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The Affection of Pipes Characteristics to Exciting Frequency for Guided Waves NDT

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Abstract: In the application of guided waves NDT, the selection of exciting frequency is not only related with the setup of sensor, but also with the characteristics of pipe's structure and material. In this paper, the characteristic of guided waves propagation in pipes that $L(0,1)$ and $L(0,2)$ have a cutoff frequency are respectively discussed, and the calculation formulas of their cutoff frequency are given. The varied relationship between the cutoff frequency of $L(0,1)$ and $L(0,2)$ mode guide waves, the outer diameter and wall thickness of pipes are discussed, respectively. For a given steel pipe, experiments are carried out by selection of different exciting frequency. The results show that the "low-pass" type cutoff frequency of $L(0,1)$ and "high-pass" type cutoff frequency of $L(0,2)$ are reduced with increasing of outer diameter of pipes, and the "low-pass" type cutoff frequency of $L(0,1)$ and "high-pass" type cutoff frequency of $L(0,2)$ are initially increased with increasing of wall thickness of pipes, but the increased amplitude is slowly changed a little. When the outer diameter of pipes is more than 351mm, both of the cutoff frequencies are not changed with varied of wall thickness of pipes. The experimental results are well agreed with theoretical computation of selected exciting frequency for pipes guided waves NDT.

Key words: Non destructive testing; Magnetostrictive sensor; Guided wave; Dispersion

1. Introduction

In recent years**,** many people have developed various sensors or transducers by application of the magnetostrictive effect of ferromagnetic material. The elastic waves induced by magnetostrictive effect can propagate in the ferromagnetic materials, and they can be reflected back when they meet a defect or a boundary, the reflected signals are pulse-echoes. This technique can overcome the limitations of conventional non-destructive testing techniques, and realize non-contact, large range or long distance, and quick inspection of defects for pipes[1,2].

Compared with ultrasonic waves used in conventional ultrasonic tests, the guided wave has a dispersive characteristic. In addition, at a given wave frequency, the guided waves can propagate in different wave modes and orders. These characteristics of guided wave bring some difficulties to analyze the wave refection signals in practical NDT. Although the properties of the guided wave are complex, which can be used to achieve 100% volumetric testing of long distance steel pipe from a single sensor location with suitable selection and proper control of wave mode and frequency.

In theory both axisymmetric and non-axisymmetric modes can be used for long range inspection. In practice axisymmetric modes are generally preferred because of their relatively simple acoustic fields and easier excitability. The original implementation of the technique used the longitudinal L(0,2) mode, but more recent testing has also employed the torsional T(0,1) mode. The latter mode exists at all frequencies whereas the former is present only at frequencies above its cut-off frequency. The longitudinal guided wave is sensitive to circle direction defects, but the torsional mode is sensitive to axial direction defects ，so both of the two type guided waves are same important in practical application. Because the longitudinal mode propagates more quickly than torsional ones, which can inspect longer distance pipes, and it is more available for long pipeline inspection compared with the torsional mode. The abroad application of longitudinal guided wave depends on the next two aspect problem to be solved. The first one is how to design and setup longitudinal transducer to restrain the generation of L(0,1) mode. The second one is how to correctly select exciting frequency for according to different pipe characteristics. The mode of the guided wave can be controlled mainly by setting-up of transducer, which had been discussed in the paper [3]. The latter, which is the relation between selected exciting frequency and pipe material characteristic, will be discussed in this paper, the phase velocity and group velocity dispersive curves are analyzed, and the "low-pass" cut-off frequency of L(0,1) and the "high-pass" cut-off frequency of L(0,2) are calculated respectively according to relative formula. The variation rules between the cut-off frequency of longitudinal guided wave and the radius and wall thickness of pipe are studied for the optimal selection of exciting frequency. At last, the experimental inspection of pipe is carried out by compared with theoretical analysis.

2. Relation between selected guided wave frequency and pipe characteristic

A sample steel pipe is 6m long, 32mm outer radius and 4mm wall thickness, which is shown in Fig.1. The group and phase velocity dispersive curves of the sample pipe are shown as Fig.2, respectively. The methods for calculating guided wave dispersive curves in cylindrical pipe had been discussed in many papers[4,5], which is not repeated again in this paper. In order to label different modes in pipe consistently, L(0,n), T(0,n) and F(n, m) are used to denote longitudinal, torsional and flexural modes in Fig.2, respectively. The first index ‘m’ indicates the harmonic variation order of displacement and stresses around the circumference and the second one ‘n’ is a counter variable.

