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High-frequency lowest torsional wave mode ultrasonic inspection using a necked pipe waveguide unit

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ABSTRACT

We propose an effective method to transmit only the non-dispersive lowest torsional wave mode at a high frequency range even above the cutoff frequency of the third torsional mode. Unlike existing methods that tune the wavelength or phase of the target wave mode, the proposed method is based on the thickness change and the cutoff phenomenon. A specially configured necked waveguide, consisting of three regions of which the middle region is thinner than the so-called cutoff thickness, is put in end-to-end contact with a test pipe to transmit only the first torsional wave mode to a test pipe. After explaining the underlying role of the proposed necked waveguide, we propose a technique to mainly transmit the lowest torsional wave mode at a frequency where higher modes can also propagate. Numerical simulations and damage detection experiments were carried out to show the effectiveness of the proposed method.

1. Introduction

The torsional wave is one of the most preferred wave modes in the guided-wave-based nondestructive evaluation of pipes because of its non-dispersive property. Since the phase and group velocities of the lowest torsional wave mode are constant at all frequencies, the identification of defects would be easier even without sophisticated signal processing. However, the appearance of higher-torsional wave modes in addition to the lowest mode is inevitable if the excitation frequency is higher than the cutoff frequency. Although high-frequency waves may be preferred for small-sized defect inspection, the co-existence of multiple modes including dispersive higher modes makes signal analysis difficult. For this reason, a torsional wave has been used typically at a low-frequency below the cutoff frequency of the T(0,2) mode or in a thinner pipe than the first cutoff thickness at a given excitation frequency [1–3]. The symbol T(0,m) denotes the mth torsional wave mode [4].

There were earlier efforts to suppress unwanted higher-order wave modes to allow the T(0,1) mode to be used effectively at higher frequencies. The lowest torsional mode can be effectively enhanced by using a spatial array of multiple elements, as found in comb transducers and meander-type transducers. In these methods, the distance between adjacent elements is adjusted to be the wavelength or half the wavelength of the lowest torsional wave mode at a given excitation frequency [5–7]. Another method is to use a phased array of multiple elements. As each element generates a wave with specific time delay, the desired lowest torsional wave mode can be constructively superposed [8]. Even though these methods can effectively enhance the desired wave mode, the undesired wave mode cannot be completely suppressed, because the desired wave mode is relatively enhanced in comparison with undesired higher modes. Based on this, a wave mode selection technique suppressing the undesired wave mode has been recently proposed [9]. Using this technique, only the first torsional mode can be selected, while the second torsional mode is almost completely suppressed. However, all of these techniques have a critical limitation in that they are not effective when two or more wave modes need to be suppressed. A typical case is an excitation at a frequency above the cutoff frequency of the T(0,3) mode, where there are non-dispersive and two dispersive torsional wave modes.

We propose a method to transmit only the first torsional wave mode to a test pipe at a frequency higher than the second cutoff frequency for which three torsional wave modes exist. The proposed method is to use a specially designed necked waveguide and install transducer units on it, as illustrated in Fig. 1. The necked waveguide unit should be in end-to-end contact with a test pipe so

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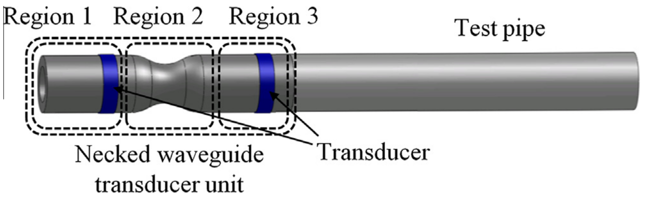


Fig. 1. Schematic illustration of the necked waveguide inspection unit that is in end-to-end contact with a test pipe.

that it may have limited applications. However, this method can be an effective method to transmit only the lowest mode among multiple modes as long as it is applicable (as in testing newly fabricated pipes). The employed waveguide has a gradually thinning middle region. Note that only the lowest torsional wave mode exists in the middle region of the waveguide if its thickness is smaller than the cutoff thickness of the T(0,2) mode at a given excitation frequency or if the excitation frequency is lower than the cutoff frequency of the T(0,2) mode at a given thickness. In dealing with the cutoff phenomena, it is convenient to use the frequency-thickness product as a key parameter. (Depending on the product value, certain higher wave modes cannot propagate.) Some works on wall thinning detection have been done using the cutoff phenomenon [10,11]. In the present work, however, cutoff phenomena of higher-wave modes are directly used to filter them out, transmitting only the lowest torsional wave mode into a test pipe. Therefore, unlike existing methods, the proposed method can be effectively applied even when the excitation frequency is higher than the cutoff frequency of the T(0,3) mode where three or more wave modes exist. The uniqueness of the present approach is that while earlier efforts were effective mostly at a frequency below the second cutoff frequency, the present method can go beyond the cutoff frequency of the T(0,3) mode.

