Nonlinear Ultrasonic Guided Waves for Microstructure Characterization of Hollow Cylinders

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Abstract
The issue of non-destructive characterization of material microstructure with respect to precursors to macroscale damage initiation is addressed. Ultrasonic guided waves are known to be sensitive to material nonlinearity, which is evident through the generation of higher harmonic modes. Thus, nonlinear guided waves have strong potential to identify precursors to macroscale damage and revolutionize condition-based maintenance. Hollow cylindrical waveguides are analyzed herein. As guided waves are multi-modal, the first step in this direction is to identify a primary mode that generates a cumulative higher harmonic mode. The second step is to select transducers to emit the primary mode and receive both primary and secondary modes. After discussing mode and transducer selection, a simulation of second harmonic generation from localized microstructure evolution is presented.

Keywords: nonlinear ultrasonics, higher harmonic generation, guided waves, piezoelectric, magnetostrictive

1. Introduction

The capability to non-destructively characterize the evolution of microstructure that precedes macroscale damage in structural material is highly desirable. Macroscale damage modes can lead to failure very quickly, e.g., high cycle fatigue crack propagation. In such cases, detection of macroscale damage is insufficient to adequately plan operational alternatives and maintenance actions. Thus microstructural evaluation, whether performed in a non-destructive testing mode or as online structural health monitoring with permanently affixed transducers, is a key to effective condition-based maintenance, minimal life cycle costs, and safety.

Technologies to non-destructively characterize material microstructures are quite limited. Two reports from the Pacific Northwest National Laboratory [1-2] review the capabilities of nonlinear acoustics, magnetic Barkhausen emission, and others relative to the nuclear power industry. One application of considerable interest involves hollow cylindrical waveguides, whether pipes or tubing, and is the subject discussed in this paper. In this paper we discuss the generation of ultrasonic guided waves at the second harmonic frequency as a method to assess microstructure evolution. The generation of second harmonics is contingent upon a finite amplitude primary wave mode and a nonlinear material model. A nonlinear elastic material is used herein, specifically a hyperelastic with a third order strain energy function.

The paper unfolds as follows. Section 2 summarizes the key elements of nonlinear guided wave mechanics that enable us to intelligently select modes and frequencies that generate strongly cumulative secondary modes. Then Section 3 discusses considerations involved in the selection of transducers for a pitch-catch characterization mode. Both piezoelectric and magnetostrictive based transduction modes are discussed relative to hollow cylinders. A finite element simulation that shows the effect of localized microstructure evolution on the generation and reception of secondary modes is presented in Section 4. Finally, the conclusions are provided in Section 5.

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2. Mode Selection

2.1 Bulk Waves

Nonlinear elastic materials are known to distort pure sinusoidal ultrasonic waves, and when transformed into the frequency domain harmonics at integer multiples of the excitation frequency are observed [3]. The distortion, and therefore the amplitude of the higher harmonics, is dependent upon the material nonlinearity so as the microstructure evolves (e.g., through dislocation density, persistent slip bands, or precipitates) so too does the higher harmonic generation. While the amplitude of the higher harmonic is small compared to the primary wave, it increases linearly with propagation which makes it discernible from instrumentation nonlinearities. Bulk waves are either longitudinal or shear, making mode selection not an issue.

2.2 Guided Waves in Plates

Ultrasonic guided waves in plates are multi-modal and dispersive [4]. There is no assurance that any mode excited at a particular frequency will generate a cumulative higher harmonic. Thus, mode selection is an important first step. In order to generate cumulative higher harmonics two criteria, known as internal resonance, must be satisfied [5]: (1) the phase velocities must be synchronized and (2) there must be power flux to the secondary mode. The issue of group velocity matching is controversial and remains unresolved, but it is clearly not a necessary condition for internal resonance. Analysis of mode interactions and identification of primary shear-horizontal and Lamb wave modes that generate cumulative higher harmonics has been conducted [6-7].

2.3 Guided Waves in Hollow Cylinders

Here, we restrict the type of guided wave modes in hollow cylinders to be axisymmetric, although analysis of flexural modes in pipe is forthcoming in another publication. However, both torsional modes denoted T(0,m) and longitudinal modes denoted L(0,m) are considered, where m represents the family order. The phase velocity dispersion curves for these axisymmetric modes are shown in Figure 1 for a steel pipe (ρ = 7932 kg/m^3, c_L = 5.96 mm/µs, c_T = 3.23 mm/µs) having an inner radius of 9 mm. Secondary longitudinal modes are plotted at the double frequency to enable identification of points having synchronized phase velocities. Only longitudinal secondary modes are plotted because power flux analysis [8] indicated that there is no power flux to torsional secondary modes from a single primary mode. Moreover, the relation between guided wave modes and higher harmonic generation in plates and pipes has recently been analyzed [9-10]. Internal resonance points, where the internal resonance criteria are satisfied, are identified in Figure 1 and tabulated in Table 1. The internal resonance points occur at phase velocities equal to c_T, c_{Lame}, c_L, and at mode crossing points. These are the points at which cumulative second harmonics will be generated, and may be measurable if a sufficiently large primary mode amplitude is activated. Second harmonics may also be generated at other points, but these are not cumulative.