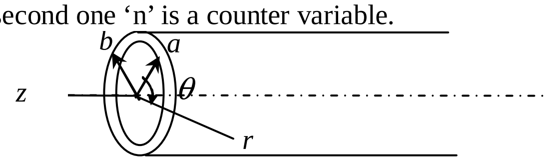
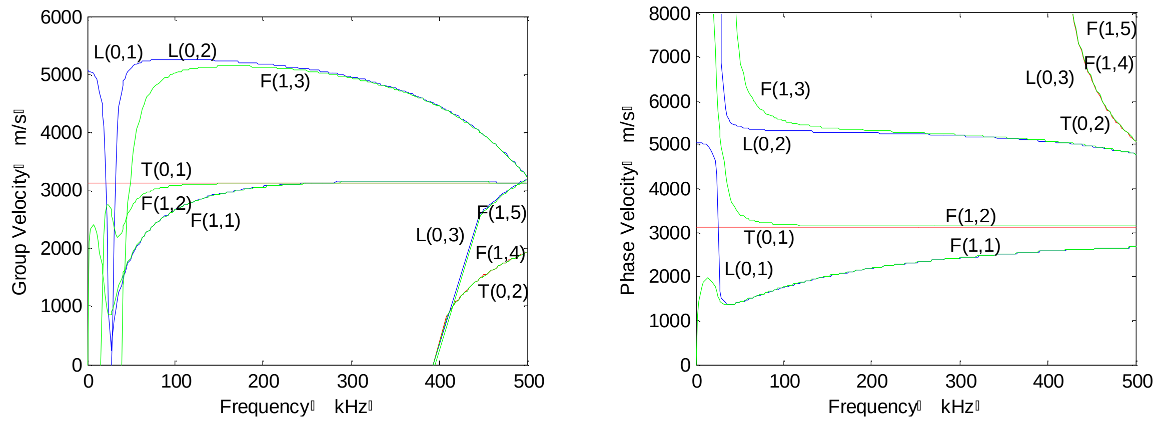


Fig.1 Feature description of sample pipe



(a) Group velocity dispersive curves (b) Phase velocity dispersive curves

Fig.2 Dispersive curves of 6m long, 32mm outer radius and 4mm wall thickness steel pipe

Fig.2 shows that L(0,1), L(0,2), T(0,1), F(1,1), F(1,2), and F(1,3) mode guided wave appear at the same time when the frequency is less than 100kHz, on the other hand, there are multi-mode guided waves which propagate simultaneity at a given frequency. The cut-off frequency of L(0,1) and L(0,2) mode guided waves emerge on the group dispersive curves in Fig.2(a). By calculating, their cut-off frequencies can be gained as 26.75 kHz and 28.31 kHz, respectively.

For inspecting a given pipes, the selection of exciting frequency of guided waves is very important in practical engineering application. The selected exciting frequency cannot lie in the cut-off frequency area which defined as “dead zone”. In order to improve the signal-noise ratio, single mode guided waves should be generated, at the same time unwanted modes must be restrained, and the exciting frequency is also selected to locate in non-dispersive zone. The mode of guided waves is controlled by the configuration of sensor, one kind of magnetostrictive sensor is designed in to generate longitudinal guided wave in pipes[3]. To optimal select the excited frequency, the characteristics of longitudinal guided waves propagating in different material and dimension pipes must be considered, Junger、Rosato and Naghdi、Cooper had investigated the propagating theory of elastic wave in cylindrical shells[6,7], the two branches of the dispersion curve are identified as the first and second modes of axisymmetric longitudinal wave. The first mode L(0,1) shows a “low-pass” type cut-off behavior, and the second mode L(0,2) shows a “high-pass” type cut-off behavior. Based on these theory, H.Kwun、K, A.Bartels have gone on experimental study the guided waves dispersive characteristics [8], and given the calculation formulas of the two cut-off behavior frequency. L(0,1) mode “low-pass” cut-off frequency $f_{lowpass}$ and L(0,2) mode “high-pass” cut-off behavior frequency $f_{highpass}$ are respectively as follows:

$$f_{lowpass} = \frac{v_0}{2\pi c} \tag{1}$$

$$f_{highpass} = \frac{K v_p}{2\pi c} \tag{2}$$

Where c denotes the average radius of the steel pipe. v_0 is “bar” velocity and $v_0 = \sqrt{\frac{E}{\rho}}$, E and ρ are the Young’s modulus and density of the pipe material. $K = \sqrt{1 + \frac{h^2 \cdot (2+\sigma)}{6c^2(1-\sigma)}}$ is constant. $v_p = \frac{v_0}{\sqrt{1-\sigma^2}}$ is plate longitudinal velocity. h is the half of wall thickness. σ is Poisson’s ratio.

