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Longitudinal Ultrasonic Guided Waves for Monitoring the Minor Crack of Rotating Shaft with Galfenol Transducer

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Abstract: The safety of rotating machinery is important for the manufacture industry. As the core component of the rotating machinery, the rotating shaft with racks or damages will lead to the terrifically disaster. Compare with the vibration signal diagnosis of the rotating shaft, it presents a novel method to detect crack on rotating shaft with longitudinal ultrasonic guided wave. In the view of elastic wave propagating mechanism in the cylindrical waveguide, it discuss the influence of rotor dynamics effect on the system, from the govern equation of wave propagating in rod, it consider the lateral effect of the rotating shaft, the reflection and transmission of the guided wave in the waveguide. It takes the Galfenol transducer as a pulse-echo transducer to detect the crack on the rotating shaft. Finally, it gives the simulation of experiment results, the results indicated the method can locate the crack accurately after conducting the wavelet transformation on the difference between cracked and non-cracked rotating shaft experiment waveform. *Copyright © 2013 IFSA.*

Keywords: Ultrasonic guided wave, Rotating shaft, Galfenol, Elastic wave, Transducer.

1. Introduction

The demand for non-destructive health monitoring of machinery systems has been steadily increasing. Especially in case of rotating machinery, most non-destructive health monitoring techniques are based on vibration signals. In this investigation, we consider the use of longitudinal ultrasonic guidedwaves instead of vibration signals for early-stage crack detection in a rotating shaft. Rotating cylindrical bars are fundamental components in mechanical engineering and there are many applications of non-destructive testing of such objects. Thus far, ultrasonic testing of such bars has been studied mostly by using bulk ultrasonic waves and usually conducted from the free end surface of the bars. Moreover, ultrasonic testing by means of ultrasonic guided waves could be promising especially for long-range inspections [1, 2]. There have been studies of ultrasonic guided wave testing of bars, the guided waves are basically generated in the vicinity of the end surface of bars. There have been several researches of ultrasonic guided wave testing that could be conducted from a side area of bars [3, 4].

The guided-wave technique has been used in stationary waveguides, such as pipes, The application of guided-waves in a rotating shaft was made by Han [5] et al. but no guided-wave based health monitoring of rotating shafts has been reported yet. For practical applications of the guided-wave method in rotating shafts, Motivated by the need of wave generation and measurement should be carried out without affecting shaft rotation motion. A new ultrasonic transducer capable of transmitting and receiving guided-waves in a rotating shaft without mechanical contact is developed [6]. Specifically, a Galfenol transducer based on the magnetostrictive effect is proposed. Magnetostrictive transducers have unique characteristics in that they do not require direct wiring between magnetostrictive materials and sensing/actuating solenoids. For guided-wave generation and measurement, magnetic field is supplied to and measured from magnetostrictive material by solenoids [7]. In this context, we have investigated ultrasonic guided wave generation and testing on steel bars by using Galfenol transducers attached to the sides of the bars. To show the effectiveness of the proposed transducer, we used it to carry out the damage inspection of a rotating shaft having an artificial crack.

2. Ultrasonic Guided wave Propagation in Shaft

In this study, we utilized a rotating shaft with crack as study object. The experiment setup can be seen in Fig. 1, the rod was driven rotating by motor connected with coupler. The Galfenol transducer responsible for transmit and receive the ultrasonic guided wave. Guided-waves denote elastic waves propagating along cylindrical waveguides. Traveling along a structure guided by boundaries, guided-waves can propagate relatively long distances so that the whole part of a structure can be inspected at one time. Where we assume the Galfenol transducer generates the displacement and transmit it to the rod. So the incent wave from the Galfenol transducer will propagate along the rotating shaft. According to the reflect wave from the end and crack, we can get the damage information about the rotating shaft. In the view of elastic wave propagate in rotating cylindrical waveguide. The following problems will be encounter in the study.

