultrasonic pulses (the amplitude,

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pulse duration, etc.) that follow rotation. This is achieved by a purpose-designed signal processing program run on a PC.

2. DESCRIPTION OF THE MEASURING SYSTEM

The object of this study was to examine the possibility of both excitation and reception of ultrasonic pulses with coupling to rotating bodies. A compressor turbine of a centrifugal pump of diameter 30 cm was used as the test object. Figure 1 shows the block diagram of the system. A body (1) under test (a turbine) fitted on a shaft (2) (diameter of 45 mm) is set in rotation by a drive (3). Fastened on the body surface are receiving (4) and emitting (5) piezoelectric transducers. An electric pulse generated by a generator (6) is conducted through a brush assembly (7–9) to the transducer (5). Ultrasonic waves propagating in the body are received by the receiver transducer (4) and are preprocessed by a reception unit (a preamplifier (10), an optocoupler (11) to an amplifier (12)). The signal then arrives at the controller (13) and after analog-to-digital conversion is read in the computer (14). The clock rate of an analog-to-digital converter is 8 MHz.

The optocoupler assembly consists of a light-emitting diode with a separate photodiode receiver in order to facilitate transmission of the signal without contact with the rotating body.

The ultrasonic transducers consist of piezoceramic plates of thickness 0·5 mm and cross-section of 4 mm × 6 mm. The plates were covered by a brass foil of 0·15 mm thickness and were sealed with epoxy resin filled with lead powder, of mean particle diameter 0·2 mm. The transducers were coupled to the brush assembly (the emitter) or to the preamplifier (the receiver) by a coaxial cable. Transducer weight was less than 0·5 g, and they were fastened to the test piece by threaded bolts. Transducer centre frequencies were between 2·5 and 3·0 MHz.

The preamplifier had a minimum sensitivity of 10 μV, an input resistance of 50 kΩ and an effective passband from 100 kHz to 10 kHz. A low-frequency filter was set at an input of the preamplifier. The filter was designed to suppress low-frequency components of acoustic noise, the amplitude of which was many times that of the signal (Figure 2). An independent power-supply is built into the shaft, and the preamplifier power-supply and optocoupler photodiode are mounted on a plate of dimensions 240 mm × 26 mm.

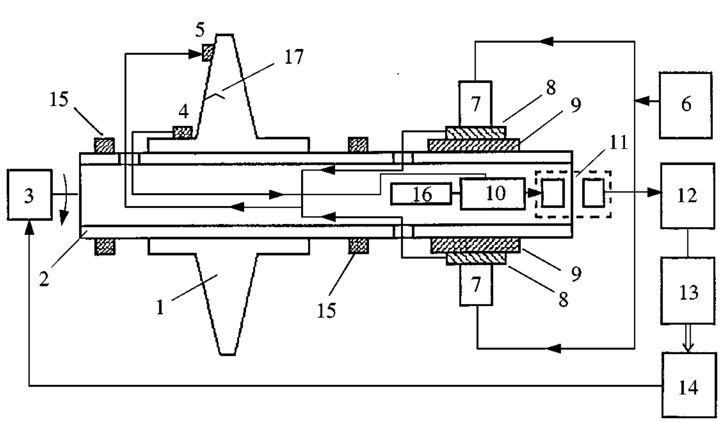

Figure 1. Block diagram of the unit: 1—a turbine, 2—a shaft, 3—a motor, 4, 5—recieving and emitting piezotransducer, 6—a generator, 7—a brush, 8—an electrode, 9—a dielectric bush, 10—a preamplifier, 11—an optocoupler, 2—an amplifier, 13—a controller, 14—PC, 15—a support bearings, 16—an independent power-supply, 17—a defect.

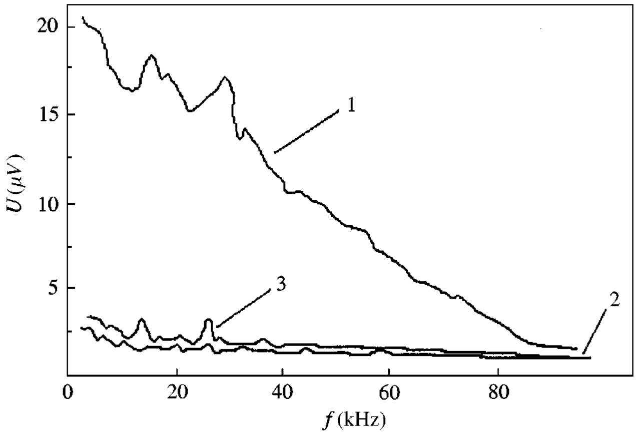

Figure 2. The amplitude–frequency characteristics of received signals. Piezotransducer is attached to: 1—a static mounting, 2—the output of the optocoupler in a static regime, 3—the output of the optocoupler in a dynamical regime.

