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Modeling of second-harmonic generation of circumferential guided wave propagation in a composite circular tube

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A B S T R A C T

This paper investigated modeling of second-harmonic generation (SHG) of circumferential guided wave (CGW) propagation in a composite circular tube, and then analyzed the influences of interfacial properties on the SHG effect of primary CGW. Here the effect of SHG of primary CGW propagation is treated as a second-order perturbation to its linear wave response. Due to the convective nonlinearity and the inherent elastic nonlinearity of material, there are second-order bulk driving forces and surface/interface driving stresses in the interior and at the surface/interface of a composite circular tube, when a primary CGW mode propagates along its circumference. Based on the approach of modal expansion analysis for waveguide excitation, the said second-order driving forces/stresses are regarded as the excitation sources to generate a series of double-frequency CGW modes that constitute the second-harmonic field of the primary CGW propagation. It is found that the modal expansion coefficient of each double-frequency CGW mode is closely related to the interfacial stiffness constants that are used to describe the interfacial properties between the inner and outer circular parts of the composite tube. Furthermore, changes in the interfacial stiffness constants essentially influence the dispersion relation of CGW propagation. This will remarkably affect the efficiency of cumulative SHG of primary CGW propagation. Some finite element simulations have been implemented of response characteristics of cumulative SHG to the interfacial properties. Both the theoretical analyses and numerical simulations indicate that the effect of cumulative SHG is found to be much more sensitive to changes in the interfacial properties than primary CGW propagation. The potential of using the effect of cumulative SHG by primary CGW propagation to characterize a minor change in the interfacial properties is considered.

1. Introduction

A composite circular tube is generally joined together by two circular parts of different metals through the mechanical or metallurgical technique [1,2]. As a kind of common engineering structures, composite circular tubes have been widely used in many practical fields such as chemical, pharmaceutical, food and nuclear engineering industries [3,4]. However, the factors such as fatigue, ageing and/or corrosion during service will generally lead to the degradation of mechanical properties of an

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interface between the two circular parts, namely the formation of the so-called weak (imperfect) interface. This will seriously deteriorate the structural safety of the composite circular tubes in service [3]. That is, the mechanical performance of a composite tube is to a great extent dependent on its interfacial properties, which can be effectively described by the interfacial spring model [5–8]. As a kind of elementary guided wave mode, the circumferential guided wave (CGW) propagating along the circumference of a tube-like structure has been shown to be suitable for monitoring change in its mechanical properties [9–11]. Previous investigations have found that changes in the interfacial properties can essentially influence the dispersive nature of CGW propagation [12–14]. However, it is usually ineffective to monitor a minor change in the interfacial properties via using primary (fundamental) CGW propagation, since the dispersion relation of primary CGWs is almost kept unchanged in the early stage of degradation of the interfacial properties (characterized by the normal and shear interfacial stiffness constants [5–8]). Referring to the sensitivity of nonlinear ultrasonic Lamb waves for accurate evaluation of material micro-damage and weak interface in plate-like structures [15–23], it can be expected that the response characteristics of second-harmonic generation (SHG) of primary CGW propagation may sensitively reflect a minor change in the interfacial properties of a composite circular tube.

When the primary and double-frequency CGW modes satisfy the phase velocity matching and the nonzero energy transfer from primary to double-frequency wave mode (i.e., nonzero power flux), previous investigations have shown that the double-frequency CGW mode has a strong nonlinear effect and its amplitude can accumulate along the circumference of the circular tube [24–26]. In practice, the said condition of generation of second harmonics with a cumulative effect is of particular interest due to the potential of accurately evaluating the interfacial properties of a composite circular tube. For guaranteeing the structural safety of a composite tube in service, it is necessary to model SHG of primary CGW propagation, and then to investigate the influence of a minor change in the interfacial properties on the effect of SHG. Through modeling and investigating that mentioned here, this paper will provide an insight into the complicated physical process of SHG of primary CGW propagation in a composite tube with different interfacial properties, as well as a means through which a minor change in the interfacial properties can be accurately monitored by the effect of cumulative SHG of primary CGW propagation.

2. Theoretical fundamentals

The two-dimensional model based on the polar coordinate system of a composite circular tube used for modeling and investigating CGW propagation is shown in Fig. 1, where there is an interface between the two adjacent solids (i.e., inner and outer circular parts). It should be noted that the model shown in Fig. 1 is also used for the Finite Element (FE) simulations, where the cut ends E and E' as well as the radial stress component T_{rr} exerted will be elaborated in more detail in the following Section 4. Generally, the interface can be assumed to be a thin interfacial layer, where its thickness h is much smaller than the ultrasonic wavelength λ, and its mechanical properties are different from that of the two adjacent solids [5–8]. Unquestionably, it is of great significance to develop a model through which the complex properties of the interface can be effectively characterized with as few parameters as possible. So far, an effective model (commonly called as the interfacial spring model) has been proposed and examined for describing the properties of the thin interfacial layer just using the two interfacial stiffness constants [5–8]. Specifically speaking, under the condition that h is much less than λ and the mass of the interfacial

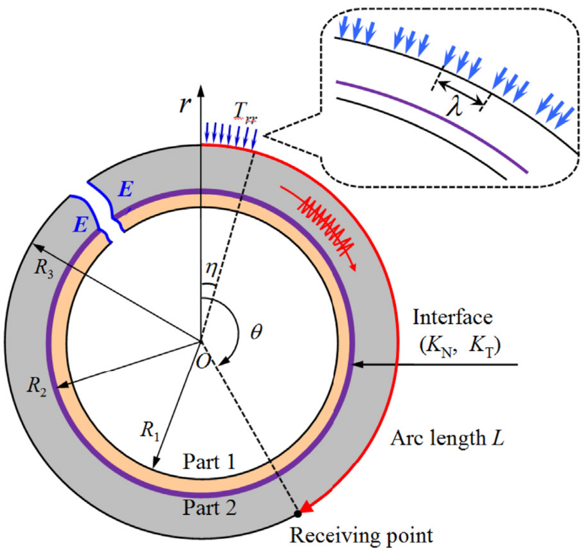

Fig. 1. Schematic diagram of a two-dimensional model for analyzing CGW propagation in a composite circular tube.