Numerical study on optimum design of a clad waveguide for ultrasonic pulse-echo measurements with high signal-to-noise ratio

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Abstract
Ultrasonic waveguides have been widely used for material characterizations, flaw detections and health monitoring by ultrasonic pulse-echo methods. Although a clad waveguide consisting of a core rod and a cladding layer has been expected to be the most promising waveguide for practical applications, little is known about an appropriate material combination for the cladding and core. In this work, numerical simulations are performed to investigate an optimum combination of the materials for the cladding and core of a clad waveguide. Wave propagations are examined for a series of clad waveguides having different combinations of material properties using a two-dimensional finite different analysis. In the analysis, steel is used as the core material, and the density and ultrasonic wave velocity of the cladding material are systematically changed, and the signal-to-noise ratios (SNRs) of ultrasonic pulse waves propagating through the clad waveguides are estimated. It is found that the SNR changes drastically with the material combination for the cladding and core and the highest SNR is appeared when the velocity and density of the cladding are approximately 120% and 70% of the core, respectively. It should be noted that an appropriate SNR is obtained when the velocity of cladding is approximately 110% of the core regardless of the density value of the cladding on the condition that the density value is within the range from 75% to 150% of the core. This fact obtained here could be useful for designing desirable ultrasonic clad waveguides used for practical applications.

Key words: Nondestructive evaluation, Ultrasonic pulse-echo measurement, Clad waveguide, Numerical simulation, Optimum design, Signal-to-noise ratio

1. Introduction

Ultrasonic measurement techniques have been extensively used for nondestructive evaluations in many fields of science and engineering because of its capability to probe the interior of solid and liquid materials. In particular, ultrasonic pulse-echo methods are successfully applied to materials characterizations and structures health monitoring such as flaw detections, sizing and locating of objects, mechanical property determinations and microstructural estimations (Krautkramer, et al., 1990, Thurston, et al., 1990, Rose, 1999, Kundu, 2004). This technique is also available for online monitoring of materials processing at high temperature and in-situ observations in hazardous environments. For such applications, a buffer rod is often used as an ultrasonic waveguide (Lynnworth, 1989). A conventional piezoelectric ultrasonic transducer is installed to the one end of the buffer rod and the other end is in contact with the material to be measured so that the ultrasonic transducer can be protected from high temperature or hazardous environments. The crucial problem in ultrasonic pulse-echo measurements using such buffer rods is, in most cases, caused by spurious echoes (also called trailing echoes) due to interference of mode converted waves, dispersion, and diffraction within the rod of finite diameter (Thurston, 1978). These spurious echoes deteriorate the signal to noise ratio (SNR) because of their possible interference with desired signals to be measured. To overcome such problem, clad waveguides (often called clad buffer rods) consisting of a core rod and a cladding layer were developed and it was
experimentally demonstrated that the spurious echoes are significantly reduced by the cladding effect (Jen, et al., 1996, Jen, et al., 2000). Such clad waveguides were applied to several materials and process monitoring at high temperatures, such as die-casting process monitoring (Moisan, et al., 2001), curing process monitoring of molten polymer (Legros, et al., 1999), plastic forming process monitoring (Piche, et al., 1999), imaging and material characterization in molten zinc (Ihara, et al., 2000), injection molding process monitoring of semi-solid magnesium die casting (Jen, et al., 2004), cleanliness evaluation of molten light metals (Ono, et al., 2004), in-situ observation of solid/liquid interface of aluminum alloy (Burhan, et al., 2005) and molten glass measurement (Ihara, et al., 2015). Thus, clad waveguides provide desirable pulse-echo measurements with high SNR and are highly expected to be a powerful tool for various materials monitoring at high temperatures. Although it has been known that the SNR may strongly depend on the material combination of the cladding layer and core rod of a clad waveguide, little is known about the appropriate material combination. This is basically because of difficulty in theoretical prediction of the SNR of ultrasonic waves propagating through a clad waveguide (Jen, 1985, Hoppe, 2003). Therefore, trial and error is indispensable to find the appropriate material combination and consequently, the designing and fabrication of a clad waveguide are not straightforward procedure. Such difficulty in materials selection is a crucial problem to be solved for spreading practical applications of clad waveguides. It is noted here that a difference of the acoustic impedances at the interface between the cladding layer and core of a clad waveguide plays an important role in generating spurious echoes that deteriorate the SNR of ultrasonic waves (Thurston, 1978). Considering this fact, in this work, an optimum combination of the materials for cladding and core was examined by numerically analyzing ultrasonic pulse waves for a series of clad waveguides having different combinations of the cladding and core materials. It is expected that the new finding on such an optimum combination could be very beneficial for designing and fabricating a desired clad waveguide. For fabricating a clad waveguide designed appropriately, an advanced manufacturing technique such as a 3D printer system may be successfully employed in the very near future.

