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Evaluation of Thermal-damages in Tube-like Structures using Ultrasonic Guided Waves

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Abstract: This paper aims at an experimental method for detecting thermal-damages in a tube-like structure using acoustic nonlinear parameter of ultrasonic guided waves. The material nonlinearity of aluminum pipe specimens, which have been subjected to different heat-loading cycles, is measured to characterize the micro-damages. Flexible Polyvinylidene Fluoride (PVDF) comb transducers are used to generate and receive the fundamental and second harmonic waves. The amplitude of the second harmonic wave is extracted from the Fast Fourier Transform (FFT) spectrum of a received signal. The measured relative nonlinear parameter increases monotonically as a function of the propagation distance, and the relative nonlinear parameter becomes greater when the specimen is exposed to higher heat-loading cycles. These results indicate that the proposed experimental setup is applicable to assessment the micro-damages in a pipe, and the relative nonlinear parameter is a potential candidate for the prediction of micro-damages in a tube-like structure.

Keywords: PVDF transducers, Ultrasonic guided wave, Thermal damage, Nonlinear parameters.

1 Introduction

Ultrasonic guided wave is a very important tool for nondestructive evaluation, and the second harmonics can include more information about the structures and materials. Considering the high sensitivities of nonlinear ultrasonic approach and great advantages of guided wave techniques, nonlinear ultrasonic guided wave has attracted considerable interesting [3, 6]. However, there are few studies of nonlinear ultrasonic guided wave propagation in pipe-like structure. W.J.N. de Lima and M.F. Hamilton [5] theoretically studied the elastic wave in waveguides with arbitrary cross-section media, harmonics generation of ultrasonic guided wave propagation in cylindrical rods and shells were reported in their work.

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The experimental verification of second harmonic generation of ultrasonic guided wave in tube-like structure is essential and important. In this work, we study the second harmonic generation of longitudinal axi-symmetric modes in an isotropic metal pipe. Flexible Polyvinylidene fluoride (PVDF) comb transducers are used to generate guided wave modes, a guided wave mode verification method is also introduced. The proposed measurement technique is used to assess thermal fatigue damage in the Aluminum alloy pipes, and testing the nonlinearity under different loading conditions. The comparison among damage degree, nonlinear parameters and micro-structure image of specimens is also studied in the work.

2 Nonlinear ultrasonic waves in pipe

The method to detect ultrasonic nonlinearity is to launch a singular frequency ultrasonic wave into the specimen, and receive the signal after a certain propagation distance. Due to the material nonlinearity, after propagating over a certain distance, the singular frequency wave will distort and generate higher harmonics. As mentioned in [2], for Lamb wave, acoustic nonlinearity could be written analogously as

$$\beta = \frac{8}{k^2 a}\frac{A_2}{A_1^2}f \tag{1}$$

Where$a$ is the wave propagation distance, f is a frequency independent function, in experimental work, A_1 and A_2 are the measured amplitudes of the fundamental and second harmonic waves. Usually, we use relative parameter $\bar{\beta}$ to represent material nonlinearity, which defined as

$$\bar{\beta} = \frac{A_2}{A_1^2} \propto \beta a \tag{2}$$

Constructing the second order solution using model expansion [1], the total second harmonic fields could be written as

$$u_2 = \sum_{m=1}^{\infty} A_m(z)u_{(2,m)}(r)e^{-i2wt} \tag{3}$$

Where $u_{(2,m)}(r)$ is displacement field function of the mth double frequency components, $A_m(z)$ is the corresponding expansion coefficient, according to [5], $A_m(z)$ is the solution to the following ordinary differential equation:

$$4p_{mn}(\frac{d}{dz} - ik_n^{(2w)})A_m(z) = (f_n^{surf} + f_n^{vol})e^{ikz} \tag{4}$$

The terms f_n^{surf} and f_n^{vol} are defined as the complex external power due to the surface $p^{2w} \cdot n_z$ and due to the volume force f^{2w}respectively. In De Lima [4] analysis, the solution of equation (18) with the source condition: $u_2 = 0$, at $z = 0$, is

$$A_m = \bar{A}_m(z)e^{i2kz} - \bar{A}_m(0)e^{-ik_n^* z} \quad (5)$$

Where

$$\bar{A}_m(z) = \frac{i(f_n^{surf} + f_n^{vol})}{4p_{mn}(k_n^* - 2k)}, \quad k_n^* \neq 2k \quad (6)$$

$$\bar{A}_m(z) = \frac{(f_n^{surf} + f_n^{vol})}{4p_{mn}} z, \quad k_n^* = 2k \quad (7)$$

To generate accumulative second harmonic waves for ultrasonic guided wave in tube-like structure, there are two conditions needed to be satisfied: 1) nonzero power flux from the primary waves to the modes in the secondary fields ($f_n^{surf} + f_n^{vol} \neq 0$). Through the analysis, it is shown that all axi-symmetric modes are satisfy this condition, which means that it is possible for all Longitudinal wave modes and torsional modes to generate harmonic wave of guided wave in pipe. 2) To generate cumulative second harmonic wave, "phase matching" is necessary to select a pair of wave modes ($k_n^* = 2k$). The primary waves and secondary waves should have same velocity.

