AN OUTLINE OF APPLICATIONS OF ULTRASONIC GUIDED WAVES IN NON-DESTRUCTIVE TESTING OF LARGE STRUTURES*

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Abstract

Guided waves have been the attractive ways for the nondestructive inspection of the large structure because of their many advantages. The characteristics of guided waves are presented; some consideration of guided waves in the large structure inspection is stated; excitation methods and their merits and shortcomings are introduced. Several typical applications of guided waves in the large structures are followed. It is concluded that the ultrasonic guided waves would be developed continuously in the future, However, owing to the complex dispersion, the inevitable noise and useless signal are met with together which results in the difficulties of extraction and analysis of the useful signal. Therefore some problems still exist in current applications of guided waves.

Keywords: Ultrasonic, Guided waves, Large structures, Dispersion

1. Introduction

Due to their many advantages, the inspection methods using ultrasonic guided waves have been developed rapidly in NDE. Compared with conventional ultrasonic methods, guided waves are characterized by quick inspection speed and low cost. As is known to all, conventional ultrasonic inspection method is to scan the surfaces of structures with a probe point by point. When the structure is large, the results are commonly displayed as a C-scan, which is time consuming and expensive. However, the guided waves method is a very attractive solution to this problem, because guided waves can propagate long distance along the structure, so line scan can de done. Especially, they are very suitable for the inspection of coating or insulating structure without removing coat layer or insulated layer. At present, a lot of research work has been done on them. For example great advances have been gotten by the Imperial college NDT group [1], the Pennsylvania State University[2], the Beijing University of Technology [3], Tongji University[4] and so on.The main points are concentrated on plates, pipes and rails, etc, some of which have been applied in practical inspection.

2. Characteristics of Guided Waves

The main difference between traditional ultrasonic bulk waves and the guided waves is that the propagation of the latter requires boundaries for their existence such as Lamb waves and interface waves. Just because of the boundaries often there is interaction with boundaries by way of reflection and refraction. When constructive interference takes place guided wave modes are generated which is associated with the generation of a wave resonance. And mode conversions occur between longitudinal waves and shear waves. All these makes the guided waves different to bulk waves. The main characteristics are as follows.

2.1.1. Disperse

When longitudinal waves and transverse waves travel in media, their vibration phases will not vary with frequency, so their phase velocities are same to their group velocities. However, the velocities of guided waves are dependent on frequency. Figure 1 shows the dispersion curves for Lamb waves propagating in an Aluminum plate. From this diagram, it can be seen that the group velocities is a function of frequency-thickness product. This means that if the ultrasonic pulse is consisted of many waves with different frequencies, the guided waves will propagate in different velocities. The vibration of particles is the composite of actions of many frequencies. At last, their phase velocities are the velocity of the wave-before of same frequency, and their group velocities are the ones of wave packets consisted of different frequencies. As the distance increases, the wave packets will be wider. The corresponding waveforms away from the edge of the plate 100mm, 200mm, 300mm are shown in Figure 2.

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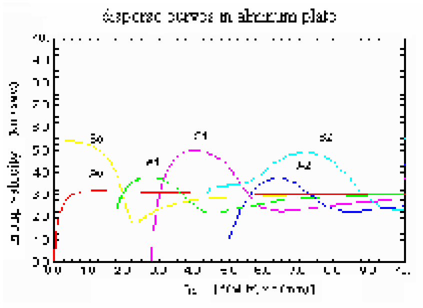
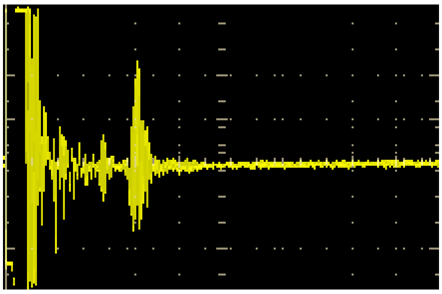
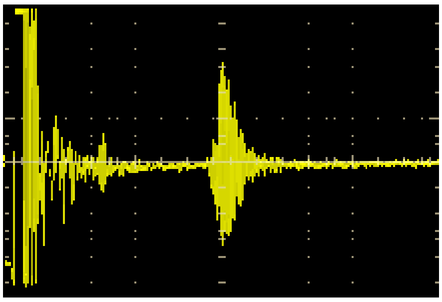


Figure 1*: Disperse curves in Aluminum*



(a)



