Acoustics'08 Paris
June 29-July 4, 2008
www.acoustics08-paris.org

Determination of the width of an axisymmetric deposit on a metallic pipe by means of Lamb type guided modes

Mustapha El Moussaoui[a], Farid Chati[a], Fernand Leon[a], Aleksander Klauson[b] and Gerard Maze[c]

[a]LOMC FRE 3102 CNRS Groupes Ondes Acoustiques, Université du Havre (IUT), Place Robert Schuman, 76610 Le Havre, France
[b]Tallinn University of Technology, Dept. of Mechanics, Ehitajate tee 5, 19086 Tallinn, Estonia
[c]LAUE, Université du Havre, Place Robert Schuman, F-76610 Le Havre, France
farid.chati@univ-lehavre.fr

The non-destructive evaluation of pipes using guided waves is extensively used for the detection and the size estimation of defects. The important number of investigations concerning with the interaction between a guided wave and a defect show the growing need to improve our knowledge of this phenomenon in order to detect and to characterize as well as possible the defect. This work is devoted to the evaluation of the width of an axisymmetric resin deposit coupled to the wall of a metallic pipe by means of longitudinal modes S_0, S_1. To that end, we interest us to the damping of these modes provoked by a resin deposit. The study is carried out both from the numerical point of view and from the experimental point of view in considering a deposit of variable width. The finite element method is employed to model the propagation and the diffraction of Lamb-type waves. The experiment is based on the generation of axisymmetric waves on the section of a pipe by a piezoelectric transducer. Measurements of temporal echoes reflected by the deposit and transmitted after the deposit are achieved. A mathematical law of the attenuation as function of the width is deduced for each wave.

1 Introduction

In the infrastructure of many industries, such as oil, gas and water transport, the different types of inventoried defects in the pipes can provoke malfunctions, failures or even major damages. Many researchers have been interested in the application of ultrasonic guided waves for the inspection of the pipe filled with a fluid [1-3].

Among the considered modes in these works for the study of the interaction with the defect, the longitudinal modes are widely employed. When a pipe is filled with a fluid, the use of a longitudinal mode is conceivable when its phase velocity is close to the longitudinal velocity. Indeed, it is well known that the leakage of energy in the fluid can be substantially reduced when the phase velocity comes close to the longitudinal one [4].

In this paper, the interaction of axisymmetric Lamb modes S_0 and S_1 (denoted also L(0,2) and L(0,4)) with a resin deposit coupled to the outer wall of a stainless steel pipe is studied. The goal of this work is to analyze in detail the damping of the modes S_0 and S_1 as function of the deposit width *w*. We seek to know whether it is possible to establish a relation between damping and *w*. The study is carried out both from the numerical point of view and from the experimental point of view. The studied problem has not a simple analytic solution. A numerical model based on the finite element method is then used to compute the propagation of guided waves. The use of the commercially available finite element code *ANSYS* allows us to predict numerically the temporal signals at the external surface of the stainless steel pipe. Experimentally, the generation of the axisymmetric waves is realized on the one of edge sections of the pipe by a piezoelectric transducer. Measurements are achieved using a monostatic method and a bistatic one.

2 Experimental setup

Two investigations are carried out: examination of the damping of the reflected mode S_0 at the frequency f_0=238 kHz and of the damping of the transmitted mode S_1 at the frequency f_1=2.565MHz. Two measurement methods are then used: a monostatic method and a bistatic one. The first is characterized by a single broadband Panametrics transducer operating alternately as an emitter and as a receiver. Its central frequency is equal to 250 kHz and its useful frequency range is about 125-375 kHz. This transducer is put on one edge section of the pipe like shown in Fig. 1. The monostatic method is mainly employed to measure the reflection of the mode S_0.

The bistatic method is characterized by a broadband Panametrics transducer with a central frequency of 2.25 MHz (useful frequency range of about 1.1-3.4 MHz) operating as an emitter and a comb transducer operating as a receiver. This method is used to measure the transmission of the mode S_1. The receiver is a handmade PVDF comb which is wrapped around the pipe. This one is identical to the flexible comb transducers studied by Hay and Rose [5]. It is featured by its finger spacing, which is equal to the wavelength of the mode S_1 at the frequency f_1=2.565MHz (λ_1=2.27mm), a fingers number of 15 and a finger width of 1mm. The temporal signals detected by the receiver are displayed on a numerical oscilloscope via a wide bandwidth voltage amplifier and then recorded on a computer for the numerical treatments.