The preamplifier was mounted inside the shaft at the lowest possible radius in order to minimize the effects of centrifugal forces. The preamplifier components were subjected to a preliminary test (rotation at 500 rev/s at a rotation radius of 2 cm) in order to confirm successful operation in a centrifugal stress field.

Figure 2 presents amplitude–frequency spectra of the signal from a piezoreceiver under different conditions, as measured using a serial spectrum analyser connected to the exit of the optocoupler. Curve 1 corresponds to the signal when the piezotransducer is fixed on a static mounting with turbine rotation at 140 rev/s without the low-frequency filter. The curve indicates that noise has significant amplitude at frequencies which are less that 100 kHz. Curve 2 corresponds to the signal at the exit of the optocoupler in a static regime and results from the random noise of electronics pathway. Curve 3 corresponds to a signal at the exit of the optocoupler in a dynamical regime ($f = 140$ Hz). In these last two cases, the filter was connected to the preamplifier. At frequencies more than 100 kHz the noise level at the exit of the preamplifier with the connected filter was, in fact, the same as without the filter and did not depend on frequency. In acoustic diagnostics regime (see further) the signal amplitude was 10–20 times that of noise level.

The brush assembly was constructed using a brush assembly from a commutator motor of 500 W rating. To secure a reliable contact two coaxially disposed and parallelly connected carbon brushes of dimension 10 mm × 20 mm were used, they bore a bronze sleeve of outer diameter 50 mm and active surface of 20 mm long fitted to the shaft and electrically isolated from it. The turbine frame and rotor precluded the return connection.

This arrangement was found to give reliable excitation of ultrasonic waves at frequencies up to 5 MHz for rotation speeds up to 500 rev/s.

3. TEST RESULTS

As stated earlier the object of this study was to investigate the application of UNDI for testing rotating bodies, and here we present results obtained with the prototype system.

Figure 3 shows time-domain traces of ultrasonic pulses recorded and stored in a computer at different rotational speeds. The transducer excitation pulse had an amplitude

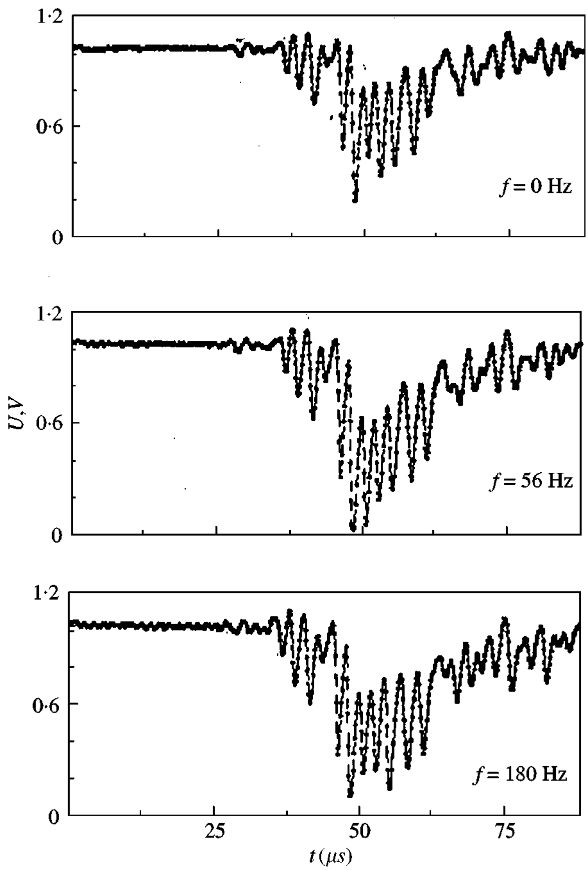

Figure 3. Time-domain traces of signals for different rotational speeds.

to 40 V and a duration of 1 μs. One can see from this figure that both the amplitude and the form of ultrasonic pulse from the output of the optocoupler changes only slightly with rotational speed, and corresponds closely to that recorded with no rotation.