3 Experimental procedure

Al-6063 pipe specimens are used in this work. All the specimens have same dimensions of outer diameter 40 mm, length 400mm, and thickness 3mm. They are delivered by the same supplier. In order to change the microstructure and generate micro-damages, the pipe specimens are subjected to 0, 5, and 10 cycles of heat-loading, respectively. In one heat-loading cycle, the pipe specimen is heated in a heating furnace at 240^0C temperature for 15 minutes, and then be kept in room temperature (20^0C) for another 15 minutes.

Fig. 1 shows a schematic of the experimental setup. The source signal for guided wave generation is a high power amplifier (RITEC advanced measurement system RPR-4000). The generated waveform is a sinusoidal tone burst with 20 cycles at a central frequency of 1.68 MHz. Flexible PVDF comb transducers, which have certain width electro fingers to control the generated wave length, are coupled to the pipe specimen by using ultrasonic couplant. Fixed pressure is applied on the PVDF transducers to make the couplant thickness consistent.

In this work, longitudinal wave modes are incident in an isotropic metal pipe, the most critical issue is to determine the mode pair which satisfies phase matching condition to generate cumulative second harmonic wave. Numerical dispersion curves help us to find the "phase matching" modes as shown in figure 2. It indicates the phase velocity matching mode pair at fd=5.05 and 10.10 MHz mm, with the equal phase velocity of 8.25 km/s. This mode pair also satisfies the group velocity matching requirement. Therefore, for the OD40 mm Al-6063 pipe of 3 mm thickness used in this study, the generated fundamental frequency is:

$$f = \frac{fd}{d} = \frac{5.05 MHz mm}{3 mm} \approx 1.68 MHz \tag{8}$$

$$f = \frac{c_p}{f} = \frac{8.25}{1.68} mm \approx 5mm \tag{9}$$

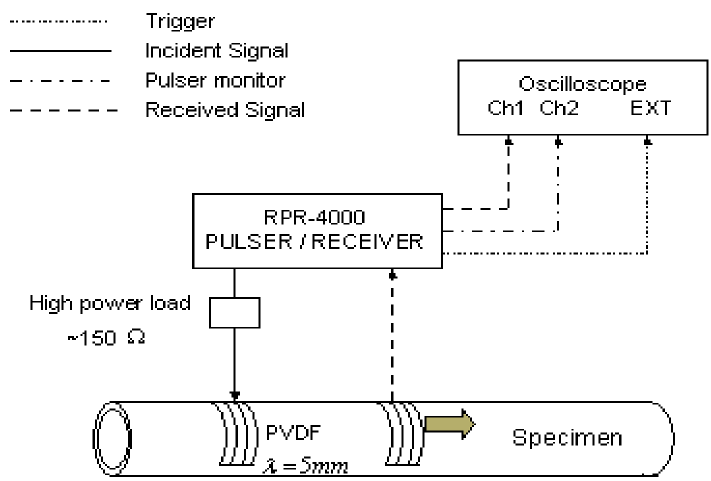

Figure 1: Schematic of the experimental setup

4 Result and discussion

The measured relative nonlinearity should include damage-induced nonlinearity plus any nonlinearity from instrumentation and couplant. To make sure what measured from the specimens are truly due to the specimen micro-damage but not only due to the nonlinearity arising from the measurement system, it is necessary to show the change of A_2/A_1^2 with various propagation distances. A standard measurement is common to all four specimens, which ensure that the change of nonlinear parameter is the change of material inherent nonlinearity. Figure 3 shows the measured

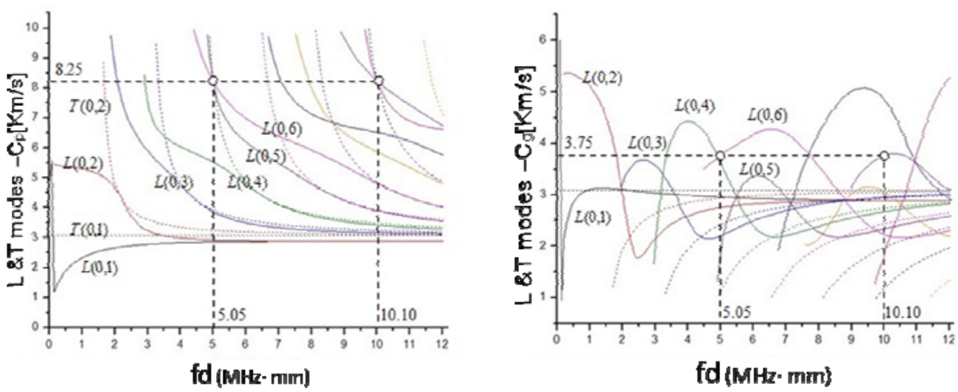

Figure 2: Numerically dispersion curves for Longitudinal and Torsional modes of Aluminum -6063 pipe: (a) phase velocity versus frequency; (b) group velocity versus frequency.