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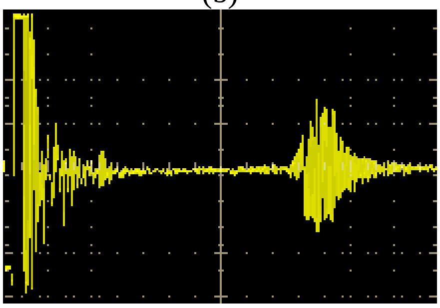


(c)

Figure 2*: Predicted time histories of the propagation of a s0 mode in a 1mm thick aluminum plate excited by 1.5MHz pulse with a single variable beam transducer.(a)at 100mm (b)at 200mm (c)300mm*

2.1.2. Multiple Modes

Guides waves have many modes. And the modes in Different structures are not same. For the instance, the plate wave modes can be divided into two kinds of modes, namely symmetric ones and anti-symmetric ones, where the symmetric ones can be subdivided into S0, S1,…and the anti-symmetric ones into A0, A1,….as shown in Figure 1.However, there are three kinds of modes in pipes: longitudinal modes, torsional modes and flexural modes, where the longitudinal modes are subdivided into L(0,1), L(0,2),…;.the torsional ones into T(0,1), T(0,2),…;and flexural modes into F(1,1), F(1,2),….The guided wave modes in rails are more complicated.

2.1.3. Long Distance

Another main characteristic of guided waves is that they can travel over longer distance than common ultrasonic waves. The distance may be reach up to several meters. The received signal contains all the information of the line between the transmitting and receiving transducers. So line scan can be done to quickly finish the large inspection, which can shorten the inspection time to a large extent and can be used in some cases that the inspection structures are coated with insulator layer or be placed underground, for example the pipes across the road. Only removing some little of coat layer, the entire structure can be inspected. The inspection cost is reduced more.

3. Some considerations for large structure inspection

The use of guided waves for non-destructive inspection falls into two categories depending on the distance of propagation [5]: short-range applications and long-range ones. For the former, sensitivity is of key importance and the effect of dispersion is relatively unimportant as the propagation distances are small. However some factors are important and must not be ignored for the latter. Some considerations for the large structure applications are stated as follows.

3.1.1. Effect of dispersion

The effect of dispersion is that the energy in a wave-packet propagates at different speeds depending on its frequency. This manifests itself as a spreading of the wave-packet in space and time as it propagates through a structure. Figure 3 illustrated this phenomena, the detailed statement is well documented [5].

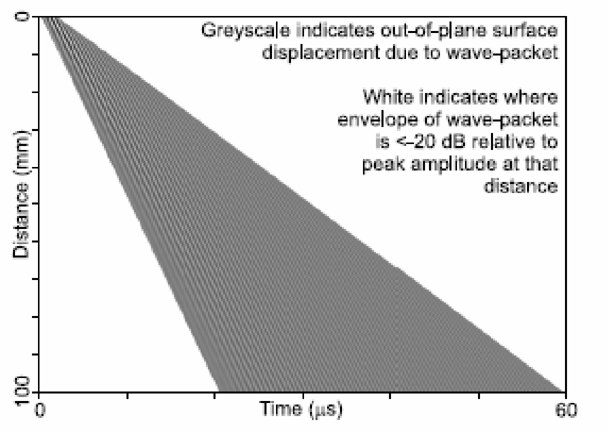
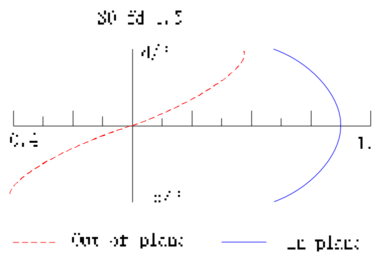


Figure 3: *numerical simulation of the space-time map illustrating the dispersive propagation of the S0 mode in a 1-mm thick aluminum plate when the input signal is a 5-cycle hamming windowed toneburst with a centre frequency of 2Mhz*

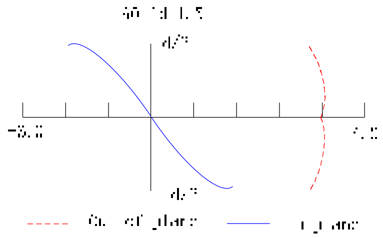
The propagation and spreading of the wave-packet in space and time can be clearly seen on the space-time map above. The effect of dispersion appears as an increase in the duration of the wave-packet in time and a decrease in its amplitude, which is undesirable in long range guided wave testing and consequently reduces the resolution and the sensitivity of the testing system. The variation of waveforms can be seen in figure1 as the distance increases. A parameter called minimum resolvable distance (MRD) has been introduced in document [5] that enables a comparison to be made among the effects of dispersion at different operating points.

