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New Ultrasonic Guided Wave Testing using Remote Excitation of Trapped Energy Mode

Morio ONOE [1], Kenji OKA [2] and Takanobu SUZUKI [2]

[1] Professor Emeritus, University of Tokyo, Tokyo, Japan

Phone: +81 3 5790 6321; e-mail: m.onoe@ieee.org

[2] KGK Co. Ltd., Kawasaki, Japan

Phone: +81 44 277 0121, Fax: +81 44 277 0120; e-mail: kgk@probe-kgk.com

Abstract

Ultrasonic guided waves have been used in testing of such an elongated object as pipe. Its sensitivity and distance resolution, however, have been limited by velocity dispersion and interference of numerous propagation modes of guided waves.

Trapped energy mode of vibration of thickness shear waves in a quartz plate has been widely used in frequency control and selection due to its high Q and localization. One of the authors (MO) found similar trapped modes of horizontal shear or torsional waves in a cylinder, which are suitable for inspection of pipes. The resonant frequency and Q of a trapped energy mode can be remotely measured by reflection of a propagating guided wave at its boundary. The lowest mode is preferred, because it propagates without waveform distortion due to dispersion. A part of energy in a propagating guided wave excites the trapped energy mode through mode conversion and then leaks out to the original propagating wave. This leak appears as a long-tailed ringing due to a high Q of the trapped mode. The resonant frequency and Q of a trapped energy is sensitive to changes in its vibrating region and hence can be used to sense changes in plate thickness, surface condition (roughness and corrosion) and liquid loading (density and viscosity), etc.

An analysis based on a multiple transmission line model and an experimental verification of remote excitation of a trapped mode are presented.

Keywords: ultrasonic testing, guided wave, trapped energy mode, pipe inspection, remote sensing

1. Introduction

Traditional ultrasonic testing commonly uses bulk, either longitudinal or shear, waves traveling in a free space with occasional reflection at boundaries. Guided waves travel along boundaries of such elongated object as plates, rods, pipes, etc with nearly uniform cross section. These objects are called waveguides. Since the divergence of energy is limited by boundaries, spreading loss of guided waves is much smaller than that of bulk waves. This is an attractive feature in testing of such elongated objects.

Velocity of bulk waves is a constant solely determined by material properties. In the case of guided waves, however, phase and group velocities and also distributions of displacement and stress usually depend on frequency, which is called (velocity) dispersion. This is because its formula called dispersion equation, which governs relationships between frequency and wave number (propagation constant), includes terms of some dimensions of cross section of a waveguide, for example thickness of a plate or a surface layer. Notable exceptions are Rayleigh surface wave on a semi-infinite medium, the lowest mode of horizontal shear (SH) wave in a plate and the lowest mode of torsional wave in a solid or hollow cylinder, of which details will be discussed later.

Besides of dispersion, guided waves have plural modes of propagation. A higher mode has a cutoff frequency, above which a wave can propagate freely, whereas below which a wave becomes evanescent and its amplitude decay exponentially with distance.

Mathematical studies of elastic guided waves began with surface wave by Rayleigh [1] and plate wave by Rayleigh and Lamb [2][3]. Although both waves were used from the very beginning of ultrasonic testing, their range of application has been rather limited. [4] In 1960's, Lamb waves were used in online inspection of thin steel plates. [5] Recently there have been renewed interests on guided wave inspection and many new fields of application have been explored. [6][7]

In all these traditional applications, both velocity dispersion and multiple modes of propagation have been constant problems, because it distort shape of a pulse used in ultrasonic testing and hence degrade time (distance) resolution and make an interpretation of test result difficult.

This paper presents a new ultrasonic guided wave inspection method which will overcome these two major problems. It rely on remote excitation of a trapped energy mode through mode conversion from the fundamental non-dispersive mode of propagation. A region of interest of a test object is deformed, for example by increasing the thickness, so that a trapped energy mode can exist. As the name suggests, the vibration energy of a trapped energy mode is concentrated in the region of interest. The quality factor (Q) of resonance is usually very high, because there is no leak of energy to surrounding regions. Hence its resonant frequency and Q sensitively reflect such characteristics of the region of interest as thickness, corrosion and liquid loading. Therefore a region of trapped energy mode can be considered as a sensor.

