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Dispersion analysis of guided waves in the finned tube using the semi-analytical finite element method

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ABSTRACT

To increase heat exchange efficiency, finned tubes are widely used in petrochemical facilities. Recently, the application of guided wave testing to finned tube inspection has received attention. Since dispersion curves have not been obtained, the guided wave propagation process is still not clearly understood. Hence, the purpose of this paper is to calculate dispersion curves of the finned tube based on an accurate theoretical model, then features of guided waves propagating in finned tubes are further investigated. As fins are helicoidally welded around the outer surface of the tube with an equal interval, the semi-analytical finite element method is extended to this geometrically periodic waveguide. The shape of the discretized cross section is determined by geometric parameters of the finned tube. Numerical solutions show that group velocities of longitudinal modes in finned tubes are significantly slower than those in bare tubes and a special phenomenon of frequency pass bands and stop bands is presented. The changes of dispersion curves are also investigated with various geometric parameters of fins. Besides, torsional modes cannot propagate in finned tubes. By using an electromagnetic acoustic transducer, experimental results are in good agreement with numerical solutions, which indicates features of the guided wave propagation in finned tubes can be well predicted based on the proposed theoretical model.

1. Introduction

As an essential component to increase heat exchange efficiency, finned tubes are typically applied in heat exchangers, heating furnaces and other petrochemical facilities, which require regular inspections to ensure their safety and reliability [1,2]. Compared with the bare tube, helical fins on the outer surface of the tube make it infeasible to inspect finned tubes from the outside. The common testing methods are limited to magnetic flux leakage (MFL), remote field eddy current (RFEC), ultrasonic internal rotating inspection systems (IRIS) and laser optics [3]. All of these testing methods are required to inspect from inner surface of the finned tube. Therefore, there is currently no reliable, non-intrusive method for finned tube inspection.

The guided wave testing (GWT) is another useful testing technique for tube inspection, which benefits from the ability of scanning the whole tube with a fixed transducer installation position [4,5]. To expand its application scope, more researchers focused on applying GWT to new testing objects [6,7] or special testing conditions [8,9]. Recently, the application

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of GWT to finned tube inspection has received attention. The study of Malinowski et al. [10] indicated that the detection sensitivity was approximately 10% cross-sectional area loss by utilizing longitudinal guided waves, which manifested the feasibility of GWT for finned tube inspection. But due to lack of dispersion curves in his study, the guided wave propagation process in finned tubes is still not clearly understood.

Generally speaking, as a crucial basis for proper selections of wave modes and frequencies, dispersion curves should be obtained firstly to provide scientific guidance for GWT. However, dispersion curves of the finned tube have not yet been obtained [11–15]. Hence, this paper focuses on dispersion curves of the finned tube and the guided wave propagation process. As we know, dispersion curve calculation methods are mainly divided into analytical methods and numerical methods. The former methods are often applied to some simple waveguides such as plates [16], solid rods [17] and hollow cylinders [18]. But for waveguides with a complex geometry, analytical solutions may not generally exist. In this case, some useful and efficient numerical methods based on finite element analysis are preferably selected [19,20]. The semi-analytical finite element (SAFE) method is well applied to these waveguides by using a finite element discretization of their cross section. This method assumes the elastic wave is a harmonic motion along the wave propagation direction with an analytical expression. Hence, only the cross section needs to be discretized which drastically reduces the number of degrees of the freedom when compared with a three-dimensional discretization of the entire waveguide. The advantage of computational savings also arouses great interests of researchers. The dispersive spectrum of an isotropic square beam was successfully calculated by the SAFE method in 1973 [21], which indicates its applicability to waveguides with an arbitrary cross section. Then, this method began to be used for laminated composite plates [22], anisotropic composite cylinders [23], functionally graded plates and cylinders [24,25], wedges [26], rails [27,28], etc.

As another important kind of applications, dispersive properties of periodic waveguides are also well researched by the SAFE method. Onipede et al. [29,30] studied natural frequencies of vibrations and corresponding modal patterns in a pretwisted beam based on a uniformly rotating coordinate system. Predoi et al. [31] presented dispersion curves and displacement/stress fields of guided wave modes in anisotropic and absorbing periodic waveguides. Treyssède et al. [32] theoretically investigated the propagation of elastic waves in helical waveguides by utilizing a non-orthogonal curvilinear coordinate system. Furthermore, a detailed investigation of elastic modes propagating in multi-wire helical waveguides was also given [33]. Recently, Treyssède [34] further interpreted the origin of dispersion curve veering phenomenon when longitudinal guided waves propagated in prestressed seven-wire strands.

As for finned tubes concerned in this paper, since fins are helicoidally welded around the outer surface of the tube with an equal interval, the SAFE method extended to this geometrically periodic waveguide is feasible. An accurate theoretical model is established based on the actual structure of helical fins. Dispersion curves of the finned tube are firstly obtained and then features of the guided wave propagation in finned tubes are further investigated through the mode shape analysis. In Section 2, considering the finned tube can be reconstructed by rotating a particular shaped cross section along the tube axis with a constant rotation rate, the mathematical framework of the SAFE method is described in a rotating coordinate system to establish the proposed theoretical model. Section 3 gives the discretization of the cross section whose shape is determined by geometric parameters of the finned tube. In Section 4, dispersion curves of the finned tube and corresponding features are presented firstly. Dispersive properties are then studied with various geometric parameters of helical fins. Experiments are carried out to verify numerical solutions in Section 5. Brief conclusions are given at the end of this paper.

2. The mathematical framework of the SAFE method

Based on the SAFE method, the strain-displacement relation and Hamilton's principle are utilized in a rotating coordinate system. The relationship between the frequency and wavenumber is obtained by solving a twin-parameter generalized eigenvalue problem. The theoretical model is described in this section.

2.1. Problem definition

Fig. 1 shows the three-dimensional schematic diagram of a finned tube. It consists of two simple components: the bare tube and helical fins. Fins are helicoidally welded around the outer surface of the bare tube which cover a large part of the

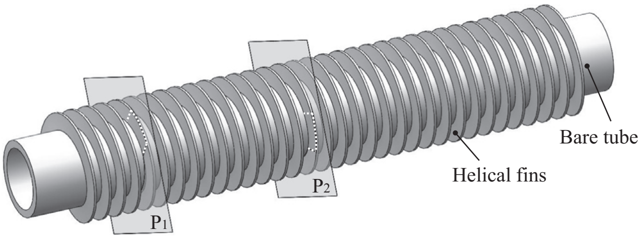

Fig. 1. Three-dimensional schematic diagram of the finned tube.