3.1.2. Wave structure

It is important to study the wave structure variation when one tries to find a most suitable operating point for a particular structure. At one point the in-plane displacement, out-of-displacement, or actual stress distribution itself varies across the thickness of the structure. Moreover the ratio of the in-plane to out-of-plane displacement changes as one moves along the mode. Figure 4 depict solutions at a varity of fd values to modes S0 and A0 for an aluminum plate[1].



(a) S0 mode



(b) A0 mode

Figure 4: *wave structure for various points on the S0 mode and A0 mode of an aluminum plate*

The various wave structures affect penetration power and sensitivity in a guided wave inspection. When the large structure is tested, the mode and frequency could be selected to obtain the maximum sensitivity according to the wave structure.

3.1.3. Mode Selection

In view of dispersion, in a large structure test, it is practically essential to excite a mode in a non-dispersive frequency–thickness region since otherwise the shape of the wave packet will change as it propagates along the structure and the maximum amplitude present in the signal will decay towards the noise floor, even in the absence of attenuation. It is most conveniently achieved by testing at frequency-thickness products close to the maxima in the group velocity dispersion curves[6][7].

In addition, before choosing a particular mode, it is obviously essential to check that it is sensitive to the defect types of interest. The wave structures give a good indication of the likely sensitivity to defects at different positions through the plate or shell thickness.

3.1.4. Excitation Method

The dispersion makes it not easy to excite the wanted modes. If the signal spectrum is too wide, many modes will overlap together. So it is difficult for the useful signal to be abstracted from complicated signal. Therefore in order to get the ideal signal, it is better to utilize the pure mode as possible. Commonly the pulse can be generated by tone burst function generator, and then be amplified to form excitation pulse with enough power and duration time. Through the ultrasonic pulser–receiver, the pure modes can be excited.

Based on couplant, the excitation methods are mainly classified into two classes: contact ones and non-contact ones. For the former, the probe contacts the surfaces of tested structure. The variable-angle beam transducer and phased array are commonly used.

An alternative transducer array system for generating guided waves is comb transducer [1]. It is made of some bulk waves transducers (usually longitudinal waves) that are pasted on comb structures. The transducer element size and spacing dimensions (along with the excitation frequency variables) allow us to select modes and frequencies on the guided wave dispersion diagrams.

Although the contact methods have advantage of simple operation, strict surfaces and couplant are needed. All these limit their application ranges. For example it is unsuitable for the inspection of the rough surface, curve surface, complex structure or structures that prohibit using couplant.

Based on the excitation, the non-contact methods are mainly divided into two classes: laser excitation and EMAT excitation [8]. These two techniques do not contact the surface and so need not couplant. They can be used to inspect complicated structures. But they are expensive, mainly used in some particular conditions.

3.1.5. Source Influence

The ability to get onto a dispersion curve at particular phase velocity and frequency is often difficult than one expects [9]. The reason is that all the dispersion curves developed for a variety of structural configurations are based on the assumption of an infinite plane excitation producing a particular phase velocity value at a specific frequency. But it is hardly difficult to build the ideal condition because of the effect of experiment environments, apparatus and probes in fact. For a specific transducer, given by a specific angle of incidence the phase velocity is not a specific but rather a complete phase velocity spectrum. This phase velocity spectrum changes with the actual phase velocity and frequency itself. As a result, the source influence of an ultrasonic transducer is something to be aware of to duplicate test for various practical non-destructive testing situations as well as to generate isolated test modes.

4. Some Examples

Guided waves are suitable for large structures inspection because of their long travel distance and high efficiency. Main practical applications are the inspection of plate shells, pipes and rails.

4.1.1. Plates and Shells

Many applications of guided waves are the inspection of plate and shells. At a given frequency, there are fewer modes in a plate compared with other one dimensional structure such as pipe or rail. It is easier to excite the wanted mode and the coherence noise is easily controlled. The guided wave signal in a plate is shown in Fig5.