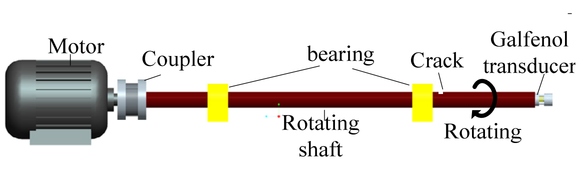

Fig. 1. Experiment setup for longitudinal ultrasonic guided wave to detect the crack.

2.1. Rotor Dynamics of Rotating Shaft

The rotating shaft as elastic medium. Consider an infinite homogeneous, isotropic, linear elastic medium characterized by a density, a shear modulus and a bulk modulus. These quantities determine, in the usual fashion, a shear wave speed c_s and a pressure wave speed c_p. the medium is rotating uniformly with respect to an inertial frame, and the constant rotation vector in an x_1, x_2, x_3 rectangular Cartesian frame rotating with the medium is $\Omega = \Omega\hat{w}$, the unit vector $\hat{w}$ will denote the direction of the axis of rotation (according to the right-hand rule) throughout.

The displacement equation of motion in such a rotating frame has two terms that do not appear in the non-rotating situation. As we are looking for time-varying dynamic solutions, the time-independent part of the centripetal acceleration

$$(c_p^2 - c_s^2)\nabla(\nabla \bullet u) + c_s^2\nabla^2 u = \ddot{u} + \Omega\times(\Omega\times u) + 2\Omega\times\dot{u} \tag{1}$$

$\Omega\times(\Omega\times x)$, as well as all body forces, will be neglected. Thus our dynamic displacement u is actually measured from a steady-state deformed position, the deformation of which, however is assumed small.

Where the dot denotes time differentiation. The term $\Omega\times(\Omega\times u)$ is the additional centripetal acceleration due to the time-varying motion only, and the term $2\Omega\times\dot{u}$ is the coriolis acceleration. All other terms are as usual for a linear elastic medium under the assumptions of small strains and displacements. For the axial direction, the equation can be reduced to the normal wave equation. Because the Ω is the same direction to the u. so whatever the magnitude of u_z, the last two terms of the equation(1) are equal to zero.

2.2. Govern Equation

For the rotating shaft, we can conclude that the rotating speed has little effect on the longitudinal guided wave propagating. So we can employ the govern equation when the shaft is stationary. The governing equation for the thin rod will be derived and the basic propagation characteristics considered. The rod most aspects are similar to the case of waves in strings, Consider a straight, prismatic rod as shown in below, the coordinate x refers to a cross-section of the rod, while the longitudinal displacement of that section is given by u (x,t). We presume the rod to be under a dynamically varying stress field σ (x,t), so that adjacent sections are subjected to varying stresses. A body force q (x,t) per univolume is also assumed present. The equation of motion in the x direction then becomes

$$-\sigma A + (\sigma + \frac{\partial\sigma}{\partial x}dx)A + qAdx = \rho A dx\frac{\partial^2 u}{\partial t^2}, \tag{2}$$

where A is the cross sectional area of the rod. We are considering a prismatic rod, so this parameter is a constant in this development. We note that tensile stress is assumed positive. (2) reduce to

$$\frac{\partial \sigma}{\partial x} + q = \rho \frac{\partial^2 u}{\partial t^2} \tag{3}$$

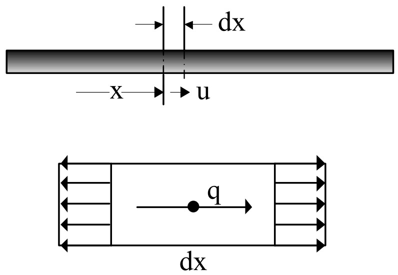

Fig. 2 (a) A rod with coordinate x and displacement u of a section, (b) the stresses acting on a differential element of rod.