With appropriate choice of a transducer and a frequency, it is possible to transmit a pulse only in the desired non-dispersive mode from a remote location. There is no problem of wave distortion due to dispersion. When a propagating pulse hits a boundary of a trapped energy region, a part of energy is converted into the trapped energy mode. This conversion can be detected by a sharp change of mechanical impedance of reflection coefficient at the resonant frequency of the trapped mode. Also trapped energy gradually leaks out again in the propagating mode, which can be observed as a long-tailed ringing. Plural regions of interest of differently assigned frequency can be interrogated by a single transmitted pulse. Since the location of interested regions is predetermined, there is no problem of ambiguity in distance resolution.

This paper starts with a brief review of trapped energy modes. A catalog of trapped energy modes in various objects is given, which includes a few newly found modes. A theoretical analysis of remote excitation of trapped energy mode is presented based on a multiple transmission line model. Experiments using SH waves in a plate and circumferential shear (C-SH) waves in a hollow cylinder (pipe) are conducted with a good agreement with the theory.

2. Trapped energy modes

A dispersion equation governs a relationship between frequency and wave number (propagation constant) of guided waves propagating along an elongated medium with nearly constant cross-section which is called waveguide. Many guided waves have dispersion curves (solid line) shown in Fig.1. There is a cutoff frequency, which is usually equal to the fundamental thickness resonant frequency of an infinite plate or its harmonic overtone. Above the cutoff frequency, a wave propagates freely, whereas below the cutoff the wave becomes evanescent. We make a portion of a plate, which is called here center portion, a little thicker than the surrounding regions, so that its cutoff frequency becomes lower than the cutoff of the surrounding regions. Then the dispersion curve of the center portion is shifted down as shown by a dotted line in Fig.1.

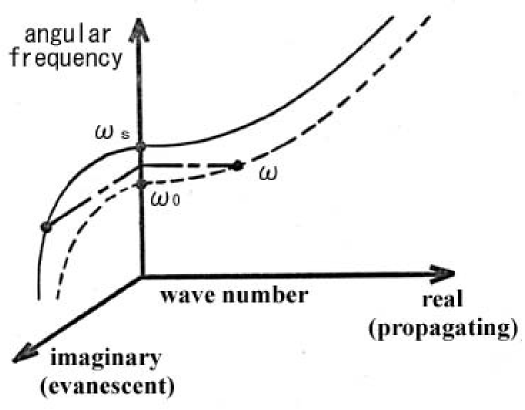


Fig. 1 Dispersion curves.

In-between two cutoff frequencies, a wave propagates freely in the center portion, whereas the wave becomes evanescent in the surrounding regions and its amplitude decay exponentially with distance. This decay is not due to material loss, but due to reactive reflection from a virtual boundary. Hence the wave reflects back and forth between virtual boundaries at both sides, thus forms a standing wave, that is a resonance. Since the vibration energy is trapped in the vicinity of the center portion, this mode of vibration is called a trapped energy mode. The intrinsic quality factor (Q) of a resonance of a trapped energy mode is determined by loss of material itself and very high. Hence both a resonant frequency and a Q are sensitive to changes of its environment. It can be used as a sensor to detect changes in plate thickness, surface condition (roughness and corrosion) and liquid loading (density and viscosity).

Trapped energy modes of thickness shear waves in a plate have been widely used in frequency control and selection. [8][9] Similar trapped energy modes exist in various waveguides as shown in Table. 1.

Items	References
SH waves in a plate	Shockley [8], Onoe [9]
Torsional waves in a solid cylinder	Johnson, et al [10]
Axially symmetric torsional waves in a plate	Knowles, et al [11-13]
Torsional waves in a hollow cylinder	Onoe [14]
C-SH waves in a hollow cylinder	Onoe [15]

Tabel 1: Family of trapped energy modes in plates and cylinders.

Dispersion curves of this family of trapped energy modes are very much similar to Fig. 1. When the thickness is small, analyses based on SH waves in a plate yield a good approximation for all the family.

