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Coil Spring Inspection for Reliability Assurance of Automobile Suspension System using Guided Wave

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Abstract. Coil spring of automobile suspension system is very important to safety and dynamics of passenger car and requires a highly advanced quality control during manufacturing processes. Surface cracks on the coil spring rod produced by mechanical machining and heat treatment may cause a severe accident and large cost to the manufacturer. In order to detect surface cracks of the rod, guided wave technique is applied for a fast total volumetric inspection. Pochhammer equation is studied to investigate the dispersion characteristics of the guided wave in the spring rod and optimal wave modes sensitive to the surface crack are selected experimentally to design the experimental arrangement for the generation of guided wave. Rod samples with different size of artificial axial EDM notch on the surface ranging from 50μm to 1mm are examined by guided wave and inspection results discussed.

Key Words : *Guided wave, Coil spring, Suspension system, Surface crack.*

1. INTRODUCTION

Modern automobiles have been improved during the past decade not only in performance but also in reliability such as durability and life. Suspension system of automobile is very important in terms of dynamics and reliability. It reduces the impact and disturbance from the road and stabilizes the vibration of automobile body. Thus coil spring of suspension system is likely to be subjected to a dynamic fatigue and impulsive loading which may cause a dangerous failure of automobile. Surface breaking crack

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produced often during surface peeling process or heat treatment is one of main defects that spring makers are concerned about. It is because the surface crack decreases the fracture toughness of coil spring and initiates stress cracking corrosion. As of July 2003, Product Liability Act comes into effect in Korea to improve the reliability of all domestic products and exporting goods. Under the Act, all products manufactured in Korea should be compensated for any damage and loss due to its failure and faults. Therefore, quality assurance and on-site inspection are now indispensable for safety of automobiles in automobile industry. It is also needed to find out what makes the surface cracks for improvement of manufacturing process itself. In order to detect the surface crack, non-destructive evaluation (NDE) techniques have been used in the manufacturing line including the magnetic particle method and eddy current method. However, those methods are too slow to inspect whole products in the manufacturing site, so that only sample inspection is conducted in the factory. The reason for the long inspection time is that the spring should be scanned by moving a sensing coil or optical instrument mechanically along the axial direction from one edge to the other. Another problem associated with these conventional methods is that they give a different inspection result depending on inspector's experience and physical condition. Also the methods are hard to be performed by automatic operation. Guided wave technique has been reported with great interests to be able to conduct a total volume inspection which does not require any mechanical movement of sensor for scanning of test specimen (Desimone et al.(1998); Alleyne and Cawley(1992); Berthelot et al.(1999)). Guided wave has several advantages over traditional ultrasonic techniques, one of which is that it can propagate through the whole volume of a long bounded medium like coil springs or plates. Therefore it makes possible a real time inspection of coil spring during manufacturing process. In this paper, the guided wave technique is applied to investigate the possibility of real time inspection of the surface crack on the coil spring rod and the detectable minimum crack size is evaluated experimentally.

2. GUIDED WAVE IN A SOLID ROD

The propagation of time-harmonic waves in an elastic circular cylinder of infinite extent is governed by the Pochhhammer equation. The traditional derivation of this equation is through the Helmholtz decomposition of the Navier equation of classical elasticity. The displacements and boundary condition of no stress at the surface yields the dispersion relation or frequency equation known as the Pochhammer frequency equation. Three different wave modes including torsional, extensional, and flexural modes are generated at the same time in a solid rod. However, owing to its complexity of the guided wave only limiting cases are usually considered. In a cylindrical rod of radius a consisting a homogeneous, isotropic elastic medium, propagation of extensional waves is described by (Popovics (1997); Wilcox et al.(2001))

$$\bar{\alpha}\left(\bar{\beta}^2+\bar{k}^2\right)J_1\left(\bar{\alpha}\right)J_1\left(\bar{\beta}\right)-\left(\bar{\beta}^2-\bar{k}^2\right)^2 J_0\left(\bar{\alpha}\right)J_1\left(\bar{\beta}\right)-4\bar{k}^2\overline{\alpha\beta}J_1\left(\bar{\alpha}\right)J_0\left(\bar{\beta}\right)=0 \quad (1)$$

$$\bar{\alpha} = \alpha a,\ \bar{\beta} = \beta a,\ \bar{k} = ka$$

$$\alpha^2 = \frac{\omega^2}{c_1^2} - k^2,\ \beta^2 = \frac{\omega^2}{c_2^2} - k^2$$