Internal resonance points 1-6 occur for primary longitudinal modes, while internal resonance points 7-13 occur for primary torsional modes. There are more internal resonance points, but they occur at higher frequencies. Table 1 indicates the power flux from the primary to secondary mode. Clearly this is very dependent on the mode pair. The power flux at points 6 and 13 is essentially zero. Internal resonance points 3 and 4, which occur at the Lamb wave
speed \( (\sqrt{2c_T}) \) also have very low power flux because the secondary modes approach antisymmetric Lamb modes in the asymptotic limit. It is well-known that nonzero power flux from a single primary mode in a plate only occurs to symmetric secondary Lamb modes. Table 1 also shows the group velocities for the primary and secondary modes. The internal resonance points for longitudinal primary modes have good group velocity matching, except for the mode crossing points. On the other hand, for torsional primary modes only the internal resonance points (11 and 12) at the Lamb wave speed have good group velocity matching.

3. Transducer Selection

In order to generate cumulative second harmonics internal resonance points should be selected in conjunction with transducer selection because it is necessary to excite the primary mode with a transducer and receive the primary and secondary modes with another transducer. Each mode/frequency combination has a unique wavestructure with its own excitability and receivability.
Table 1. Internal resonance points for a steel pipe having a 9 mm inner radius.

<table>
<thead>
<tr>
<th>Internal Resonance Point</th>
<th>Mode Pair</th>
<th>Frequency-Thickness (MHz-mm)</th>
<th>Phase Velocity (mm/µs)</th>
<th>Group Velocity (mm/µs)</th>
<th>Normalized Power Flux Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>L(0,4)/L(0,5)</td>
<td>3.85</td>
<td>5.96</td>
<td>4.86/4.92</td>
<td>2.81×10^4</td>
</tr>
<tr>
<td>2</td>
<td>L(0,5)/L(0,9)</td>
<td>7.70</td>
<td>5.96</td>
<td>4.92/5.18</td>
<td>1.36×10^5</td>
</tr>
<tr>
<td>3</td>
<td>L(0,2)/L(0,3)</td>
<td>2.28</td>
<td>4.57</td>
<td>2.32/2.31</td>
<td>1.35×10^3</td>
</tr>
<tr>
<td>4</td>
<td>L(0,3)/L(0,6)</td>
<td>4.56</td>
<td>4.57</td>
<td>2.31/2.34</td>
<td>2.18×10^2</td>
</tr>
<tr>
<td>5</td>
<td>L(0,4)/L(0,8)</td>
<td>6.84</td>
<td>4.57</td>
<td>2.31/2.38</td>
<td>3.63×10^2</td>
</tr>
<tr>
<td>6</td>
<td>L(0,1)/L(0,1)</td>
<td>0.15</td>
<td>1.73</td>
<td>0.85/2.34</td>
<td>2.68×10^-6</td>
</tr>
<tr>
<td>7</td>
<td>T(0,1)/L(0,2)</td>
<td>1.72</td>
<td>3.23</td>
<td>3.23/4.43</td>
<td>1.29×10^2</td>
</tr>
<tr>
<td>8</td>
<td>T(0,2)/L(0,4)</td>
<td>1.92</td>
<td>5.96</td>
<td>1.74/4.86</td>
<td>4.10×10^3</td>
</tr>
<tr>
<td>9</td>
<td>T(0,3)/L(0,5)</td>
<td>3.85</td>
<td>5.96</td>
<td>1.75/4.92</td>
<td>1.27×10^4</td>
</tr>
<tr>
<td>10</td>
<td>T(0,4)/L(0,7)</td>
<td>5.78</td>
<td>5.96</td>
<td>1.74/5.09</td>
<td>5.47×10^4</td>
</tr>
<tr>
<td>11</td>
<td>T(0,2)/L(0,3)</td>
<td>2.28</td>
<td>4.57</td>
<td>2.27/2.31</td>
<td>1.23×10^1</td>
</tr>
<tr>
<td>12</td>
<td>T(0,3)/L(0,6)</td>
<td>4.56</td>
<td>4.57</td>
<td>2.27/2.31</td>
<td>2.36×10^2</td>
</tr>
<tr>
<td>13</td>
<td>T(0,1)/L(0,1)</td>
<td>0.06</td>
<td>3.23</td>
<td>3.23/4.97</td>
<td>1.62×10^-6</td>
</tr>
</tbody>
</table>

3.1 Piezoelectric Transducers

The most common means to activate ultrasonic waves is through piezoelectric transducers. There are many options for activating ultrasonic guided waves: normal incidence, angle beam, comb, interdigitated, and phased array transducers. Some of the transducer selection considerations are that mode control is not possible with normal incidence and if gel couplant is used with an angle beam transducer then only the out-of-plane displacement component can be excited. Comb and interdigitated transducers provide mode control through the element spacing, but can have significant side lobes. Multi-element phased array transducers provide flexible mode control and beam steering capability, but require more sophisticated and expensive instrumentation.