Heretofore piezoelectric or magnetostrictive transduction has been used for direct excitation and detection of trapped energy modes. This paper presents a remote excitation of trapped energy modes through mode conversion from a propagating mode.

When a propagating wave hits a boundary of a trapped energy region, a part of energy is converted into the trapped energy mode. The stored energy in the trapped mode gradually leaks out by reconversion to the propagating mode, which appears as the ringing. Since the Q of the trapped mode is very high, the ringing lasts a long time.

This also reflects in a change of mechanical impedance or reflection coefficient, which allows a measurement of the resonant frequency and the Q of the trapped mode. Plural regions of trapped mode with differently assigned resonant frequencies can be located in a single plate or cylinder without mutual interference, so that a simultaneous remote interrogation of all interested regions can be done.

The lowest (zero-th) mode of SH waves in a plate and torsional waves in a plate or a cylinder is non-dispersive and hence can propagate a long distance without distortion in waveform. If the frequency of excitation is lower than the first cutoff frequency, all higher modes become evanescent and cause no interference on observed waveform. This makes an interpretation of measured results simpler.

A pulse used in transmission has a finite bandwidth of frequency around a center frequency. A part of which has to include a resonance frequency of a trapped energy mode for an efficient mode conversion. The cutoff frequency of surrounding regions is higher than, but close to, the resonant frequency of the trapped mode. Hence a higher propagating mode may also be excited. Fortunately group velocity of this mode near the cutoff frequency is very low, a resultant pulse is well separated in time from the main pulse after some distance of propagation. Also its amplitude become small due to a spread of energy in time caused by severe velocity dispersion.

3. Analysis based on Model of Multiple transmission lines [16][17]

As already mentioned in the previous chapter, analyses of SH waves in a plate yield a good approximation for all the family of trapped energy modes shown in Table 1, when the thickness is small. We consider a cross section of a central trapped energy region and surrounding regions as shown in Fig. 2.

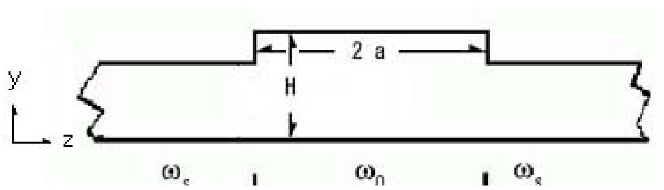


Fig. 2 Cross section of a plate with a central trapped energy region.

Distribution of displacement across the thickness of each mode of SH waves in a plate, constitute a Fourier cos series, which can expand any distribution. [17] Propagation characteristics of each mode can be represented by a transmission line, based on the force-voltage and particle velocity- current analog. Transmission matrix of the m-th mode is given as follows:

$$\begin{pmatrix} T_{2m} \\ \rho V_s v_{2m} \end{pmatrix} = \begin{pmatrix} \cos(\chi\sqrt{\Omega^2-m^2}) & j\dfrac{\sqrt{\Omega^2-m^2}}{\Omega}\sin(\chi\sqrt{\Omega^2-m^2}) \\ \dfrac{j\Omega}{\sqrt{\Omega^2-m^2}}\sin(\chi\sqrt{\Omega^2-m^2}) & \cos(\chi\sqrt{\Omega^2-m^2}) \end{pmatrix} \begin{pmatrix} T_{3m} \\ \rho V_s v_{3m} \end{pmatrix} \quad (1)$$

where $v = j\omega u$: particle velocity, $\chi = \pi d / H$, $d = 2a$

Each region of Fig. 2 can be represented by multiple transmission lines as shown in Fig. 3. M12 and M34 are transformers represent mode conversion at boundaries and mutual couplings between lines in surrounding regions and lines in the center region. The displacement as well as the stress in each region constitute Fourier cos series, boundary conditions can be expanded in Fourier series. [17] As an example, a case of step boudary shown in Fig. 4 is treated.