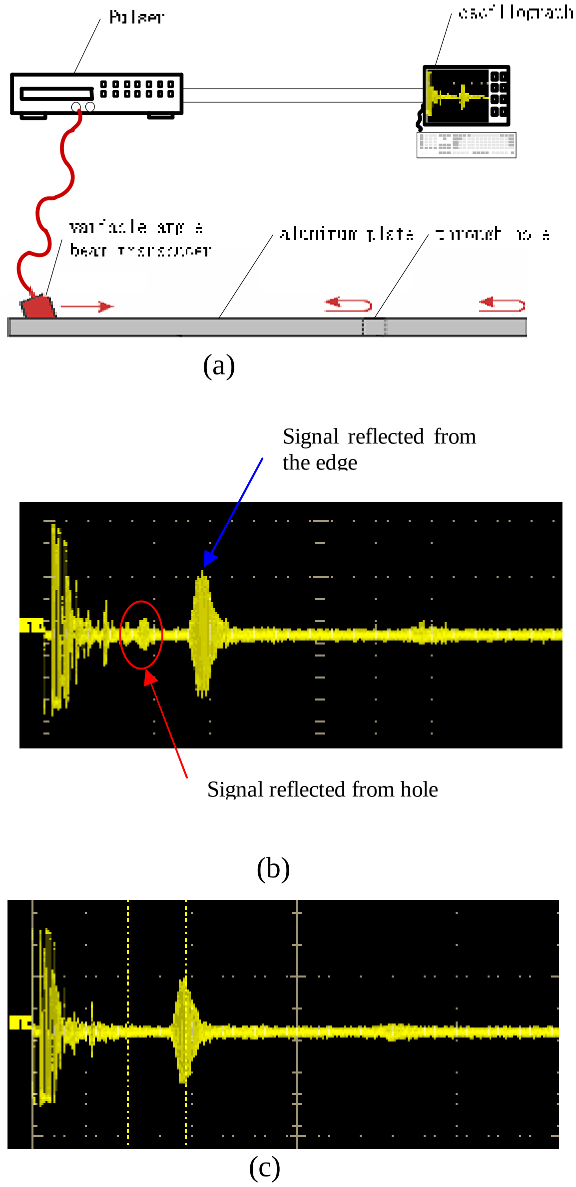


Figure 5: *(a)Example of guided wave inspection setup (b)signal in a plate with a hole (c)signal in a plate without hole*

A lot of work has also been done on the inspection of the defects in multi-layers plates and shells. The technique of two line scans is used to detect impact–induced delamination defect and quantitatively evaluate its size and linear position in composite laminations [10]. A mode tuning technique is demonstrated for finding suitable modes for the inspection of a multi-layered structure [11].The experimental results show that sweeping frequency and phase velocity can be performed to find suitable modes for inspecting a layer of interest for a given multi-layered structure.

Of course, the effect of interaction of guided waves with defects should be emphasized on. David N. Alleyne[12] investigated the interaction of individual Lamb waves with a variety of defects simulated by notches. The results have shown that the sensitivity of individual Lamb waves to particular notches is dependent on the frequency-thickness product, the mode types (symmetric or anti-symmetric), the mode order, and the geometry of the notch. The transmission ratios of Lamb waves across defects are highly frequency dependent, particularly at higher frequency-thickness. The positions of maxima and minima in the transmission curves are a function of notch depth that suggests that monitoring the change in the transmission ratio with frequency may provide a means of defect sizing.

4.1.2. Pipes

The inspection of pipe in service is promising. Especially when the pipe is underground for a limited distance or it is insulated or through the wall, it is quick and low expense to use guided waves in case of removing only some of the insulation. As mentioned before, the modes in the pipe are deferent to the guided waves in the plate. The dispersion curves in a pipe are shown in figure 6, see [13][14].

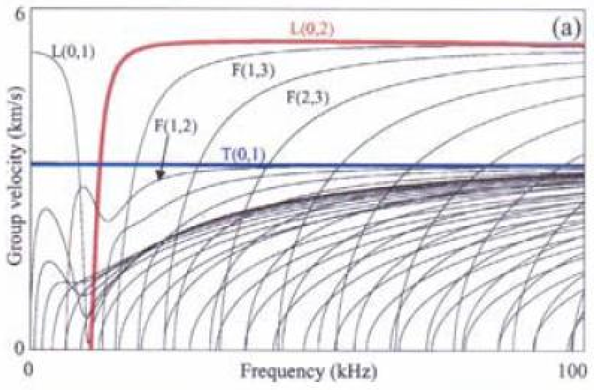


Figure 6: *dispersion curves for 6 inch, shedule 40 steel pipe*

The Imperial College NDT group has developed a guided wave technique that is designed for the screening of lengths (>10m) of pipes for corrosion. It seeks to detect corrosion defects removing of the order of 5-10% of the cross sectional area of the pipe at any axial location. It has been used on pipes on the 2-24 ,36,48 and 52 inch diameter.