The characteristics of the L(0,1) guided waves “low-pass” cut-off frequency and the L(0,2) modes “high-pass” cut-off frequency can be described as Fig.3. There exists a cut-off frequency zone between L(0,1) and L(0,2) mode.

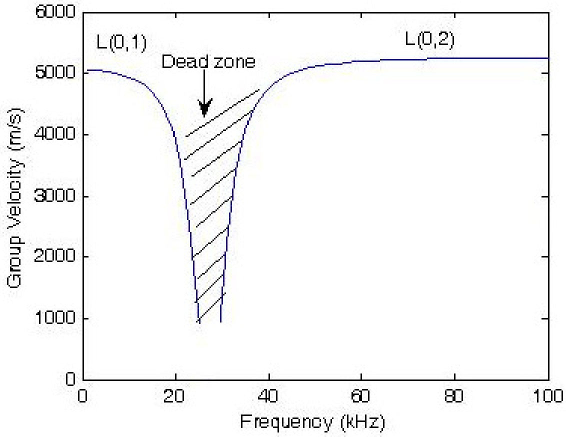


Fig.3 The dispersive characteristics of L(0,1) and L(0,2)

The cut-off frequencies can be calculated for a given pipe according to equation (1)-(4). The material density is 7.8g/cm^3 and Poisson ratio is 0.3, the cut-off frequency of L(0,1) and L(0,2) are calculated respectively as follows:

$$f_{lowpass} = 26.9kHz \quad (5)$$

$$f_{highpass} = 28.3kHz \quad (6)$$

Compared with the cut-off frequencies shown from dispersive curves in Fig.2, which are 26.75kHz and 28.31kHz for L(0,1) and L(0,2) respectively, the results which are calculated by equation (1) to (4) differ from very little for observing equation (5) and equation (6). The two results agree very well each other. So when selecting the exciting frequency for a given detected pipes, the first step is to calculate cut-off frequency of longitudinal mode, the second step is to select the exciting frequency, which are either lower than “low-pass” cut–off frequency or higher than “high-pass” cut-off frequency.

To research the relationship between the exciting frequency of longitudinal guided waves and material characteristics of different dimension pipes, much of data and literatures of pipes material characteristics are collected and referred[4, 9], by classifying and comparing, which are shown as Table 1.

Tab.1 Material characteristics of pipe

Pipe material	Density ρ (g/cm^3)	Young’s modulus E*10^6(kg/cm^2)	Poisson’s ratio σ	Wave velocity (m/s)		Notes
				Longitudinal	Transverse	
Steel	7.8-7.9	2.0-2.1	0.25-0.30	5850-5960	3230-3260	These parameters allow varied in a given range because of the different components of material.
Copper	8.1-8.9	1.0-1.3	0.31-0.35	3530-4430	2120-2230	
Aluminum	2.7-2.8	0.69-0.7	0.32-0.36	6250-6350	3100	
Zinc	6.8-7.2	0.84	0.27	4170	2410	
Nickel	8.3-8.9	1.9-2.3	0.25-0.30	5630	2960	
Titanium	4.51-4.54	7.87	0.3	6100	3120	
Tungsten	19.25	3.5-4.1	0.28	5180	2870	
Glass	2.23-2.51	0.56	0.25	5570-5770	3430-3440	
Organic glass	1.18	0.06	0.31	2670	1120	

According to the handbook of mechanical engineering materials [9], there are standard specification between outside diameter and wall thickness of pipes manufactured in industry field. So the outer diameter and corresponding wall thickness of steel pipe are accorded with the standard specification. By calculating from equation (1) to (4), it is concluded that the cut-off frequency of guided waves alter with the material and structure character of pipe. The relationship between the two type cut-off frequencies of guided waves, metal material and structure character of pipe is analyzed in detail as following. Other materials’ pipe analysis is similar with the example.

Fig.4 and Fig.5 show curves between the cut-off frequency and outer diameter alteration under the condition of different wall thickness of pipes.