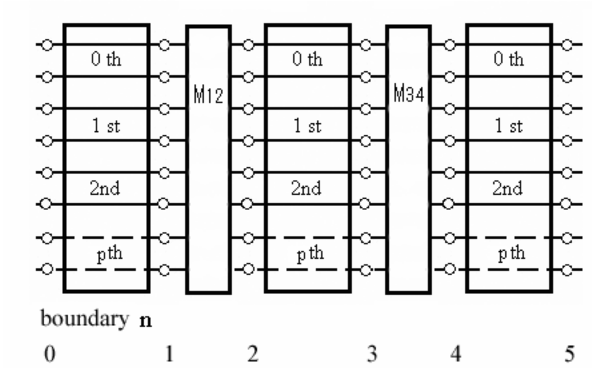


Fig. 3 Multiple transmission line model

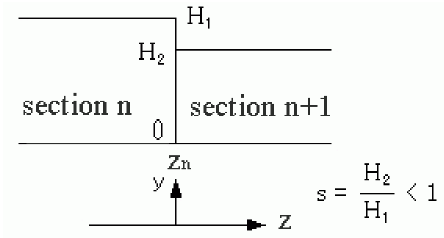


Fig. 4 Enlarged dimensions of a step

First the continuation of displacement in the range (y = 0 – H2) at the boundary is satisfied by the expansion of particle velocity in each line of the (n+1)th section in terms of cos series of the nth section, yielding the matrix (2).

Second the continuation of stress in the range (y = 0 – H2) and the traction-free condition in the range (y = H1 – H2) at the boundary is satisfied by the expansion of stress in each line of the nth section in terms of cos series of the (n+1)th section, yielding the matrix (3).

$$\mathrm{Mv:}\quad \begin{pmatrix} v_{n+1,0} \\ v_{n+1,1} \\ v_{n+1,2} \\ v_{n+1,3} \\ v_{n+1,m} \end{pmatrix} = \begin{pmatrix} 1 & \mathrm{sinc}(s\pi) & \mathrm{sinc}(2s\pi) & \mathrm{sinc}(3s\pi) & - \\ 0 & -\dfrac{2\,\mathrm{sinc}(s\pi)}{1-(\frac{1}{s})^2} & -\dfrac{2\,\mathrm{sinc}(2s\pi)}{1-(\frac{1}{2s})^2} & -\dfrac{2\,\mathrm{sinc}(3s\pi)}{1-(\frac{1}{3s})^2} & - \\ 0 & \dfrac{2\,\mathrm{sinc}(s\pi)}{1-(\frac{2}{s})^2} & \dfrac{2\,\mathrm{sinc}(2s\pi)}{1-(\frac{2}{2s})^2} & \dfrac{2\,\mathrm{sinc}(3s\pi)}{1-(\frac{2}{3s})^2} & - \\ 0 & - & - & (-1)^m \dfrac{2\,\mathrm{sinc}(sp\pi)}{1-(\frac{m}{sp})^2} & - \\ 0 & - & - & - & - \end{pmatrix} \begin{pmatrix} v_{n,0} \\ v_{n,1} \\ v_{n,2} \\ v_{n,3} \\ v_{n,p} \end{pmatrix} \quad (2)$$

$$\mathrm{MT:}\quad \begin{pmatrix} T_{n,0} \\ T_{n,1} \\ T_{n,2} \\ T_{n,3} \\ - \end{pmatrix} = s * \mathrm{Mv}^T * \begin{pmatrix} T_{n+1,0} \\ T_{n+1,1} \\ T_{n+1,2} \\ T_{n+1,3} \\ - \end{pmatrix} \quad (3)$$

It should be noted that the following normalized frequency has to be used in these equations.

$$\Omega_1 = \omega/\omega_s \quad \text{for surrounding regions}$$
$$\Omega_2 = \omega/\omega_s \quad \text{for the center region}$$
$$s = H_2/H_1 = \omega_0/\omega_s < 1 \qquad (4)$$