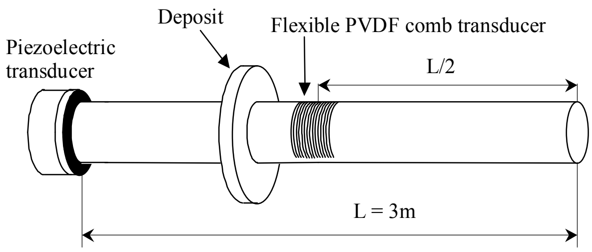

Fig.1 Schematic diagram of experimental setup

The excited modes are analog to Lamb modes in a plane layer. We consider then that the behaviors of these longitudinal modes at the inner and outer surfaces of the pipe are pratically similar. Therefore, for a pratical reason in our investigation, we chose to fix the deposit of variable width to the outer wall of the pipe.

Five axisymmetric epoxy resin deposits of variable width *w* and constant height *h* coupled to, successively, the external wall of the stainless steel pipe are analyzed (Fig.2). The length of the pipe and the deposit height *h* are respectively equal to 3 m and 16.5 mm. The considered deposit widths *w* are 3 mm, 8 mm, 19 mm, 30 mm, 40 mm for the study of the mode S_1 and 5 mm, 17 mm, 27 mm, 37 mm and 55 mm for the study of the mode S_0. Each deposit is fixed at 1.3 m from the edge section where the modes S_0 and S_1 are generated. The conditions of measurement (amplification, gauges...) does not change for these various widths.

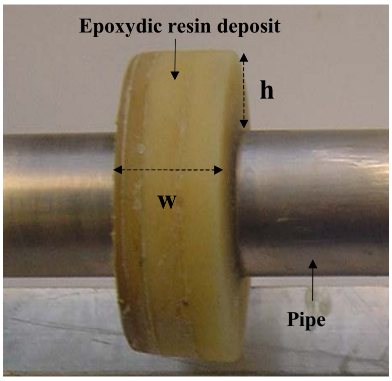

Fig. 2 Resin deposit coupled to the stainless steel pipe

The longitudinal modes S_0 and S_1 are generated respectively at frequencies f_0=238 kHz and f_1=2.565MHz by means of a function generator which supplies a gated sinusoidal signal of 50 cycles. The pipe is either empty or filled with water.

At the frequency f_1, the mode S_1 has a radial displacement at the inner and outer surfaces close to zero. Indeed this mode is pratically uncoupled to water which can be enclosed in the pipe (Fig. 3).

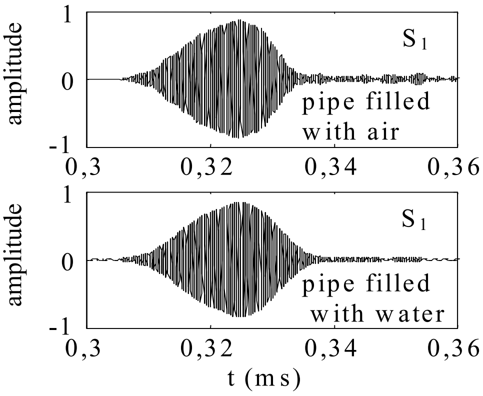

Fig.3 Two examples of temporal signals recorded from a comb transducer, S_1 wave at f = 2565 kHz for a pipe (filled or not with water) with a deposit characterized by w = 19 mm

At the frequency f_0, the mode S_0 has a displacement strongly axial; its radial displacement is comparatively weak [6,7]. The study of the damping of the mode S_0 in reflection is only carried out experimentally for an empty pipe.