where $J_n (n = 0,1)$ is the n-th order Bessel function; $k = \frac{\omega}{c(\omega)}$ is the extensional wavenumber ; ω is angular frequency; $c(\omega)$ is the extensional phase velocity as a function of frequency. c_1 and c_2 are longitudinal and shear velocities respectively given by

$$c_1 = \sqrt{(\lambda + 2\mu)/\rho},\ c_2 = \sqrt{\mu/\rho} \tag{2}$$

Eq. 1 gives rise to a series of extensional wave modes in the rod. The lowest (or fundamental) wave mode is the most important mode from a practical point of view. In the case when the rod is thick like coil spring rod and the wavelength becomes small (ka ? 1), the phase velocity of guided wave approaches that of Rayleigh surface wave. The velocities approach the bar velocity toward zero frequency which is $\sqrt{E/\rho}$. As frequency increases, the curves take on different modes according to frequency. In addition to the extensional wave mode, more complicated flexural wave mode is generated with different dispersion relation. Since each wave modes has a different sensitivity to surface crack, it requires a tremendous work in computation and experiment to find the most sensitive wave mode to detect the crack (Wilcox et al.(2001), Chahbaz, et al.(1998)). Therefore in this study, the optimal guided wave mode for the crack detection is sought experimentally by changing the incident angle of ultrasound and wave frequency.

3. CHARACTERISTICS OF SURFACE CRACK IN COIL SPRING

Surface crack frequently found in the coil springs has a unique geometric characteristic different from other types of crack. The crack is very short in depth in the radial direction and very long in axial direction as shown in Fig. 1. Typical depth of the crack is about 100-200 μm and its length along the axial direction is normally in order of few inches. Cross-sectional view of a surface crack in a coil spring rod is described in Fig. 2, where the crack appears vertically in black. It is usually produced during the drawing process of steel production, but sometimes caused by mechanical machining and heat treatment conducted during the deforming process such as winding process. Surface finishing of the rod is not good in general because the rod is peeled a little by lathe to remove corrosion product or surface defects. Surface roughness of spring rod after peeling process is measured up to 300μm as large as the crack depth. This surface condition makes it difficult to detect the surface cracks because a lot of reflection waves form the surface roughness is confused with the crack signal in experiment.

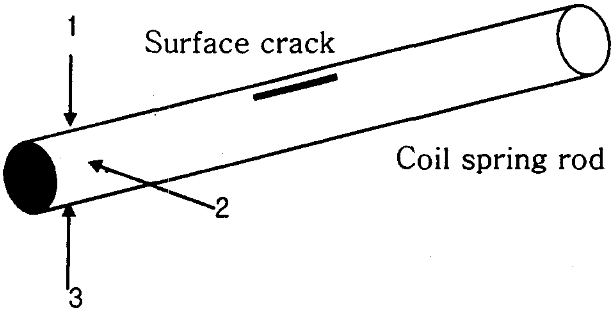
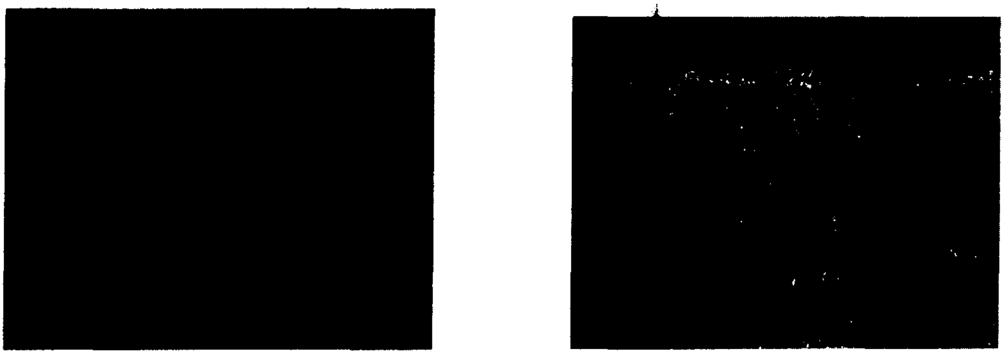


Fig. 1. Surface crack in coil spring rod



(a) Surface without crack

(b) Surface with crack

Fig. 2. Optical images of surface breaking crack in coil spring rod (x 200)