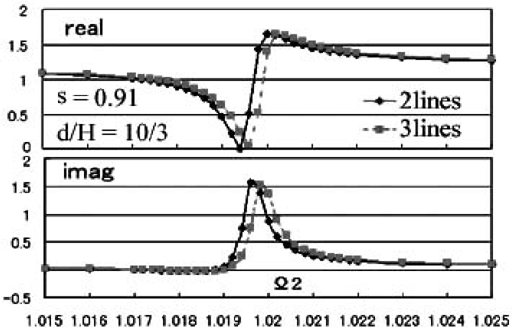


Fig. 5 Mechanical input impedance

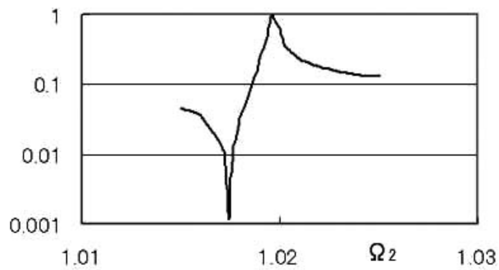


Fig. 6 Reflection coefficient

Now characteristics of the whole network shown in Fig. 3 can be calculated by a simple matrix multiplication. Fig. 5 shows a calculated mechanical impedance at the terminal (0 – 0') for a step height of 9 percent for the incoming zero-th mode. Solid lines are calculated using two transmission lines (m=0,1), whereas dotted lines are calculated using three transmission lines (m=0,1,2). For a smaller step height, two approximations yield almost same results. Fig. 6 is a reflection coefficient calculated from mechanical impedance. There is a sharp minimum followed by a sharp maximum in the reflection due to the trapped energy mode.

The transmission line model is also useful to analyze characteristics of both edge-mouted and surface-mounted transducers.

4. Experiments [18][19]

Extensive experiments have been conducted. A few examples to prove a feasibility of remote excitation and detection of a trapped energy mode are shown here.

Both SH waves in a plate and C-SH waves in a partial hollow cylinder (pipe) were studied. In the former, a steel plate of 2.7mm thick is used. In the middle of plate, there is a mesa of the step height of 0.3mm and the z-length of 4mm, which yields a resonant frequency of thickness shear mode of 0.55 MHz. In the latter, a steel pipe of 3 mm thickness and the inner diameter of 600 mm with a similar messa is used. The cylinder is cut into a sector of 73 degree, so that back echo is available for calibration.

Fig. 7 compares impulse responses of back echo and echo from the mesa, respectively. A notable ringing can be seen in the latter. These are more apparent in 2D plot of Fourier frequency spectrum with moving short time window.

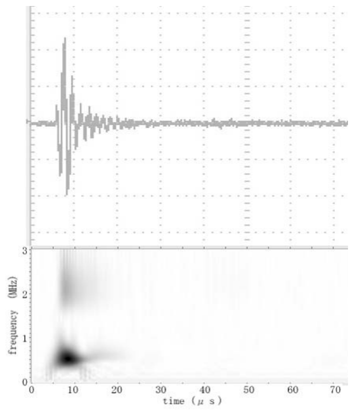
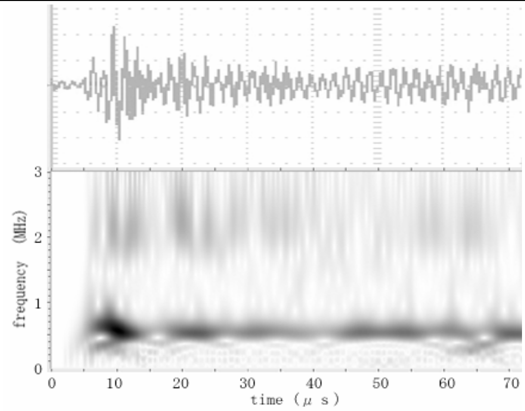
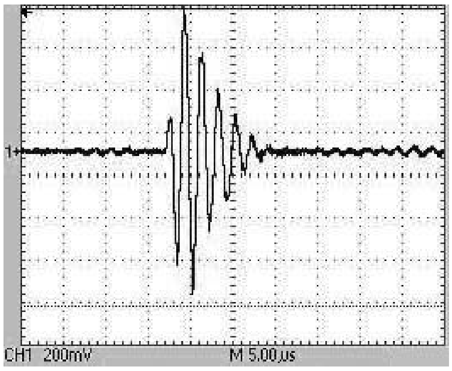
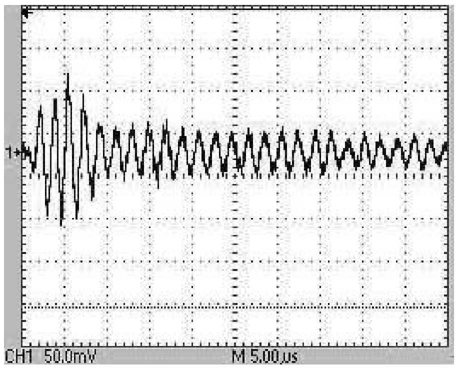
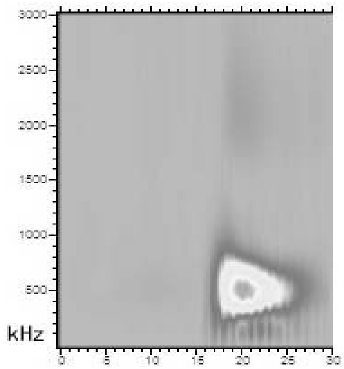
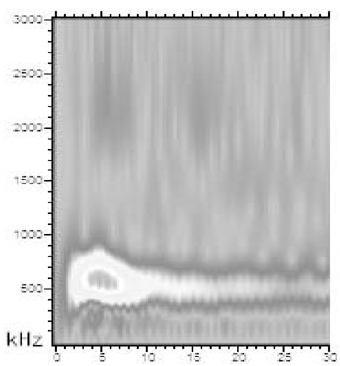
	Back echo	Echo from mesa
SH wave in Plate Waveform 2DFFT		
C-SH wave in partial hollow cylinder (pipe) Waveform		
2DFFT		