The signal form is determined by the properties of the transducers, the transmission and the reception electronics, and the acoustic pathway. The small thickness of the turbine parts (5 mm) comparable with ultrasonic wavelength and the long propagation path from the emitter to the receiver (around 12 cm) make it possible to interpret the coming signal as a Lamb wave. In Figure 3 the component at 25 μs corresponds to a symmetrical mode of vibration, whilst the component at 42 μs corresponds to an antisymmetrical one. Modes of vibration were discriminated by their speed of propagation, which for the symmetrical mode was 500 m/s and for the antisymmetrical one about 3000 m/s.

An experiment on crack detection was carries out to investigate the possibility of detecting flaws which appear in a body under rotating. A crack was cut inside the turbine body, located near to one of the transducers, and the assembly was rotated at various speeds.

Figure 4 shows the signal changes for different rotation frequencies as the crack changes. In the range of rotational frequencies from 0 to 70 rev/s both the pulse amplitude and its form do not change significantly and the acoustic contact is not disrupted by the crack. When the frequency rises from 70 to 80 Hz the signal amplitude begins to fall without

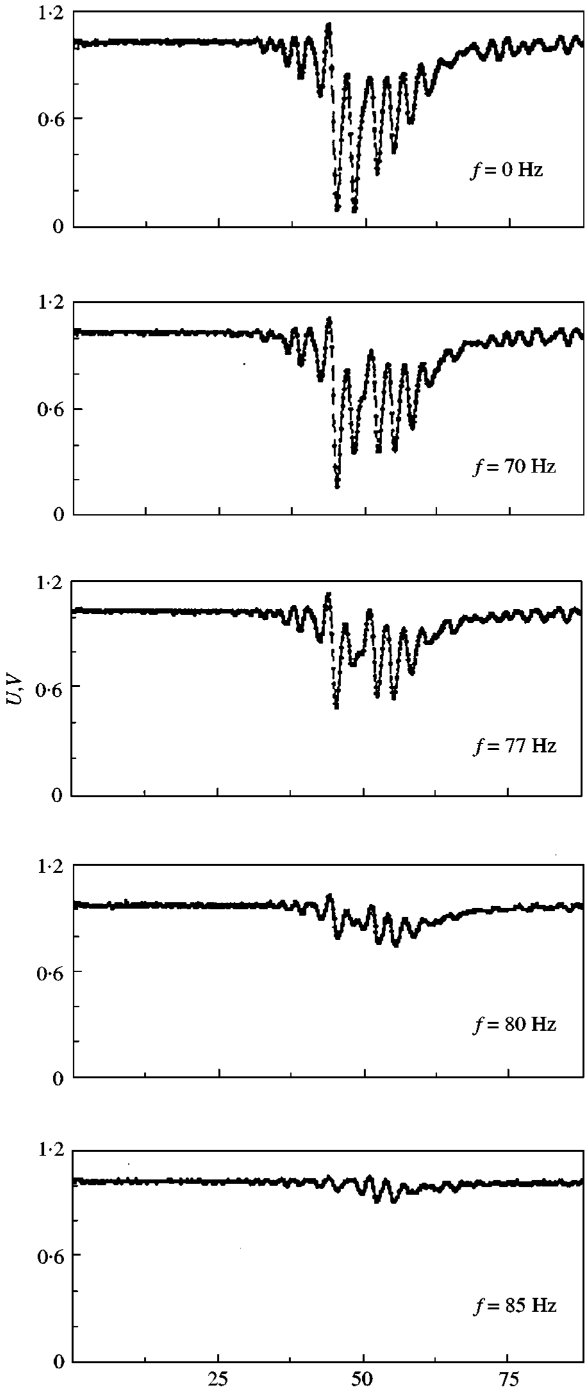

Figure 4. Change of a signal with a simulated crack for different rotational speeds.

a marked change in its form. When the rotation frequency exceeds 80 Hz the pulse amplitude continues to fall and its from changes. For $f > 90$ Hz the pulse amplitude falls below the background noise level, as a complete break in acoustic contact occurs due to rotation. When the rotation frequency is reduced again complete recovery of both the amplitude and the form of the signal is observed.

4. CONCLUSION

This brief study has shown that pitch-catch ultrasonic diagnostics can detect defects when they occur in bodies rotating at high speed and a practical system has been presented which is based on brush/slip ring coupling to a transmitting transducer, and optical coupling from an amplifier embedded in a rotating shaft.

As a result of this study two Russian patents [8, 9] on the invention were gained.

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