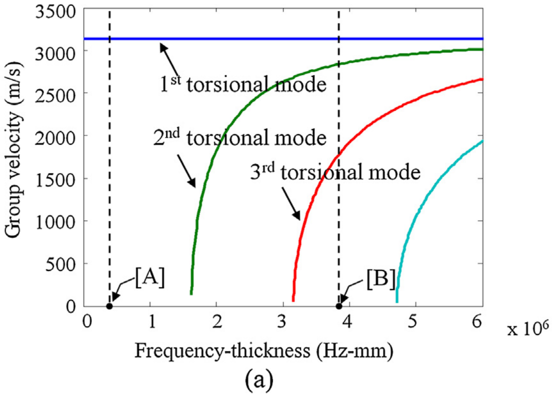
To design the shape of the necked region, two-dimensional finite element simulations were first carried out. Then experiments to detect two adjacent defects were conducted to confirm the effectiveness of the proposed method.

2. Necked waveguide inspection unit

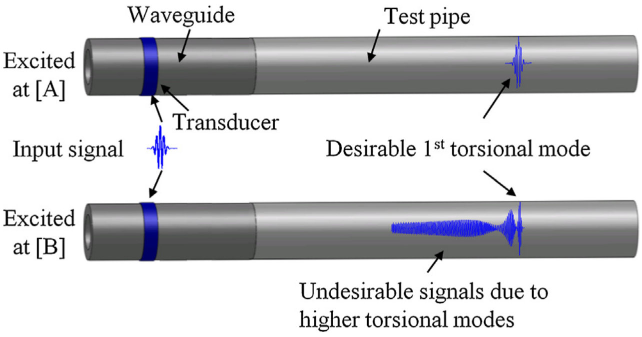
2.1. Motivation for developing a necked waveguide unit

Fig. 2(a) shows the group velocity (an example is available elsewhere [12]) for the torsional modes in an aluminum pipe with 70-mm outer diameter and 13-mm thickness. As shown in the figure, the first torsional mode exists at all frequency–thickness products, whereas other higher modes appear when the frequency–thickness product becomes larger than their cutoff frequency–thickness products. If the frequency–thickness product has the value at [B] in Fig. 2(a), the first, second, and third torsional modes will be generated in the waveguide. On the other hand, only the lowest mode can propagate if the frequency–thickness product has the value at [A]. Fig. 2(b) schematically shows the transmitted waves when the frequency–thickness product values are at [A] and [B]. The illustration in Fig. 2(b) suggests that for a given excitation frequency, one could avoid higher-mode generation by changing the thickness of a waveguide. Since the thickness of a test pipe cannot be altered, we propose using a necked waveguide, as illustrated in Fig. 1, to transmit mainly the lowest torsional mode from the waveguide unit to a test pipe for damage inspection even at an excitation frequency for which two or more propagating wave modes exist.

The waveguide employed in the proposed waveguide ultrasonic inspection unit consists of three regions made of the same material as that of a test pipe. Referring to Fig. 1, the transmitting and receiving torsional magnetostrictive transducers [13,14] are installed in Regions 1 and 3, respectively (the detailed configurations of the magnetostrictive transducers used and the data acquisition procedure will be given in Section 2.4). Because Region 3 will be connected to an open end of a test pipe by a couplant, the inner and outer radii of Region 3 should be the same as those of the test pipe to match the mechanical impedance between Region 3 and the test pipe. Then, Region 1 naturally has the same geometry as Region 3. Region 2, which has varying thickness, constitutes the key part of the necked waveguide unit because it will serve to filter out unwanted higher torsional modes at a frequency above the cutoff frequencies. We aim to use a frequency above the cutoff frequency of the T(0,3) mode where there exist three propagating wave modes. Therefore, the minimum wall thickness in Region 2 should be selected so as to locate the frequency–thickness product somewhere near [A] if a test pipe is to be inspected at [B]. If Region 2 is properly designed with the minimum thickness, only the first torsional mode among multiple torsional modes generated in Region 1 would survive as they pass through Region 2. While the underlying physics is well known [15,16], its utilization for transmitting the lowest mode at a frequency higher than the cutoff frequency has not been realized or proposed.



(a)



(b)

Fig. 2. (a) Group velocity curve for the torsional wave in an aluminum pipe of 70-mm outer diameter and 13-mm thickness. (b) Illustration of the generation of different wave modes in pipes of different frequency–thickness values at [A] and [B] for the same excitation frequency of 300 kHz.

2.2. Wave analysis in the necked waveguide

As waves move further down into Region 3, the first mode will still be dominant, although higher modes may be observed due to mode conversion occurring at the interface between Region 2 and Region 3. Therefore, the effects of the neck configuration on the transmission should be investigated to maximize the