2. Numerical Evaluation of Ultrasonic Pulse Echoes in Clad Waveguide

Ultrasonic pulse echoes propagating through a clad waveguide shown in Fig.1 are investigated by numerical simulations. The clad waveguide consists of a core rod and a cladding layer, and an ultrasonic transducer is installed on the surface at the end of the core rod. The behaviors of ultrasonic pulse echoes and accompanying trailing echoes generated by wave reverberation and mode conversion at the interface between the cladding and core during wave propagation through the waveguide, are examined for a series of clad waveguides having different combinations of the cladding and core materials.

A finite difference method with two-dimensional isotropic model is used for examining the ultrasonic wave behaviors because the propagation characteristics of the predominant guide mode in cylinder rods at relatively high frequencies can be approximately estimated by two dimensional analysis in Cartesian coordinate (McSkimin, 1956, Ihara, et al., 2004). In fact, it was successfully demonstrated with a non-clad waveguide that such two dimensional analysis provides proper estimations of wave behaviors that almost agree with experimental results (Ihara, et al., 2001). In order to make a successful calculation, the time step $\Delta t$ is chosen according to the von Neumann stability criterion (Altermann, et al., 1970), $\Delta t \leq \frac{\varepsilon}{(v_l^2 + v_s^2)^{1/2}}$, where $v_l$ and $v_s$ are the longitudinal and shear wave velocities,
respectively, and $\varepsilon$ is the grid spacing in the analysis. To obtain sufficient accuracy in the calculation, the grid spacing should be smaller than the shortest wavelength that is related to the highest frequency in the pulse and the lowest wave velocity in the medium. In the finite difference analysis, the grid points are spaced at intervals of $1/10$ of shear wavelength. The behaviors of longitudinal waves in the medium can be obtained at every time step, under the boundary conditions at every interface that impose continuity of stresses and displacements in the medium, as long as the stability requirement for the finite difference calculation is satisfied. A commercially-available software, Wave 2000 Pro, from Cyber Logic Inc. was used for the simulations.

Since it is important to examine the influence of the difference in acoustic impedances at the interface between the cladding and core of a clad waveguide, in this work, two parameters: the density and ultrasonic wave velocity of the cladding, are systematically changed from $50\%$ to $150\%$ of those of the core which is assumed to be steel. The longitudinal wave velocity, shear wave velocity and density of the steel core used in the analysis are $5900$ m/s, $3200$ m/s, and $7800$ kg/m$^3$, respectively. It is noted that both longitudinal and shear wave velocities are simultaneously changed in the simulations. The length and diameter of the rod are $25$ mm and $5$ mm, respectively, and the thickness of the cladding is $2$ mm. Although the size of the waveguide is relatively small, it is still possible to examine the influence of acoustic impedances at the interface. The diameter of the ultrasonic transducer is $1.6$ mm and a Gaussian-type longitudinal pulse of $5$ MHz is employed.

3. Results and Discussion

3.1 Wave propagation in clad waveguide

Figure 2 shows a simulation result of pulse wave propagation for a clad waveguide, where the density of the cladding is the same as the core, and the longitudinal and shear wave velocities of the cladding are $90\%$ of the core, respectively. Figure 2 shows six snapshot images of the displacement components of pulse waves using amplitude map representation at a given instant during the wave propagation through the waveguide, where the yellow arrow in each snapshot denotes the direction of wave propagation and the black arrow denotes the progress of time. A longitudinal pulse wave propagating in the core and other waves accompanying the longitudinal wave propagation is observed in Fig. 2. Such accompanying waves are produced by reflections, refractions and mode conversions at the interface between the cladding and core and result in trailing echoes due to interferences of the mode converted waves within the core (Thurston, 1978, Jen, et al., 1996). In fact, it can be seen in the images of Fig. 2 that a trailing echo is gradually being produced as time progresses and its formation is almost completed at the last image in Fig. 2. Thus, the use of the

![Simulation results showing snapshot images of ultrasonic pulse waves propagating through the clad waveguide.](image_url)

Fig. 2 Simulation results showing snapshot images of ultrasonic pulse waves propagating through the clad waveguide, where “black arrows” denote the progress of time and “yellow arrows” denote the direction of wave propagation.
numerical simulation has an advantage that not only the propagation of a main pulse wave but also the behavior of reflected and transmitted waves at the interface can be clearly observed.