The modes often used on pipes inspection are L(0,2) and T(0,1). These two modes with a simple mode shape are also easier to be excited in a pure form, which is important in controlling coherent noise.

Transducer array for a 8 inch pipe used in the Guided Ultrasonics Ltd Wavemaker Pipe Screening System is shown in Fig 3. The array comprises two rings of dry-coupled, piezoelectric transducers which apply a tangential force to the pipe surface to excite the torsional mode; the two rings of transducers positioned roughly a quarter wavelength apart along the pipe (the precise fraction of the wavelength depends on the test frequency used) enable direction control.

Figure 3*: Transducer array for 8 inch pipe*

4.1.3. Rails

Traditional ultrasonic techniques make use of transducers operating in pulse-echo mode that are applied at 0°(normal incidence) and 70°to the running surface of the rail on the center line. Except low efficiency, this method has some other shortcomings. First, the surface defects cannot be detected; Second, if there are shallow defects on the surface, the shallow defects can mask the deeper, critical ones. In addition, for Alumino-thermic welds, the large material grain size strongly scatters ultrasonic waves, the conventional method is not effective.

The guided waves can overcome these problems. A method with different surface-confined guided waves modes exist in the rail rather than a single Rayleigh wave to detect the surface defects is presented [15][16]. The frequencies are around 250 kHz, and the wave can cover a few meters of rail from a single inspection position. Since the penetration depth of the low frequencies signal is higher than that at higher frequencies, a considerable amount of energy is transmitted through the defect area and allows the detection of further features in the rail, so the critical defects in some depth can't be masked by the little spalling areas and other surface damage.

The method to detect the smooth transverse-vertical defects and the volumetric examination of alumino-thermic welds is demonstrated [17]. A photograph of the prototype system is shown in Fig 4. Guided waves are sensitive to the defects such as transverse vertical cracks of the type. In addition, at lower frequencies, material attenuation due to grain boundary scattering is very low and hence alumino-thermic weld material can be readily penetrated and tested.

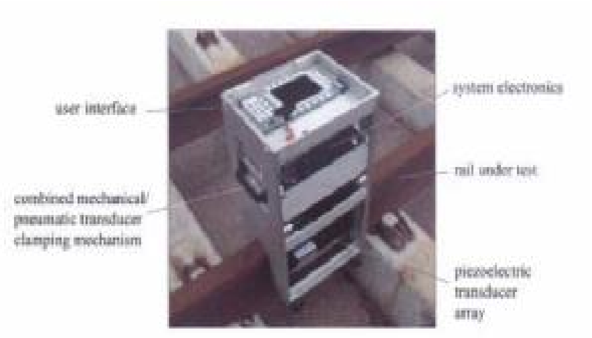


Figure 4. *A photograph of the prototype system*

But the guided waves in rails are more complicated than that in plates and pipes. For example, at the upper frequency limit of 50kHz, there are around 20 modes existing. In order to interpret the signal, the transduction system must be designed carefully and a full understanding of guided wave mode behavior is needed.

Further considering, no exact model exists for complex profiles, such as rail. A two-dimensional finite element method has to be employed to predict the modes-shapes and guided wave characteristics for rail. Recently other works have been done to this work using a resonant 3D FE mode. In addition, the BEM (boundary element methods) is potentially used to study the sizing potential of two-dimensional shaped defects in wave guides [18][19].

5. Difficulties and Future

The practical applications are very limited although guided waves have some obvious advantages in the large structure inspection, such as short inspection time and good sensitivities. This is mainly caused by the coherent noise and lower ratio of signal to noise resulted from the dispersion and multiple modes. At present, considerable work have been done in better controlling of coherent noise and abstraction of useful signal At the same time, with the development of computer and basic physics and wave mechanism, more effective signal processing method have begun to be applied into the guided waves inspection. Hence, the noise problem must be solved from both the hardware structure design and software processing if the number of practical applications of guided waves is wished to be expanded.

In addition, most of research concentrates on the relatively simple structures. Future research directions should include the inspection of more complex structures such as the structures made of anisotropic or viscoelastic material.

At last, because the sensitivity of guided waves varies with the variation of defect depth, guided wave technique has sufficient potential in flaw classification analysis, especially for distinguishing critical from non-critical defects.

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