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Ultrasonic non-destructive testing of cardboard tubes using air-coupled transducers

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ABSTRACT

Cardboard tubes are commonly used for industrial plastic film wrapping due to their low cost, high compression strength, reliability and low sensitivity to environmental changes. In order to guarantee the high radial compression strength during the manufacturing process, destructive testing such as manual peeling or non-destructive testing using acoustic impedance measurements are currently performed on a regular basis. In order to achieve a continuous quality control, automatic and non-contact inspection still need to be developed. In this paper, a method and apparatus for non-contact and rapid inspection of cardboard tubes is presented. The principle is based on the use of capacitive air-coupled transducers at frequencies below 20 kHz for generation and measurement of propagative flexural waves in a pitch-and-catch configuration. Sensitivity analysis is performed for different modes and damage types and is validated experimentally for four flaw types typically observed during the manufacturing process. Experimental validation of detection and flaw quantification is demonstrated using both amplitude and time-of-flight of wave packets at different frequencies, allowing automatic quality control of the manufacturing process.

1. Introduction

Cardboard tubes are commonly used for industrial plastic film wrapping due to their low cost, high compression strength, reliability and low sensitivity to environmental changes. However, since the cardboard tubes are subject to very large compression loads during the wrapping process, a small decrease in strength may lead to dramatic consequences such as the loss of a whole material film roll or machinery damaging. Typical reported damages encountered during the whole manufacturing process include the lack of adhesive, the presence of a liner joint while connecting successive rolls of liner, changes of liner thickness, decrease of laminated surface due to a reduction of liner width, or improper curing process leading to an excessive humidity within the tube.

For this purpose, a refined strategy for quality control of the cardboard tubes is required. Destructive testing is classically conducted at regular intervals, and include manual measurement of thickness, radius and length, or manual peeling of a tube in order to detect delaminations or voids, or radial core crush experiments. The compression limit is thus assessed and compared to reference values in order to reject or accept the whole tube batch. This process is extremely time consuming since a qualified technician is required and is relatively ineffective to reject locally damaged or improperly cured tubes.

Based on these observations, a systematic, rapid and automatic inspection procedure is required and the sensitivity to those different damage types should be demonstrated. For this purpose, the estimation of flexural modulus has been first proposed using three point bending technique [1] or traction tests [2]. Acoustic measurements have also been proposed as an attractive alternative in order to estimate the flexural modulus of a tube based on its first flexural mode resonance frequencies [1,3]. However, since this process requires installing the tube on a standard mounting device, it is also time consuming, such that difficulties may arise for practical implementation in the manufacturing process.

Numerous Non-Destructive Testing (NDT) strategies have been proposed for inspection of paper liner and sheets. Those include contact ultrasound transducers [4,5], photo-acoustic transducers for characterization of bulk [6,7], guided waves [8–11], air-coupled probes for characterization of guided waves propagation [12,13] or using through-the-thickness transmission techniques [14–17]. In all cases, those studies use propagating waves for the mechanical characterization or thickness measurement of paper sheets in static configuration. The extension to the translation movement has been then presented using laser-excitation and measurement techniques [18–22]. To the best of our knowledge, no data

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are available for cardboard assemblies and multilayer tubes, except using a modal approach that is only sensitive to large scale damages, such as large cracks, holes or excessive humidity [23,24].

In this paper, a method and apparatus for non-contact and rapid inspection of cardboard tubes is presented. The principle is based on the use of capacitive air-coupled transducers at frequencies below 20 kHz for generation and measurement of propagative flexural waves in a pitch-and-catch configuration. The novelty resides in the non-contact generation and measurement of multiple flexural modes for damage detection in small and thick cardboard tubes. Sensitivity analysis is performed for different modes and damage types and is validated experimentally for four flaw types typically observed during the manufacturing process. Experimental validation of detection and flaw quantification is demonstrated using both amplitude and Time-of-Flight (ToF) of wave packets at different frequencies, allowing automatic quality control of the manufacturing process.

Section 2 presents the structure under study and the sensitivity analysis of the flexural waves with respect to geometrical and material changes. Section 3 presents the experimental setup, signal processing steps and results obtained on 50 different tubes subject to various typical flaws.

2. Non-destructive testing using guided waves

2.1. Structure of interest

The structure under study is a cardboard tube of 460 mm length, 81 mm outer diameter and 3.55 mm wall thickness. This structure is composed of an assembly of 10 plies of recycled paper liners of 130 mm width and 0.35 mm thickness that are bonded together using water-based glue, and wrapped using a specific orientation in order to increase the core crush resistance of the assembly [25], as presented in Fig. 1. The assembly is then cut before curing in a controlled environmental chamber during 24 h.