Material effects have not been introduced, So that this stage the equation is applicable to non-elastic as well as elastic problems. We now presume that the material behaves elastically and follows the simple Hooke's law

$$\sigma = E\varepsilon , \tag{4}$$

where E is the Young's modulus and ε is the axial strain, defined by

$$\varepsilon = \frac{\partial u}{\partial x} \tag{5}$$

Using (3) and (5) in the equation of motion, we obtain

$$\frac{\partial}{\partial x}(E \frac{\partial u}{\partial x}) + q = \rho \frac{\partial^2 u}{\partial t^2} \tag{6}$$

If the rod is homogeneous so that E (and ρ) do not vary with x, the equation reduces to

$$E \frac{\partial^2 u}{\partial x^2} + q = \rho \frac{\partial^2 u}{\partial t^2} \tag{7}$$

We see that in the absence of body forces, the equation reduces to

$$E \frac{\partial^2 u}{\partial x^2} = \rho \frac{\partial^2 u}{\partial t^2} \tag{8}$$

Or

$$\frac{\partial^2 u}{\partial x^2} = \frac{1}{c_0^2} \frac{\partial^2 u}{\partial t^2} \quad c_0 = \sqrt{\frac{E}{\rho}} \tag{9}$$

So this is the familiar wave equation. And c_0 is the bar velocity. The Poisson effect causes lateral expansions and contractions under a propagating pulse. This effect is illustrated in Fig. 3

Fig. 3. Poisson expansion and contraction resulting from longitudinal stress pulses.

The particle velocity in the bar is given by

$$v(x,t) = \frac{\partial u}{\partial t} = -c_0 f'(x - c_0 t) \tag{10}$$

This may be expressed in terms of the stress, since

$$\sigma(x,t) = E \frac{\partial u}{\partial x} = Ef'(x - c_0 t) \tag{11}$$

Then we directly obtain

$$v(x,t) = -\frac{c_0}{E} \sigma(x,t) \tag{12}$$

Under elastic conditions, the stress is always much less than the elastic modulus. So the particle velocity will be much less than the propagation velocity. As an example, suppose a pulse of magnitude $\sigma=10^8 N/m^2$ is propagating in steel, we know that bar velocity of steel $c_0 \cong 5.1\times10^3$ m/s, $E=2.07\times10^{11}$ N/m^2. This gives a particle velocity of v=2.5 m/s, not only is the particle velocity less than the propagation velocity, it is less by several orders of magnitude. So we can see that, the lateral effect has little effect on the rotating shaft.

2.3. Reflection from other End Conditions and Transmission into Another Rod of Wave

When the ultrasonic guided wave was generated by transducer, the ultrasonic wave will be reflect at the end of the first end of the shaft ,and then transmission into the shaft boundary [9], in fact , if adjust the impedance of the transducer and shaft, it will optimized the transmission power efficiency. We suppose some force F(t) to be acting on the end of the rod, such as that due to the resistance of some load against which the rod end is moving. The velocity of the rod end is V(t). The stress field in the rod will be given by

$$\begin{aligned} \sigma(x,t) &= E\{f'(x - c_0 t) + g'(x + c_0 t)\} \\ &= \sigma_r(x - c_0 t) + \sigma_i(x + c_0 t) \end{aligned} \tag{13}$$

Thus σ_i and σ_r are the incident and reflected stress pulse. Similarly, the velocity field in the rod is

$$v(x,t) = c_0\{-f'(x-c_0t)+g'(x+c_0t)\}$$
$$= \frac{c_0}{E}\{-\sigma_r(x-c_0t)+\sigma_i(x+c_0t)\} \quad (14)$$

Then, balance of force at the end of the rod requires

$$F(t) = -A\{\sigma_r(0,t)+\sigma_i(0,t)\} \quad (15)$$

The velocity of the rod tip will be

$$V(t) = \frac{c_0}{E}\{-\sigma_r(0,t)+\sigma_i(0,t)\} \quad (16)$$

We consider a rod, having free end conditions, subjected to pressure pulse at one end. Physically, we may imagine the rod to be freely suspended by two light strings, So that it is free to swing under the action of applied loads. This configuration has no counterpart in the case of the string. Thus, while free end boundary conditions exist, the string is incapable of translation as a whole.