Fig. 7　Impulse responses and its 2D FFT

Fig. 8 shows reflection coefficient of the mesa to a burst excitation of 20 cycles. There is a minimum followed by a maximum as shown in Fig. 6. Waveforms at near the minimum and the maximum are shown in Fig. 9. In the latter, excitation has not yet reached a stationary state due to a high Q, and hence the measurement of maximum amplitude has not been accurate.

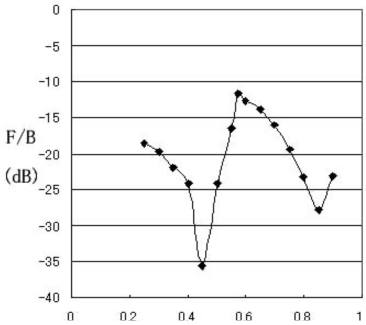


Fig. 8 Reflection coefficient

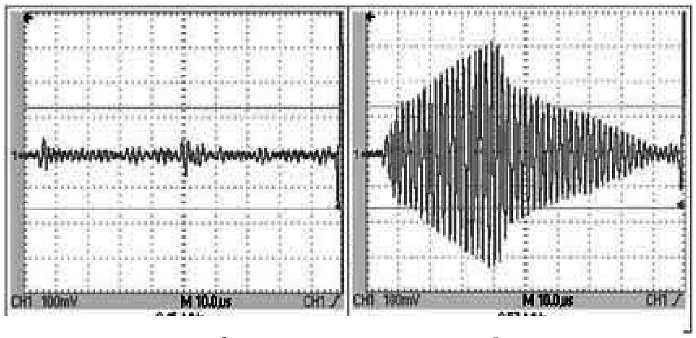


Fig. 9 Waveforms at minimum and maximum

Similar responses are obtained from a mesa formed by a thin sheet of metal pasted to a smooth surface by adhesive. This provides a practical method in field tests of non-destructive testing.

4. Conclusion

A new ultrasonic guided wave testing based on remote excitation of trapped energy mode is presented. It overcomes difficulties due to velocity dispersion and multiple mode propagation, to which conventional guided wave testing has been vulnerable.

A family of trapped energy modes in various configurations is presented. When the thickness is small, their dispersion curves are similar to those of SH waves in a plate. Hence an analysis for the latter yield a good approximation for the whole family.

An analysis based on a multiple transmission line model is presented with a good agreement with experiments. The resonant frequency and Q of a trapped energy is sensitive to changes in its vibrating region. Hence the present method is useful in remote sensing and non-destructive testing of thickness, surface condition (roughness and corrosion) and liquid loading (density and viscosity), etc of elongated objects such as pipes.

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