2.2. Guided wave propagation in cardboard tubes

Since all the tubes are to be inspected without slowing down the production line, a rapid and global inspection method has to be proposed. For this purpose, local ultrasound methods for pipes and tubes such as through transmission ultrasound, pulse-echo or phased-array offer local inspection and cannot be retained [26]. Due to their relatively small wavelength, sensitivity to various damage types and ability to travel over large distances, guided waves are proposed here, allowing global inspection of the tube over its whole surface by the use of flexural modes.

Fig. 2 presents the dispersion curves for guided waves propagating in the cardboard tube, i.e. the phase and group velocity of the first modes as a function of frequency. The nomenclature and method used for the calculation of phase and group velocity curves follow the ones proposed in Ref. [27], for which longitudinal modes are denoted by (L), torsional modes by (T) and flexural modes by (F). Two indices are used, corresponding to the radial and thickness mode orders respectively. For the calculation of dispersion curves, the tubes are considered infinitely long and free of external loads. Moreover, the cardboard assembly is assumed isotropic with a mean density of $750\ \mathrm{kg/m^3}$, a Young modulus of 3 GPa and a Poisson's ratio of 0.3 following previous study on similar materials [3].

Due to the large thickness and small diameter of the geometry of interest, a large number of modes is observed in the audible bandwidth, i.e. below 20 kHz. The longitudinal mode $L(0,1)$ and torsional mode $T(0,1)$ corresponding to pure compression and torsion in the length and radial direction, respectively, are presented but not considered in the following study. This can be explained by the difficulty to generate them using non-contact transducers in this frequency range since they are mostly constituted of in-plane motion. Thus, classical damage detection techniques used for pipeline inspection [28] using $L(0,1)$ or $L(0,2)$ modes cannot be used here.

The flexural modes are proposed instead due the ease of generation and measurement using classical contact and non-contact transducer that are mostly sensitive to out-of-plane motion. In the frequency range of interest, i.e. below 20 kHz, the first nine flexural modes $F(n,1)$, where n represents the number of cycles of variation around the circumference, have approximatively the same phase velocity of 450 m/s above 2 kHz, such that mode selectivity is difficult to achieve and multi-mode propagation occurs.

2.3. Damage sensitivity of flexural modes

In order to determine the effect of a potential damage on wave propagation of flexural modes, the variations of phase and group velocities with respect to a reduction of thickness or flexural modulus are described in Fig. 3. In order to be representative, typical decreases of 10% are applied to both parameters as suggested in Ref. [29]. Only the flexural modes $F(n,1)$ with $n<9$ are presented for clarity and the results are expressed in terms of relative changes with respect to the undamaged case. A reduction of 10% of the thickness corresponds to the case of a missing liner that may occur during the manufacturing process. The other damage scenario corresponds to a decrease of Young's modulus that may be due to excessive humidity or a reduction of laminated area.

In the case of thickness reduction, a decrease of 5% of both phase and group velocities is observed above 10 kHz for the $F(1,1)$ mode. In the case of a reduction of Young's modulus, the same overall reduction of phase velocity is observed with a peak around 8 kHz corresponding to a maximal reduction of 12%. The group velocity for this mode exhibits a strong variation in the frequency range of interest with a decrease up to 20% below 8 kHz and an increase of group velocity up to 10% above 8 kHz. In the case of a wall thickness reduction, only a decrease of group velocity up to 10% is observed for this mode. For the higher order modes,

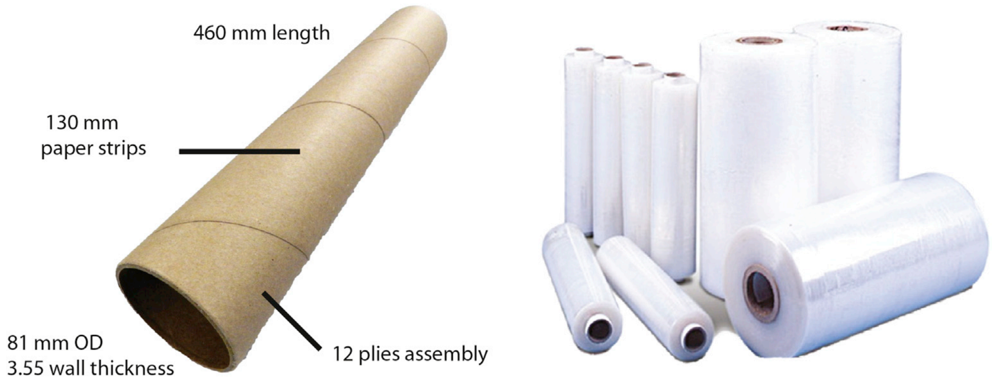

Fig. 1. Description of the cardboard tube geometry used in this study (left). Presentation of the final product wrapped with cellophane (right).