4. GUIDED WAVE GENERATION IN COIL SPRING ROD

Infinite number of guided wave modes can be generated in coil spring rod depending on geometric boundary conditions such as radius and incident angle of ultrasound. Material properties and wave frequency also affect the guided wave generation in rod as described in the Pochhammer equation of Eq. 1. Since the crack size is small, the frequency of ultrasound is selected as high as it can be to generate a guided wave with short wavelength but strong enough to propagate the entire rod without significant energy loss. Longitudinal ultrasound from 1MHz to 20MHz is transmitted to the rod with a variable incident angle to generate diverse wave modes and the reflected wave from the edge of rod detected to observe the energy of the guided wave. Highest frequency is found to be 2.25 MHz for the generation of guided wave propagating the rod without big energy attenuation. Optimal incident angle at this frequency is determined experimentally by changing the incident angle from 10° to 85° using a variable angle wedge (Panametrics, USA) to excite a guide wave most sensitive to the axial crack. A series of different guided wave modes generated simultaneously by the transducer with wedge are measured in experiment and investigated while changing the incident angle. The largest reflection wave is obtained at 72 and crack inspection is performed at the angle. In order to produce the high energy ultrasound, a high power pulser-receiver (Ritec, RAM-10000) is used and the reflected guided wave from the edge is measured thorough a digital storage oscilloscope (Lecroy 9311) as shown in Fig. 3 (Chahbaz et al.(1998); Niethammer et al.(1999)).

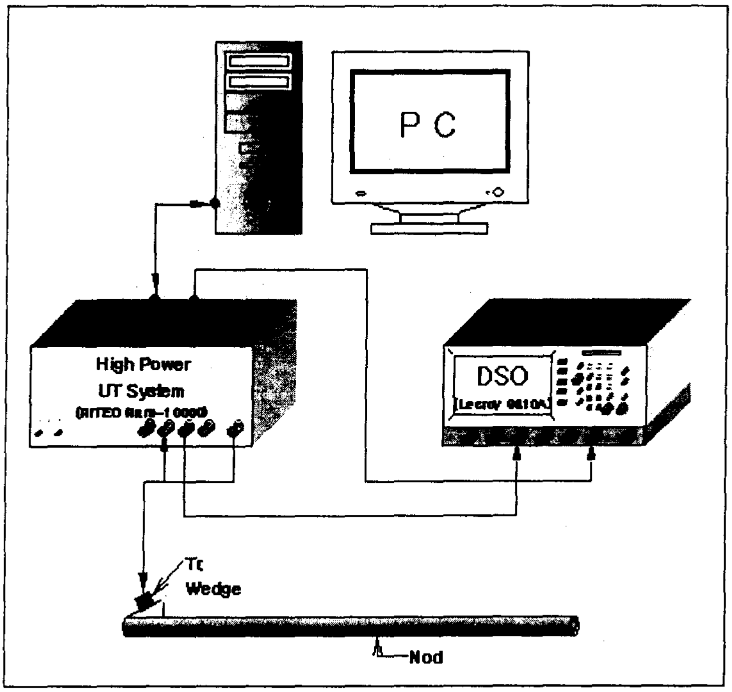


Fig. 3. Experimental equipments for guide wave generation and measurement

A preliminary experiment is conducted to make sure that the arrangement for the guided wave generation in Fig. 3 works well for a rod specimen that has an artificial defect on the surface near the one end similar to the real crack but larger in size. The defect is a notch parallel to the axial axis made by electric discharge machining (EDM) and represented in Fig. 4, where the defect is 50mm long in axial direction and 1mm deep toward the center of circular cross section. The coil spring rod used in experiment has the diameter of 12mm and the length of 1400mm as described partly in Fig. 4, where a spiral peeling traces are present on the surface even though it cannot be seen easily. Guided wave is generated on the opposite side of the notch at three different circumferential positions described in Fig. 1. The reflected waves obtained from the notch at different detection points are described in Fig. 6-8. Fig. 6 shows the reflected guided wave from notch when the detection position is on the same circumferential position represented by the position 1 in Fig. 1. Fig. 7 shows the guided wave when the generation and detection position is at 90 degree with notch as described in Fig.1. In Fig. 8 the guided wave is produced and detected at the position 3 in Fig. 1 on the back of notch. Clear reflection signal can be observed from the notch for all cases although the wave features are different due to different boundary condition. These results indicate that the guide wave technique has a total volume inspection capability for the defects in cylindrical rod. It is a very important characteristic of guided wave when the defect location is now known in priori before inspection.