Although the behaviors of pulse waves in the clad waveguide are complicated, the final waveform obtained using the ultrasonic transducer in the simulation is rather simple and gives a typical pulse-echo configuration as shown in Fig. 3: it consists of a clear first main echo, an accompanying trailing echoes, and the second main echo due to two round trips through the waveguide. In this work, SNR is defined as a ratio of the amplitude of the first main echo relative to that of the largest among trailing echoes accompanying the main echo: $SNR=A_0/A_1$. The value of SNR is used as a measure to evaluate the performance of clad waveguides.

3.2 Influence of acoustic impedance of cladding on trailing echo

In order to examine the influence of the acoustic impedance of a cladding layer on trailing echoes, pulse wave propagations are examined for different clad waveguides. In the examinations, the longitudinal and shear wave velocities of the cladding are systematically changed within the range from 50% to 150% of those of the core while the density of the cladding is kept constant to be the same value as that of the core. The core is assumed to be a steel whose longitudinal wave velocity, shear wave velocity and density are 5900 m/s, 3200 m/s, and 7800 kg/m$^3$, respectively.

Figure 4 shows snapshot images for pulse wave propagations and the corresponding final waveforms obtained using the ultrasonic transducer, for seven kinds of clad waveguides whose ultrasonic wave velocities of the cladding are different. The reflected first echo just before arrival at the ultrasonic transducer is clearly shown in each snapshot in Fig. 4. It is noted that the clad waveguide model ($V_{clad}=100\%V_{core}$) used for the snapshot shown at the fourth from the top in Fig. 4 is essentially identical to a non-clad waveguide because the cladding and core have the same acoustic impedance. As we expected for such a model, a trailing echo which is still being developed at this moment can be observed in the snapshot shown at the fourth in Fig. 4. Similar trailing echoes are also appeared in the other waveguides ($V_{clad}=90\%V_{core}$, $V_{clad}=80\%V_{core}$) whose wave velocities are less than that of the core. In fact, clear trailing echoes are observed in the waveforms shown in the right hand side of Fig. 4, where the expected area for the appearance of trailing echoes is shown by a gray halftone screening. The snapshot image for the waveguide ($V_{clad}=50\%V_{core}$) does not have such a distinct trailing echo, but many spurious echoes are observed in the reflected waveform as shown at the top of Fig. 4. It is noted that such generation status of trailing echoes for the waveguides whose wave velocities of the cladding are slower than that of the core ($V_{clad}=50$ to $90\%V_{core}$) are different from that for the waveguides whose wave velocities of the cladding are faster than that of the core ($V_{clad}=110$ to $150\%V_{core}$), i.e. almost no significant trailing echoes are generated for the waveguides having faster cladding velocities ($V_{clad}=110$ to $150\%V_{core}$). This is basically because the partial conversion of longitudinal waves to shear waves at the interface between the cladding and core is restrained in such waveguides having faster cladding velocities and less shear waves causing trailing echoes is generated at the interface (Thurston, 1978). It is also found from Fig. 4 that the amplitude, location and number of trailing echoes depend on the values of wave velocities. Such velocity dependent phenomenon of the trailing echoes is related to wave reflection and refraction at the interface. The velocity of cladding basically influences the refraction
angle in the cladding and the amplitude of reflection and refraction waves. Based on former studies on the ultrasonic wave propagation in a clad waveguide (Thurston, 1978, Jen, 1985, 2000), it is considered that faster velocities of cladding provide better wave guidance ability for longitudinal mode elastic waves in clad waveguides. Regarding the generation of trailing echo, it is basically explained on the basis of geometrical optics and the partial conversion of longitudinal waves to shear waves at the interface between the cladding and core. This means that not only the reflected shear wave which is mode-converted at the interface but also refracted waves which are transmitted into the cladding from the core play an important role in generating the trailing echoes although such partial conversion of the waves depends on the incident angle to the interface. In general, the refraction angle increases with the velocity of cladding and can be almost parallel to the interface when the velocity have a particular value with which the incident angle is near a critical angle. In such situation, it is considered that the generation of spurious noises is partially restrained owing to a kind of confinement effect of the refracted waves to the cladding. Although further study is necessary to make this mechanism clear, the faster velocity of cladding seems to be effective to reduce trailing echoes as shown in Fig. 4. However, it is also noted that such faster velocity simultaneously gives a larger difference in acoustic impedances between the cladding and core. Such larger difference in acoustic impedances may results in increasing the amplitude of trailing echoes due to the increase of the amplitude of reflected shear waves in the core. Thus, the faster velocity of cladding may not be always effective to reduce trailing echoes and there may exist an optimum value of the velocity.