3 Numerical analysis: the finite element method

Numerical computations are performed for a stainless steel pipe (outer radius a, inner radius b, length l) with an axisymmetric epoxy resin deposit (width w, height h) coupled to the wall of the pipe (Fig. 4). For that, values of the physical parameters used are:

- Stainless steel pipe:

  a = 19 mm, b = 17.5 mm,

  ρ_1= 8027 kg/m^3, C_{L1}= 5823 m/s, C_{S1} = 3210 m/s

- Resin deposits:

  ρ_2= 1093 kg/m^3, C_{L2} = 2243 m/s, C_{S2} = 1150 m/s,

  h = 16.5 mm, w = 3, 5, 8, 19, 25, 30 or 40 mm

where ρ_1, ρ_2 are the densities of respectively stainless steel and resin. C_{L1} and C_{S1} are the longitudinal and shear velocities in stainless steel, C_{L2} and C_{S2} are the longitudinal and shear velocities in resin. The physical parameters of the resin (ρ_2, C_{L2}, C_{S2}) have been obtained experimentally. Absorption due to the viscosity of the resin is assumed negligible.

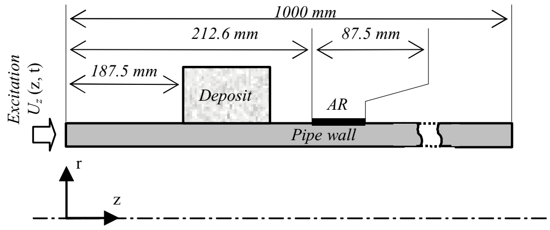

Fig.4 Schematic of a stainless steel pipe coupled to an axisymmetric epoxy resin deposit of variable width. An uniform excitation is applied on the left section of the pipe along the 0z axis.

The section of the pipe is excited uniformly by a gated sinusoidal signal of 50 cycles at a central frequency f (Fig.4). The chosen excitation mode allows us to generate a compressive wave on the section of the pipe and favors the generation of the symmetric modes in the frequency range 0-4 MHz. The computations of the temporal pulses relating to the axial displacements are realized for nodes situated between 212.6 mm and 300.1 mm from the edge of the pipe where it is excited (area AR). The step between two nodes is of 0.1mm.

For each position z (materialized by nodes on the surface of the pipe), a temporal signal corresponding to the axial displacement U_Z(z,t) is calculated. The axial contribution is only considered because of the strongly axial nature of the mode S_1 at the frequency f = 2.565 MHz. The studies of Pilarski *et al* [4] showed that for symmetric modes, when the phase velocity reaches the value of the velocity of bulk longitudinal wave, the normal component of the displacement vector vanishes on the free surfaces. This remark is valid also in the case of a pipe as confirmed by the studies of Hay and Rose [3], notably in our case for the S_1 mode at the frequency f = 2.565 MHz (axial phase velocity C_z = C_{L1}). This wave is propagated along the pipe without re-emitting in the internal fluid. Therefore, in order to minimize the numerical size of the finite element modeling and thus the time of computing, all computations of displacements have been performed for a stainless steel pipe without fluid in its inner cavity.

To compare the calculated temporal signals with the experimental temporal signals obtained by means of a comb transducer, the working of the transducer is simulated. This one is obtained by applying a spatial window to temporal signals corresponding to the axial displacement U_Z(z,t) calculated to the nodes of the area AR. The shape of this window is equivalent to that of the comb transducer. This filtering is characterized by a central wavelength $\lambda_I = C_{LI}/f$ = 2.27 mm which is equal to the space between two finger axis, by a fingers number N_f equal to 15 and by the nodes number under one finger. A spatial filtering allows us to obtain, at the outer surface of the pipe, temporal signals equivalent to that of the Fig. 3.

4 Discussion

4.1 Mode S_1

The study of the energy loss of the mode S_1 due to the presence of the resin deposit on the outer wall of the pipe is carried out by comparing the results relating to the pipe without deposit with those relating to the pipe with the deposit. To that end, the relative variation of the amplitude of the mode S_1 at the frequency f = 2.565 MHz, when the deposit width w varies, is here analyzed in details. At this frequency, this wave is practically axial ($U_r(z,t) \approx 0$) and it is capable of discriminating between the deposit and the liquid in the pipe.