Fig. 4. Rod specimen with an EDM notch

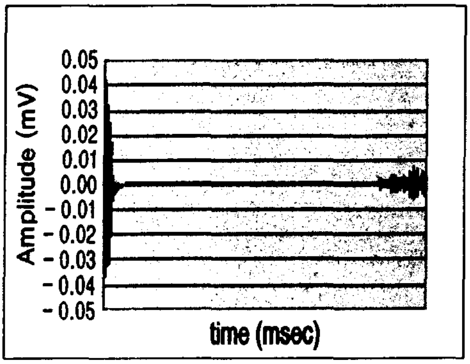


Fig. 5. Guided wave from a rod without EDM notch

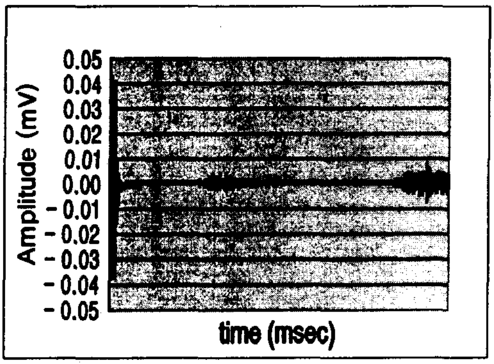


Fig. 6. Guided wave from EDM notch at the position 1

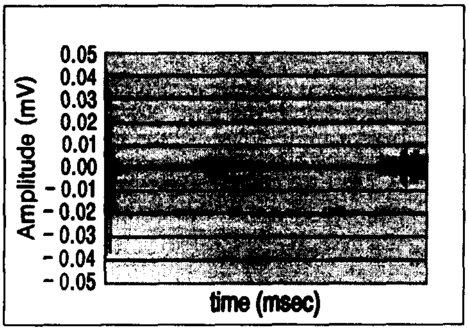


Fig. 7. Guided wave from EDM notch at the position 2

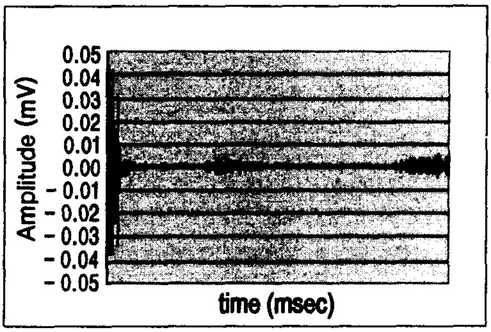


Fig. 8. Guided wave from EDM notch at the position 3

5. GUIDED WAVE INSPECTION OF SURFACE NOTCH IN RODS

5.1 Preparation of test specimen

Seven kinds of coil spring rod are made to test the feasibility of the guided wave technique described in Fig. 3 for the inspection of surface crack (notch) and determine how small crack can be detected. Each rod is a low carbon stainless steel and has a different size of EDM notch on the surface. In Table 1, the detail specification of test specimen and notches are listed. Surface crack size is represented in Table 1 by its dimensions including the depth, width and length of crack. Real crack size frequently produced in the manufacturing process is about 100μm in depth, less than 10μm in width, and longer than 30mm in length.

Table 1. Specification of test specimen with EDM notch

Diameter	EDM notch size		
	Depth (μm)	Width (um)	Length (mm)
12mm	50	60	50
	75	60	
	100	60	
	200	60	
	500	60	
	1	60	
	1	200	

5.2 Experimental results and discussion

Rods with different sizes of notch are examined by the same experimental setup used in the preliminary test. The incident angle and the wave frequency are 72° along the axial axis and 2.25 MHz. A rod without any notch is inspected first and a guided wave signal measured in experiment is described in Fig. 9, where the first big signal appearing in the beginning is the reflection signal from the wedge and the following signal of relatively large amplitude is the reflected wave from the edge. Between both signals, no reflection waves are found because there is no defects in the specimen. The guided wave signal obtained from the specimen with a notch of 1mm in depth is shown in Fig. 10, where a reflected wave from the notch can be recognized in the middle of time axis. It is not big in this diagram, but larger than the noise level enough to be identified clearly when it is zoomed. It is surely notch signal because it always appears at the same position no matter how the geometric condition of incident angle is changed. However, if the notch size decreases to 0.5mm in depth with the same width and length, the reflection wave from the notch is hardly distinguished from the noise induced by the peeling mark or surface roughness as shown in Fig. 11. When the notch size becomes smaller, the guided wave reflected from the notch cannot be seen at all. Fig. 12 represents this case when the notch is 0.2mm, where the notch signal is too small to be observed at the notch position displayed by an arrow on the time axis. For notches less than 0.2 mm in depth, the same results are obtained and no notches can be detected. Considering that the nominal roughness of the rod is about 300 μm, the probability of detection (POD) of the notch larger than the surface roughness is very low even though the axial length of notch is so long. It is because the noisy reflection waves produced by the surface roughness reduce the signal-to-noise ratio (SNR). From the experimental data, it is seen that the notch length does not affect POD significantly but the depth of notch is important to POD. The deeper notch gives the higher SNR value for the guided wave inspection. It is found in experiment that only a notch with a depth larger than 5% of rod diameter is detectable using guided wave technique. Also POD does not seem to be influenced by the circumferential position of notch while the amplitude and waveform of guided wave changes according to its position.