Consider the applied pressure to be a five peak signal described by

$$P(t) = \begin{cases} A_0(1-\cos(2\pi t/\omega))]\sin(2\pi f_0 t), & 0<t<T \\ 0 & t>T \end{cases}, \quad (17)$$

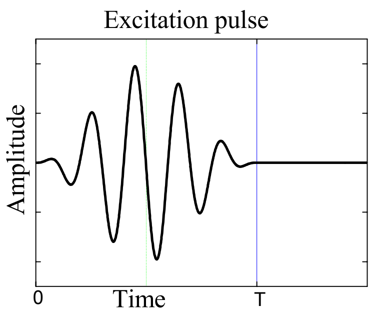

Fig. 4. Five peak signal of P(t).

where the negative sign indicates compression. The propagating stress wave will be given by

$$\sigma(x,t) = p(x-c_0t) \quad (18)$$

Before the first end reflection. Now the response of a particle at a typical point to this stress pulse can be deduced from the results presented before, according to the equation (16), the particle will be brought from rest to the velocity

$$v(x_0,t) = -c_0 p(x-c_0t)/E \quad (19)$$

Instantaneously and will remain at this remain at this constant velocity until the pulse passes, at which point the velocity will again be zero. The displacement will increase according to the relation $u(x_0,t)=c_0p_0t/E$, while the pulse passes and will remain constant after passage.

We are interested here in the case of a junction between two rods. Where there is a discontinuity in cross-section, in material properties or both. The situation is shown in Fig. 5. Proceeding in a manner similar to that used for the analogous case of the string, we have from balance of force and continuity of velocity at the junction

$$A_1(\sigma_1+\sigma_r) = A_2\sigma_t, \quad v_i+v_r=v_t, \quad (20)$$

where the stresses and velocities are determined from the wave fields

$$u_i = f_1(x-c_1t), u_r = g_2(x+c_2t), u_t = f_2(x-c_2t) \quad (21)$$

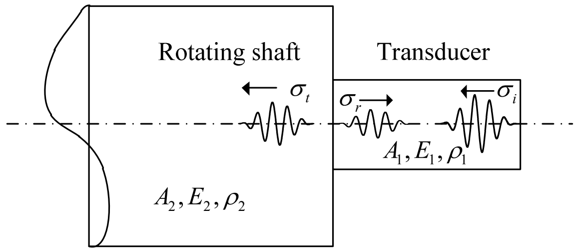

Fig. 5. Incident reflected and transmitted waves at the junction between two rods.

The results for the transmitted and reflected waves are then

$$\sigma_t = \frac{2A_1\rho_2c_2}{A_1\rho_1c_1+A_2\rho_2c_2}\sigma_i, \sigma_r = \frac{A_2\rho_2c_2-A_1\rho_1c_1}{A_1\rho_1c_1+A_2\rho_2c_2}\sigma_i \quad (22)$$

Problems involving transmission across junctions are often spoken of in terms of impedance. This term and concept borrowed from electric circuit theory expresses the ratio of a driving force to the resulting velocity at a given point of the structure. For a rod, it is easily shown that the driving point impedance is given by

$$Z = F/V = A\sqrt{\rho E} \quad (23)$$

Using this parameter, it is possible to express the results as

$$\sigma_t = \frac{2(Z_2/Z_1)(A_1/A_2)}{1+(Z_2/Z_1)}\sigma_i, \sigma_r = \frac{(Z_2/Z_1)-1}{1+(Z_2/Z_1)}\sigma_i \quad (24)$$

where $Z_1 = A_1\sqrt{\rho_1E_1}$ and $Z_2 = A_2\sqrt{\rho_2E_2}$, A number of interesting reflection-transmission situations arise as Z_1, Z_2, A_1 and A_2 are varied.