Experimentally and theoretically, a signal temporal (Fig.3, experimental case) for which the amplitude depends on the deposit width w is obtained. For each temporal echo relative to the mode S_1, it is applied a FFT. The spectrum (amplitude) of each echo is thus determined. The maximum of spectral amplitude (spectrum centered at f = 2.565 MHz) is then recorded for each deposit width w. To characterize the attenuation of this wave, we consider that the variation of this amplitude (versus the width w) of the mode S_1 obeys to the following relation:

$$M=M_0\, e^{-\alpha w} \quad (1)$$

where M_0 and M are respectively the maximum magnitudes of the considered mode at the surface of the pipe without deposit and at the surface of the pipe with the deposit. α is an attenuation coefficient which will discuss in the following paragraph.

To verify this affirmation, the experimental and theoretical evolutions of the Neperian logarithm of the magnitude of the axial displacement of the mode S_1 as function of the width w are plotted in Figs. 5 and 6.

It is also draw on each figure the best straight line through the data and given the correlation coefficient R which enables us to check the reliability of the linear relation. Figure 5 concerns the experimental results of the empty pipe and the pipe filled with water. Figure 6 concerns the theoretical amplitude decrease of the echo associated with the mode S_1 which propagates on the empty pipe with a deposit. From an examination of this last figure, it appears that the theoretical amplitude decrease is governed by the linear relation $\alpha.w$: the value of the correlation coefficient R is exactly equal to 1. In the experimental case, figure 5 shows that the variation of the attenuation versus the width is quasi linear; the relation 1 is also verified.

In the experimental part (see Fig.5), the best correlation coefficient R is obtained when the pipe is filled with water (empty pipe: R = 0.9677, filled pipe: R = 0.9976). This can be explained by the fact that water filters the echoes associated with the mode S_1 which are not featured by a "*purely"* displacement axial.

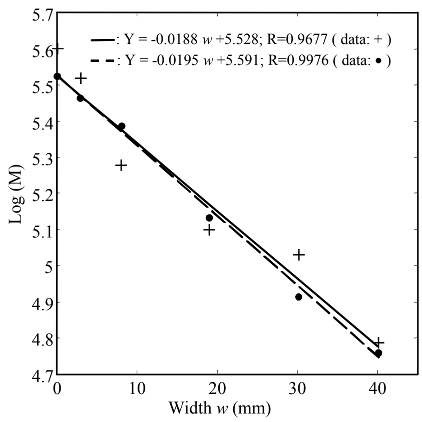

Fig. 5 Experimental attenuation evolution versus the deposit width w measured at 1.47 mm from the edge section where is generated the mode S_1:
- empty stainless steel pipe with the resin deposit; + : measurement, solid line : linear regression
- pipe filled with water and with the resin deposit; • : measurement, dotted line : linear regression

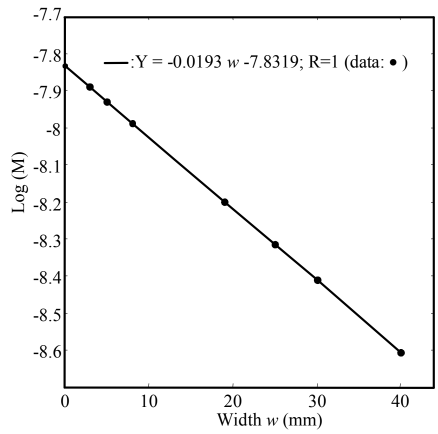

Fig.6 Theoretical attenuation evolution versus the deposit width w calculated at 222.5 mm from the edge section where is generated the mode S_1; •: calculated data, solid line: linear regression

These echoes are generated at frequencies neighboring the frequency 2.565 MHz because the employed excitation signal has a limited duration (gated sinusoid signal). Despite the fact that absorption due to the viscosity of the resin deposit has been assumed negligible in the computation of displacements, we note a good agreement between the theoretical and experimental results. Indeed, figures 5 and 6 show that the theoretical and experimental variations of the attenuation are practically identical: the theoretical slope (α = 0.0195 m^{-1}) and the experimental slope (α = 0.0193 m^{-1}) are very close.

To give a physical meaning to this slope α, we have achieved an additional study which shows that the slope α depends on the type of the displacement at the outer surface of the pipe. To that purpose, a study of the experimental attenuation versus the width *w* has been achieved for the modes A_0 and S_0 featured with the same wavelength as the mode S_1 (λ_1 = 2.27 mm). Contrary to the numerical case, the mode A_0 is generated experimentally. Its generation is possible because the machining is the edge section of the pipe is not perfect.