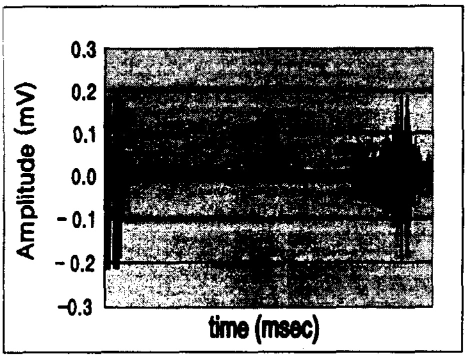


Fig. 9. Guided wave from a rod without notch

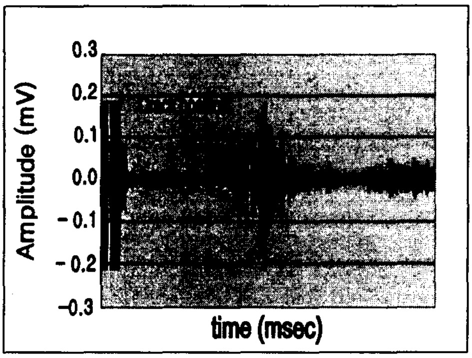


Fig. 10. Reflected guided wave from 1mm notch

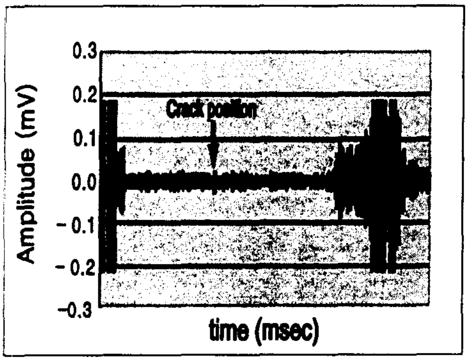


Fig. 11. Reflected guided wave from 0.5mm notch

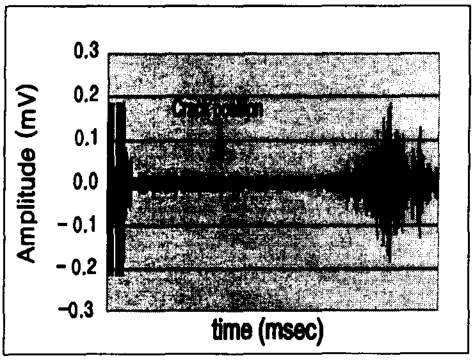


Fig. 12. Reflected guided wave from 0.2mm notch

6. CONCLUSION

Guided wave technique is applied to detect a crack-like defect on coil spring rod for passenger car. 1.4m long spring rods with different size of EDM notch are fabricated and inspected to detect the notch and investigate the POD of the guided wave methods for the circular solid rods. A simple experimental apparatus is set up to generate and detect a guided wave along the rod of 12mm diameter. Incident angle and frequency of ultrasound is optimized experimentally to generate the most sensitive guided wave for the axial notch which has the same geometric orientation as the real surface crack. Preliminary test shows that the guided wave propagates well along the three dimensional coil spring and gives a very nice reflection echoes from the EDM notch. It is proved that guided wave is very sensitive to the surface breaking crack (notch) and provides a very efficient tool for real-time inspection of defects in coil spring. A notch size down to 1mm in depth is detected using 2.25 MHz ultrasound. However, the SNR of guided wave signal is reduced significantly for the notch smaller than 1mm due to surface roughness. It is concluded from experimental results that the guided wave technique developed in this study is very fast and effective to inspect a surface defect but not enough to detect such a small crack as produced in manufacturing process.

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