3. Generation of Ultrasonic Guided Wave

3.1. Linear Piezomagnetic Equations of Galfenol

Galfenol alloys ($Fe_{1-x}Ga_x$) where the gallium content, x, varies between 12 and 20 % were also developed through scientific research by the Naval Ordnance Laboratory. These alloys have mechanical properties that are far superior to those in Terfenol-D. Galfenol has a mechanical robustness similar to steel while exhibiting a moderate magnetostriction at low saturation fields. The magnetostriction for Galfenol is around 300×10^{-6} ppm. The unique property of Galfenol makes it a potential candidate for shock-tolerant adaptive structures, as well as sonar transducers with load bearing capability. Additional, unexpected benefits. They can be machined with conventional metal working tools and welded with a normal tungsten inert gas welder. Perhaps Galfenol's most unique feature is its ability to have a uniaxial stress built in by stress annealing. The built-in stress acts exactly like an externally applied prestress and allows full strain to be obtained not only with zero prestress. But also with up to 50 MPa tension. The Fe–Ga materials are much more robust than existing high strain Materials and also provide. Reviewing the stress and magnetic variables for the structural and magnetic modes, the coupling terms can easily be implemented into the stress and magnetic field variables. In order to determine the correct terms to add into these variables, the linear magnetostrictive equations are written in the form shown in Fig. 6:

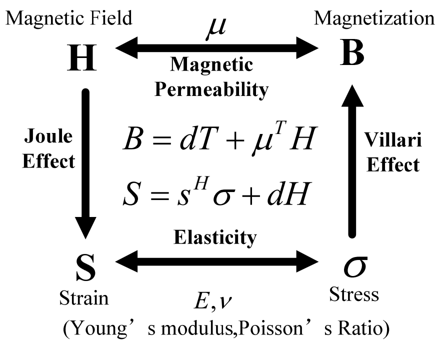

Fig. 6. Magnetostrictive effects [8].

Where T is stress, d is the compliance matrix with constant magnetic flux density, S is strain, s^H and $\mu^T$are the appropriate magnetostrictive coupling coefficients, H is magnetic field, B is flux density, and is d the inverse of permeability.

3.2. The Displacement Generation of Galfenol

Under quasi-static condition (continuous excitation under a sinusoidal alternating current), assuming zero pre-stress and assuming a linear relationship between the strain and the magnetic field, the strain is given by:

$$S = s^H \sigma + d_{33} H \tag{25}$$

The coefficient d_{33} is found to be almost constant for most frequencies. However when the frequency approaches a value causing the sample to resonate in its longitudinal direction, the amplitude of the vibration increases abruptly. For this to be observed the sample of Galfenol must be free to vibrate, so that if it was in an actuator it would be an unloaded actuator. The strain at resonance is much higher than it is under quasi-static conditions. The strain at the resonance condition is given by:

$$S = s^H \sigma + Q^m d_{33} H \tag{26}$$

The amplification factor of the strain at its first resonance over the strain under quasistatic conditions is the quality factor Qm. In the case where the actuator's vibrating end is totally free, the quality factor Qm is due to mechanical losses occurring internally in the material [9, 7] and is equal to QH. This internal material quality factor QH is in the range of 3-20 [9, 7]. On the other hand, when there is a load, when the sample of Galfenol encounters a resistance to its free movement because of the surrounding assembly, a damping feature is introduced into the vibration and the quality factor Q^H is reduced to a value Q^m.

4. Simulation and Experiment of Crack Detection with Longitudinal Wave

Where the Galfenol transducer generates the displacement and transmits it to the rod. So the incent wave from the Galfenol transducer will induced the longitudinal guided wave propagating along the rotating shaft. According to the reflect wave from the end and crack, we can get the damage information about the rotating shaft [11]. The Indicated the simulation and experiment setup, The parameters and boundary conditions list in Table 1.

Table 1. Parameters of Steel and Galfenol.