In a first time, the modulus of the ratio of the radial displacement over the axial displacement of each of these three modes has been calculated at the outer surface by using the elasticity theory. The values of these three ratios are given in table. They have been computed by using of the well-known analytic expressions of the reference 7.

In a second time, the variations of experimental attenuation of modes A_0, S_0 and S_1 versus the width *w* are determined and plotted in Fig. 7. To facilitate the examination of the last results, each variation of experimental attenuation is normalized by the amplitude of the considered mode on the pipe without deposit. The slopes of curves associated with the modes S_1, A_0 and S_0 are respectively α=0.019 (R=0.9697), α=0.042 (R=0.9931) and α=0.062 (R=0.9925).

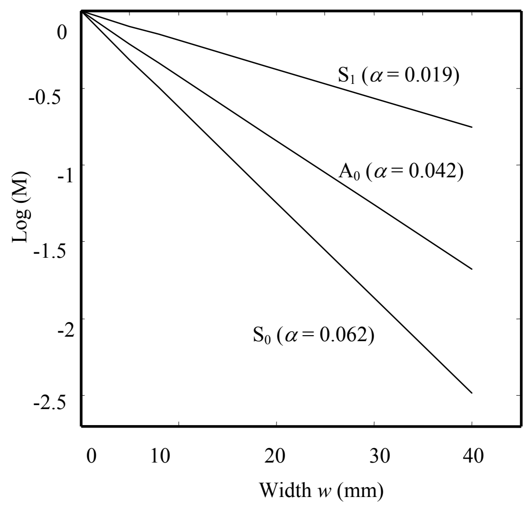

Fig. 7 Empty stainless steel pipe with a resin deposit of variable width - Experimental attenuation of the modes A_0 (1.158 MHz), S_0 (1.706 MHz) and S_1 (2.565 MHz) versus the width *w*

Mode	A0	S0	S1
f (MHz)	1.158	1.706	2.565
$\lvert U_R/U_z \rvert$	1.442	2.651	0.015
α	0.042	0.062	0.019

Table. Modulus of the ratio of the radial displacement (U_R) over the axial displacement (U_Z) of modes A_0, S_0 and S_1 featured with the same wavelength (λ_1 =2.27mm)

It appears that the mode S_1 is less attenuated than the modes A_0 and S_0: its slope is smallest of the three.

It is also observed that this slope depends on the value of the modulus of the ratio of displacements given in table. Indeed, the higher the modulus ratio of displacements is, the higher the slope (Table). The attenuation is particularly important when the considered mode has a strongly radial displacement at the surface of the pipe. This loss of the amplitude is connected to the energy radiated in the resin deposit; the amount of energy radiates in the deposit becomes increasingly important as the deposit width increases.

4.2 Mode S_0

An investigation purely experimental of the damping of the reflected mode S_0 as function of *w* is also carried out. The mode is reflected by the resin deposit coupled to the empty pipe. The temporal signals relating to the five deposit widths (5mm, 17mm, 27mm, 37 mm and 5mm) are plotted in Fig. 8.

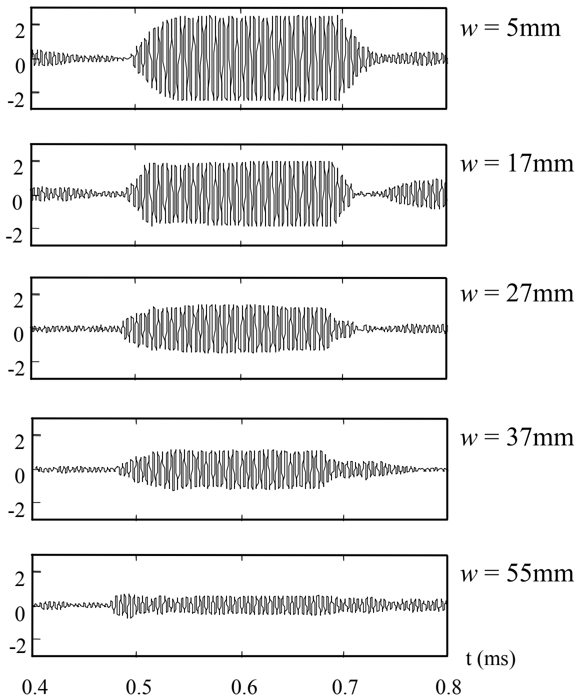

Fig. 8 Empty stainless steel pipe with a resin deposit. Temporal signals of the modes S_0 at the frequency 238 kHz reflected by the deposit of variable width