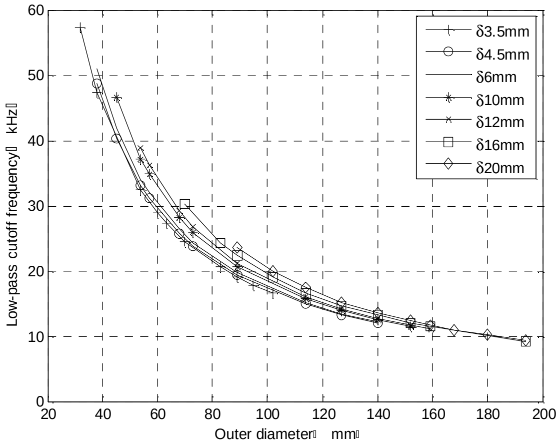


Fig. 4 L(0,1)wave “low-pass” cut-off frequency versus outer diameter of pipe

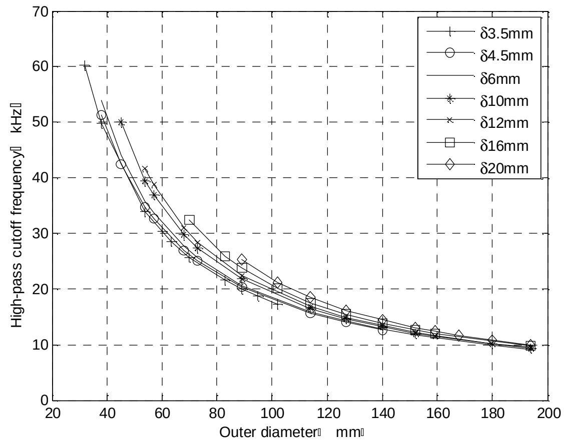


Fig.5 L(0,2)wave “high-pass” cut-off frequency versus outer diameter of pipe

From Fig.4 and Fig.5, we can conclude that both the “low-pass” cut –off frequency of L(0,1) mode guided wave and “high-pass” cut-off frequency of L(0,2) mode guided wave decrease as the increase of pipe diameter. To the same pipe diameter, both the “low-pass” cut–off frequency of L(0,1) mode guided wave and “high-pass” cut-off frequency of L(0,2) mode will increase as the increasing of pipe thickness. Doc. Li Yi-bo concluded the same relationship between outer diameter and cut–off frequency of L(0,1) mode guided wave[10]. When detecting pipe, the selection of exciting guided wave frequency should be avoided to enter the cut-off frequency zone.

Fig.6 and Fig.7 show curves between the cut-off frequency and wall thickness alteration under the condition of different outer diameter of pipes.

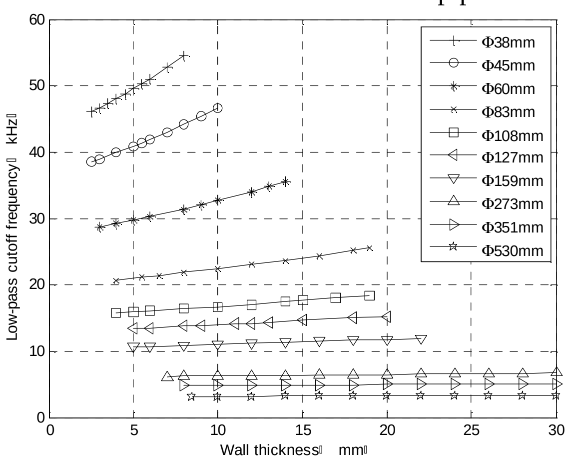


Fig. 6 L(0,1)wave “low-pass” cut-off frequency versus wall thickness of pipe

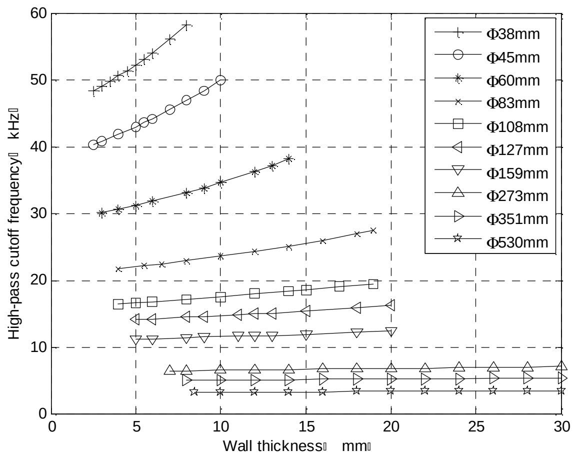


Fig.7 L(0,2)wave “high-pass” cut-off frequency versus wall thickness of pipe

From Fig.6 and Fig.7 we can conclude that both the “low-pass” cut–off frequency of L(0,1) mode guided wave and “high-pass” cut-off frequency of L(0,2) mode guided wave are increasing as the increase of pipe wall thickness, but the increasing extent decrease slowly. While the outer diameter is lager than 351mm, there are no relation between the two kind cut-off frequencies and alteration of pipe wall thickness. While the same pipe wall thickness, both the “low-pass” cut–off frequency of L(0,1) mode guided wave and “high-pass” cut-off frequency of L(0,2) mode guided wave decrease as the increase of pipe outer diameter. While the pipe outer diameter is extraordinary lager than the pipe wall thickness, the alteration of wall thickness will make no influence to the cut –off frequency just as wave propagation in plate. This conclusion is the same as Doc. Ta De-an’s investigation. His research is based on copper pipe, and he studied the dispersive characteristics from the ratio of pipe inner diameter to wall thickness. In this paper, the research object is steel pipe, the disperse characteristic of guided wave from outer diameter and wall thickness are individually researched and the same conclusions are made. The research demonstrates that the dispersive characteristic of guided wave for detecting pipe materials list in Tab.1 are same with each other, but their cut–off frequencies differ from different pipe materials. This conclusion is very important to non–destructive detection in pipes using guided wave.