3.3 Finding the optimum property for cladding layer

![Simulation results showing snapshot images of pulse wave propagations for seven kinds of clad waveguides (left) and the corresponding final waveforms obtained using the ultrasonic transducer (right).](image-url)
In order to make further investigation of such appropriate condition as mentioned in section 3.2 which provides a higher SNR, the influence of the acoustic impedance of a cladding layer on SNR is extensively examined for different clad waveguides. In the examinations, both the density and wave velocities of a cladding are systematically changed within the range from 50% to 150% of those of a core while the same steel core used in Fig. 4 is employed.

Figure 5(a) shows the variations of the SNR with the wave velocity for various densities, where the percentage of the cladding to the core for each quantity is used as a variable. As we predicted, the tendency that higher SNR can be obtained for the waveguides whose wave velocities of the cladding are faster than that of the core, is observed for any density of the cladding, while the SNR for the waveguides whose wave velocities of the cladding are slower than that of the core always takes small values less than 5. It has been found in the examination that a maximum SNR can be obtained for the combination that the density ratio of cladding is 70% and the velocity ratio of cladding is 120%.

Figure 5(b) shows the variations of the SNR with the density ratio of cladding to the core for various velocity ratios to the core. It is interesting to note here that relatively high and approximately constant value of SNR (the value is about 25) can be obtained throughout the density ratio range from 70% to 150% as the velocity ratio is 110%. Although it is not clear why the SNR can remain almost constant regardless of the density in such range, the existence of such plateau region in the SNR as shown in Fig. 5(b) is very important and beneficial for designing and fabricating clad waveguides because such plateau allows a flexibility to choose an appropriate material for a cladding layer.

Fig. 5 The influence of the acoustic impedance of a cladding layer on SNR, (a) the variations of the SNR with the wave velocity of cladding for various densities of cladding, where the percentage of the cladding to the core for each quantity is used as a variable, (b) the variations of the SNR with the density of cladding for various wave velocities of cladding.

In order to verify the validity of the optimum condition obtained above, ultrasonic pulse echoes propagating through steel waveguides with and without cladding are numerically investigated using the same simulation model used as above. Figure 6(a) shows the reflected waveform for a steel waveguide without cladding. The result is as expected: a series of significant trailing echoes are generated clearly. Figure 6(b) shows the reflected waveform for a steel waveguide with a 2 mm thickness cladding of zirconium oxide (ZrO2), where the longitudinal wave velocity, shear
wave velocity and density for ZrO$_2$ are 7200 m/s, 3660 m/s, and 5700 kg/m$^3$, respectively. The ZrO$_2$ is chosen to be able to meet the optimum condition mentioned above: the cladding velocity ratios to the core for longitudinal and shear waves are 122% and 114%, respectively, and the density ratio to the core is 73%. As we expected, an excellent waveform with no trailing echoes is successfully obtained as shown in Fig. 6(b). Needless to say, similar good waveforms can be obtained for any other cladding layers as long as the property of the cladding satisfies the condition for providing high SNR shown in Fig. 5.

4. Conclusions

To develop high performance clad waveguides for providing effective material characterizations and process monitoring by ultrasonic pulse echo methods, an optimum combination of the materials for the cladding and core used in the clad waveguide was investigated by numerical simulations based on a two-dimensional finite difference analysis. Through the investigations with clad waveguides having a steel core, it was found that the signal-to-noise ratio (SNR) of the ultrasonic pulse wave propagating through the waveguide changes drastically with the properties of the cladding, and the highest SNR is obtained when the velocity and density of the cladding are approximately 120% and 70% of the core, respectively. It was also found that an appropriate SNR can be obtained when the velocity of the cladding is approximately 110% of the core regardless of the density of cladding on the condition that the density is within the range from 75% to 150% of the core. This new finding that there exists a plateau region at where the SNR can remain almost constant regardless of the density is very beneficial for designing and fabricating clad waveguides because such plateau allows a flexibility in choosing an appropriate material for a cladding layer. Thus, it is believed that the information on the optimum materials combination estimated by numerical simulations could be useful for preparing desirable clad waveguides utilized for their practical applications such as materials characterizations and process monitoring.

One of the important future works is to verify the validity of the plateau region shown in Fig. 5(b) by experiments using a series of clad waveguides having different claddings whose densities are different while the velocity is constant. It may be possible to fabricate such clad waveguides if an advanced additive manufacturing technology such as 3-D printing system is effectively employed.

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References