3.2 Magnetostrictive Transducers

Magnetostrictive transducers have some novel features that make them an attractive option for generating nonlinear guided waves. One possibility is to adhesively bond a magnetostrictive foil (e.g., iron-cobalt) around the circumference of the cylinder. Next a meandering electric coil printed onto a flexible substrate is wrapped around the foil. Then a permanent magnetic field is applied using rare earth magnets in order to align the magnetic domains in the magnetostrictive foil. When an alternating current is passed through the electric coil the magnetostrictive foil responds to the alternating magnetic field by generating an elastic wave. The converse process is used for sensing. The polarity of the elastic wave is dictated by the bias direction of the permanent magnet, thus both torsional and longitudinal waves can be emitted and sensed.
Advantages of magnetostrictive transducers for nonlinear ultrasonics applications involving higher harmonic generation include:
1. no gel couplant, which can produce higher harmonics, is necessary for either transmitter or receiver,
2. torsional modes (and shear-horizontal modes in plate) have good excitability to magnetostrictive transducers due to the strong shear stress transfer through the adhesive,
3. the same transducer can be used to receive a primary torsional wave mode and a secondary longitudinal wave mode by simply rotating the bias of the permanent magnet 90 degrees,
4. they can conform to surfaces having a broad range of curvatures,
5. they are relatively inexpensive and easy to assemble.

4. Finite Element Simulation – Localized Microstructure Evolution

The cumulative nature of second harmonics is very important because it provides confirmation that the second harmonic signal is associated with material nonlinearity in addition to the nonlinearity inherent to the measurement system. Moreover, finite element analysis can be used to corroborate theoretical analysis without the complication of unwanted system nonlinearities. Transient dynamics analysis using finite strain and a nonlinear elastic material mode can be used to simulate second harmonic generation due to the material microstructure. The third order elastic constants (TOECs) A, B, and C used for steel are -325, -310, and -800 GPa, respectively [11]. Assume that microstructure evolution results in changes to the TOECs, but not the linear elastic constants. We would like to assess the correlation between microstructure evolution described by evolving TOECs and the second harmonic generation. The first step is to determine how much to change the TOECs. As a first trial we change all TOECs by a factor of 2, and then a factor of 3. It is important to confirm that these parameters result in realistic material behaviour for steel. The predicted uniaxial tension stress-strain response is shown in Figure 2 for three sets of TOECs and a linear elastic material. Clearly the stress-strain curves deviate very little from linearity up to the yield strength of the material and so these TOECs appear reasonable.

The generation of the \( L(0,4) \) second harmonic from a primary \( T(0,2) \) wave excited at 1.28 MHz is simulated for a steel pipe having inner radius of 9 mm and wall thickness of 1.5 mm.

![Figure 2. Uniaxial tension stress-strain response predicted for different sets of TOECs.](image-url)
An interdigitated transducer is simulated to emit the primary wave. As shown in Figure 3 the signal is received at five different points. Three simulations are performed. First the TOECs are the same throughout, but in the second and third simulations there is a domain where the TOECs are changed to represent localized microstructure evolution. In this domain the TOECs are increased to 2x and then 3x their initial values.

The received signals at point R2 are shown in Figure 4. The amplitude of the primary wave form ($u_\theta$ in Fig. 4a) is significantly larger than the secondary wave form ($u_z$ in Fig. 4b). As predicted by theory [8], there is no secondary torsional wave motion $u_\theta$, the secondary wave motion is all longitudinal, $L(0,4)$ – as is evident in Figs. 4c and 4d.

By receiving the signal after different propagation distances, T-R1, T-R2, ..., T-R5, the cumulative nature of the second harmonic is clearly demonstrated. The secondary-to-primary wave amplitude ratio, $A_2/A_1^2$, is plotted in Figure 5. The ratio increases linearly with propagation distance when the material is homogeneous, which is the case for TOECx1. When the TOECs are increased within the domain shown in Fig. 3 the ratio increases more rapidly and the accumulation is not necessarily linear as shown in Fig. 5 for TOECx2 and TOECx3.
6. Conclusions

Based on theory developed elsewhere, the internal resonance points are identified where strong cumulative second harmonics are generated in a hollow cylinder. This enables identification of the primary mode and selection of a transducer to activate it. The application of magnetostrictive transducers to generate a torsional primary mode and to receive both the torsional primary mode and the longitudinal secondary mode has been introduced. Finite element simulations provide a means to assess theory without the measurement system nonlinearities present in experiments. A simulation showed the effect that localized microstructure evolution has on the second harmonic.

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References