It shows the damping of the echo of the mode S_0 as the width increases. It appears clearly that the amplitude of this echo decreases when the width raises from 5 mm to 55 mm. The amplitude decay obeys an exponential law like shown in Fig. 9. Indeed, the correlation coefficient associated with the best straight line through the experimental data is very good and equal to 0.9986. The coefficient α is of 0.0275. The value of the frequency (i.e., 238 kHz) has been chosen as function of the modulus of the ratio the radial displacement over the axial one.

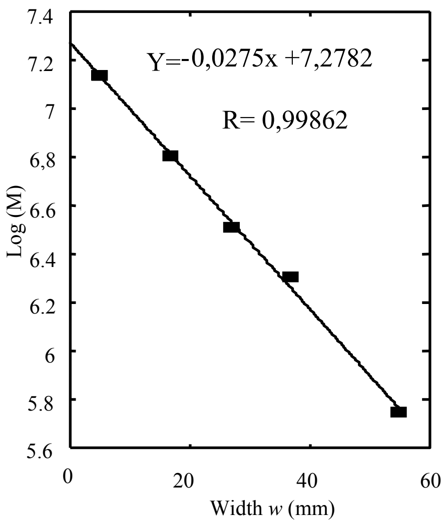

Fig. 9 Empty stainless steel pipe with a resin deposit of variable width – Experimental attenuation of the mode S_0 (238 kHz) versus the width.

The value 238 kHz corresponds to the minimum ratio; the mode S_0 is then rather axial.

5 Conclusion

The interaction of the axisymmetric the Lamb modes S_1 and S_0 with a resin deposit coupled to the outer wall of a stainless steel pipe is studied. Two studies are carried out. The first concerns the examination of the damping of the mode S_1 transmitted after the deposit versus its width. The second concerns the damping of the mode S_0 reflected by the deposit versus its width. In the first part, the experimental results and the numerical predictions shows that the damping of the mode S_1 is governed by an exponential law as function of the deposit width. Besides, its attenuation depends on its polarization. Indeed, the computation of the modulus of the ratio of the radial displacement over the axial one shows that the damping is particularly important when this ratio is high at the surface of the pipe. The same phenomenom, in the study of the damping of the mode S_0 which is only experimental, is noted. The attenuation of the mode S_0 reflected by the resin deposit when its width varies, is also governed by an exponential law.

References

[1] M.H. Park, I. S. Kim, Y. K. Yoon, “Ultrasonic inspection of long steel pipes using Lamb waves ”, *NDT&E International*, 29, 13-20 (1996).

[2] P. Cawley, D. Alleyne, “The use of Lamb waves for the long range inspection of large structures ”, *Ultrasonics*, 34, 287-290 (1996).

[3] T.R. Hay, J.L. Rose, “Fouling detection in the food industry using ultrasonic guided waves”, *Food contro*l, 14, 481-488 (2003).

[4] A. Pilarski, J.J. Ditri, J.L. Rose, “Remarks on symmetric Lamb waves with dominant longitudinal displacements”, *J. Acoust Soc. Am.*, 93 (4), 2228-2230 (1992).

[5] T.R. Hay, J.L. Rose, “Flexible PVDF comb transducers for excitation of axisymmetric guided waves in pipe”, *Sensors and Actuators A*, 100, 18-23 (2002).

[6] [M. El Moussaoui., “Evaluation non destructive de la présence d’un dépôt axisymétrique sur la paroi d’une canalisation en présence ou non d’un fluide interne ”, Ph. D. thesis, University of Le Havre, France (2007).

[7] J.L. Rose, “Ultrasonic waves in solid media”, Cambridge University Press, Chap. 12, 154-175 (1999).