	Steel	Galfenol
Young's modulus	210 GPa	40-75 GPa
Possion's ration	0.3	0.27
Mass density	7850 kg/m^3	7800 kg/m^3
Relative permeability	1500-3000	75-100
Acoustic impedance	4.5×10^6g/cm^2·s	12.7×10^6 g/cm^2·s

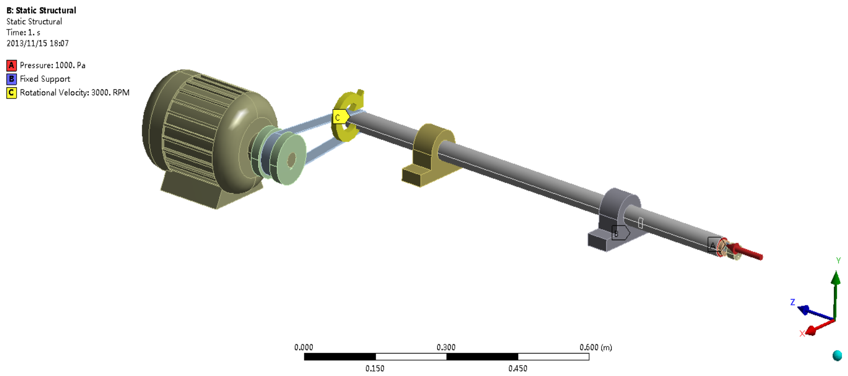

Fig. 7. Graph of Experiment setup.

As shown in Fig. 8, graph of second row is the ultrasonic guided wave which is 50 kHz propagating from the non-cracked shaft's left end to the right end back and forth. We can see the same distance between the two waves. The time between the two waveforms is the travel time which ultrasonic longitudinal guided wave travel the twice length of the shaft by group speed. From the graph, it's about 0.0036 s, So, we can get the group speed at this frequency is about 5405 m/s. from the first row graph, we can see some minor waveforms similar to the big one. The first row graph data substrates the second graph data at the corresponding location, it will get the third row graph. The third graph is the difference signal between cracked and non-cracked rotating shaft. Fig. 9 is the difference signal after the morl wavelet transformation. t_1 is 0.3 times of T. So it indicates that the crack locates the 0.3 length of the whole shaft. It proves the effectiveness of the crack located method in the simulation.

Table 2. Parameters of simulation of experiment setup.

Item	Value
Rotating speed	3000 rpm
Crack location	30 mm from one Galfenol transducer end.
Diameter of shaft	40 mm
Length of shaft	1000 mm
Fixed conditions	Bottom of two bearings journal
Material of shaft	Steel
Crack size	2 mm × 2 mm cross-section crack

5. Conclusion

In this research, in the view of elastic wave theory, we utilized the longitudinal guided wave to detect the minor crack of rotating shaft. From the theory to simulation and then practical experiment, the results indicate the new method is effective for detecting the crack on rotating shaft. Wavelet transformation was be used for difference signal analysis and locating the crack. The method can improve the simplicity of crack analysis and location. Meanwhile, Galfenol as a promising functional material, It can be used to design and fabricate ultrasonic transducer. It has greater excitation then the other ultrasonic transducer. So it will be used in the larger rotating shaft to monitor the health of the rotatory machinery.

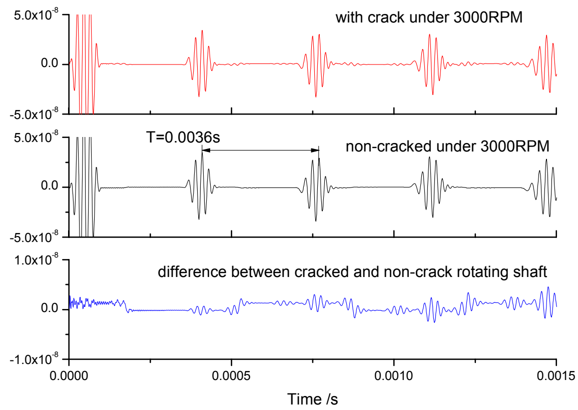

Fig. 8. Waveforms and difference between the cracked and non-cracked rotating shaft at 3000 rpm.

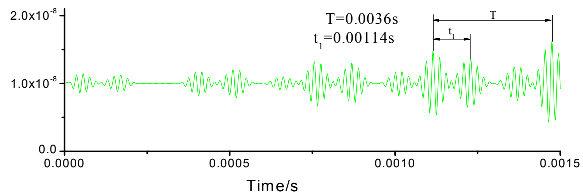

Fig. 9. Wavelet transformed difference signal by morl wavelet.

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