nonlinearity (including nonlinearity of the measurement system and nonlinearity of the specimen) of the undamaged OD40 mm pipe. Average data with error bars are shown in this figure. Obviously, the relative nonlinear parameter $\bar{\beta}$ increases linearly as function of propagation distance, indicating that the proposed procedure is applicable to detect micro-damages. This measurement consists of five propagation distances at intervals between 130 and 170 mm, and nonlinearity at each propagation distance is tested two times; the PVDF transducers and couplant are completely removed and then reattached for each test.

As shown in figure, the measured nonlinearity of the OD40 mm Al-6063 pipe as function of heat-loading cycles at fixed propagation distance 170 mm. The measured relative nonlinear parameter becomes greater when the specimen is subjected to higher heat-loading cycles. This figure gives a direct view of the relationship between nonlinearity and heat-loading cycles, and the transducer location doesn't need to be changed, thus it is a promising potential method for the diagnostics and prediction of micro-damages in a tube-like structure.

5 Conclusion

This work proposes an experimental procedure to evaluate the thermal damage induced nonlinearity of Al-6063 pipe by using ultrasonic guided waves. The experimental results show that the relative acoustic nonlinear parameter increases linearly with propagation distance, which means that cumulative second harmonic is generated in the pipe structure and the proposed procedure is applicable for nonlinearity

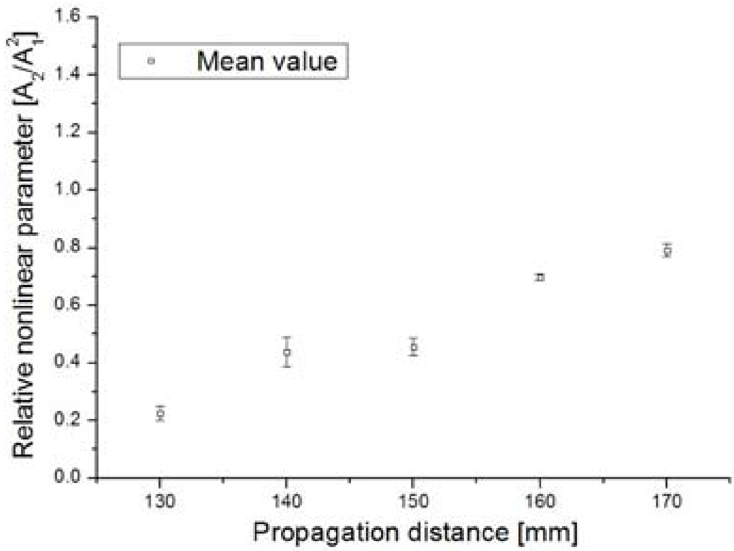

Figure 3: Measured nonlinearity of the undamaged Al-6063 pipe

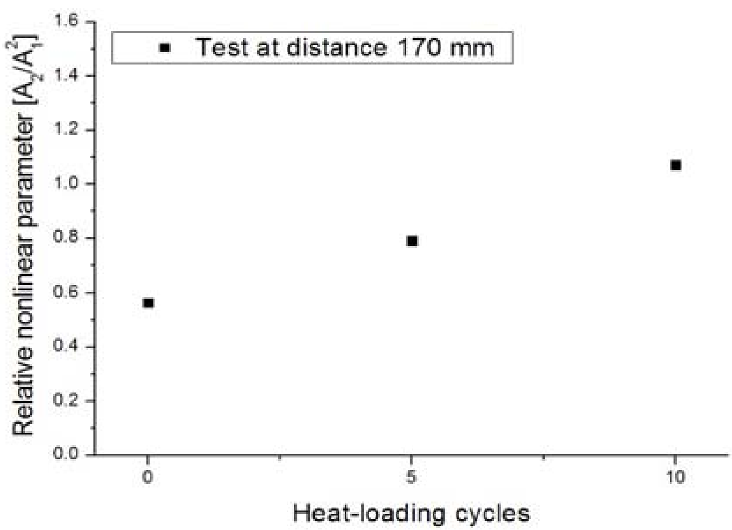

Figure 4: Measured nonlinearity of the OD40 mm Al-6063 pipe as a function of heat-loading cycles, case fixed propagation distance 170 mm

evaluation of a pipe structure. It is found that there is a significant increase of nonlinear parameters associated with thermal fatigue cycle. This work shows the potential application of measured nonlinear parameter as an effective tool to evaluate early thermal damage in pipe-like structure.

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