3. Experiment and discussion

According to above conclusion, different exciting frequencies are selected for steel pipe NDT in the experiment. The sample steel pipe, which is 6m long, 64mm diameter and 4mm wall thickness, and the received signals whose exciting frequency are 21 and 56kHz, are shown in Fig.8 and Fig.9, respectively.

As shown in Fig.8, some other modes guided wave reflected signals are existed except for L(0, 1) when the exciting frequency is 21kHz less than the “low-pass” cut-off frequency with 26.9kHz. The Fig.2 shows that T(0, 1), F(1, 1) F(1, 2) mode are existed except for L(0, 1). As the setup of transducer, the L(0, 1) mode guided wave was mainly generated in pipe, which just produce mode conversions at the end of pipe. The exciting guided wave frequency 56kHz is more than “high-pass” cut-off frequency with 28.3kHz in Fig.9. Additionally, the received signal only includes longitudinal mode L(0, 2) guided wave by setting up the transducer appropriately. According to Naghdi and Cooper’ theory[7], the movement of L(0, 1) guided wave is mostly axial at a low frequency. As the frequency is increased, many radial and rotational motions appear in the lowest phase velocity. In high frequency range, it only radically moves. On the other hand, the motions of L(0, 2) guided wave are mainly axial and rotational at first, but it converts to entire axial movement as frequency is increased.

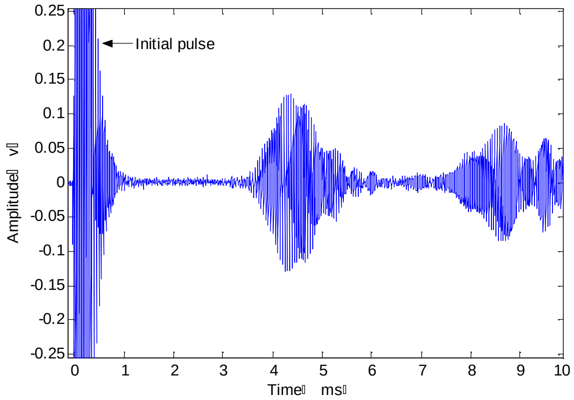


Fig.8 Received signal at 56kHz excited frequency

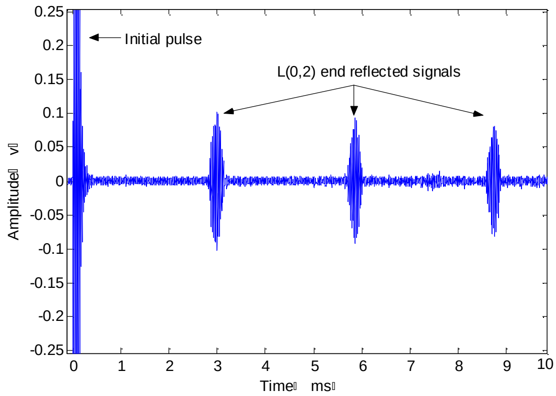


Fig.9 Received signal at 21kHz excited frequency

The above theoretical analysis is agreed well with experimental results, the dispersive characteristics of guided wave comply with certain regular pattern when propagating along the pipe. There is an important guiding action for practical application using guided wave NDT. Especially, for inspecting pipes of different material characteristic, it gives a quantitative calculated foundation for selection of the excited frequency.

4. Conclusions

The dispersive and multimode characteristics of ultrasonic guided wave bring some difficulties to analyze its reflected signals, so the generated guided wave’s mode should be controlled and the exciting frequency is appropriately selected to distinguish the inspected signal rapidly in application. The selection of exciting frequency of guided wave is not only related with the configuration of transducer, but also with the pipe’s structure and material characteristic. The cut-off frequency zone can be avoided to enter by selecting the correlative exciting frequency computed by the curves; in addition, the guided wave complies with some same regular pattern about dispersive characteristic when it propagates along the pipe, which gives some useful help for guided wave non-destructive testing of pipes in engineering application.

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