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ScienceDirect
Procedia Engineering 120 (2015) 520 – 523
Procedia Engineering
www.elsevier.com/locate/procedia

EUROSENSORS 2015

Tubular Bell - New Class of (Bio)Chemical Microsensors

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Abstract

We introduce a new class of phononic crystals, Tubular Phononic Crystals (TPC) and their application as tubular phononic crystal sensor, the Tubular Bell, for in-line monitoring of liquids in pipes. The physical challenge is formulation and physical description of a new class of phononic crystals created by radical change of phononic crystal geometry from 2D planar or 3D Cartesian with translational symmetry to 3D cylindrical with both translational and rotational symmetries. The engineering challenge is to develop a new class of sensors for volumetric liquid properties.

Peer-review under responsibility of the organizing committee of EUROSENSORS 2015

Keywords: Phononic crystal sensor; cylindrical structures, in-line liquid sensor

1. Motivation

Pipes are one of the most prominent elements in modern technical environment to transport fluids. In the medical domain vessels are biological cylindrical key elements for the transportation of blood. Sensors gaining information about physical/chemical properties of the fluid inside the tube are rather rare. They usually must be brought in contact to the fluid through specific fittings, openings or windows or via by-passes. Our concept is based on a new class of phononic crystals having a cylindrical shape. By keeping the inner surface of the cylinder free of any obstacles, one of the major concerns in chemical, biochemical, and petrol or food industry as well as in medicine, will be overcome.

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Peer-review under responsibility of the organizing committee of EUROSENSORS 2015
doi:10.1016/j.proeng.2015.08.690

2. The new design

Tubular Phononic Crystals (TPC) are a new family of periodically structured elastic cylinders for wave propagating along the revolution axis of the cylinder. The physical challenge is formulation and physical description of phononic crystals [1,2] created by radical change of phononic crystal geometry from 2D planar or 3D Cartesian with translational symmetry to *3D cylindrical with both translational and rotational symmetries*. We keep the concept of advanced artificial structures that localize acoustic energy in small resonant regions [3,4]. The Tubular Bell is new class of phononic crystal sensor [5,6] based on the TPC. Our approach considers additional structural elements independent of the periodicity along the tube. Geometries as shown in Fig. 1 have not been considered so far in literature. An additional dimension is introduced to phononic crystal structure employing the rotational symmetry of pipes or tubes. The tubular phononic crystal structure becomes periodic in both directions: along the tube and along its circumference.

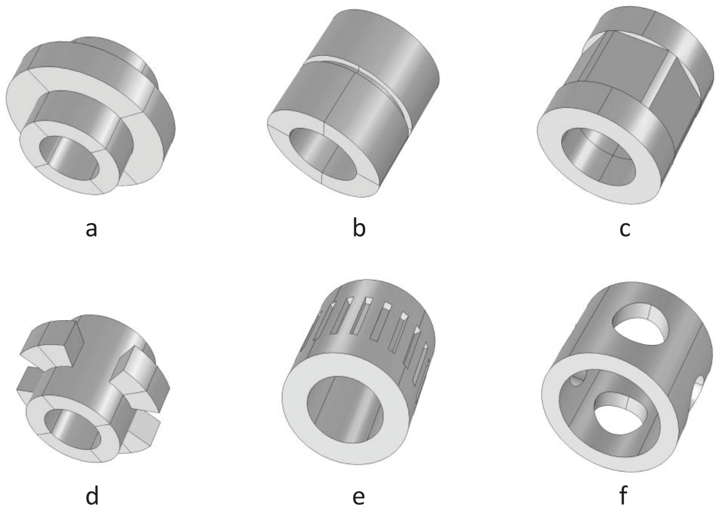

Figure 1: Examples of phononic crystal units having a cylindrical shape. All units are made of a tube segment and circumferential elements. The ring (a) and the narrow circumferential groove (b) represent solutions with longitudinal periodicity only, (c), (f) exhibit both longitudinal and circumferential periodicity. Holes (f) are not applicable in our prospective technical application. The hex washer (c), the sectioned ring (d) and the circumferential row of narrow grooves (e) fulfil the basic requirement of an unmodified inner tube surface.

3. Simulation results

3.1. Dispersion diagram

The first step of a systematic analysis is always the calculation of dispersion curves. Fig. 2 shows results for propagation along the revolution axis of a full cylinder (left), a hollow cylinder (middle) and the tubular phononic crystal of Fig. 1a (right) without liquid inside. The first branches shown in Fig. 2a correspond to the antisymmetric, symmetric (2 times degenerated) and compression fundamental branches of the full cylinder. Branches a and b in Fig. 2b correspond to new guided modes inside the hollow tube not existing in the full cylinder. With the TPC, the dispersion diagram has drastically changed and one can now observe new physical phenomena such as band gaps (hatched area) as well as flat branches like (c) and (d).

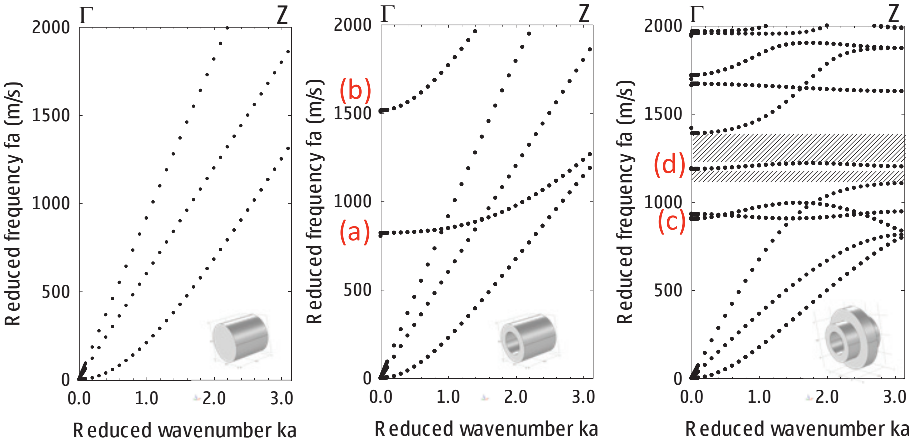

Figure 2: Dispersion diagrams of the full cylinder (left), a hollow cylinder (middle) and the tubular structure (right) without liquid inside. Parameters are: outer radius r_{out} = 0.5 mm, inner radius r_{in} = 0.3 mm, thickness and height of the collar t_{col} = h_{col} = 0.3 mm. For mode allocation, see text.

The distributions of the elastic fields at the frequencies of modes (a) to (d) are represented Fig. 3. It remains that band gaps occur only in the tubular phononic crystal. Note further that mode (d) in the collar is localized within the band gap, one key challenge of the proposed sensor.

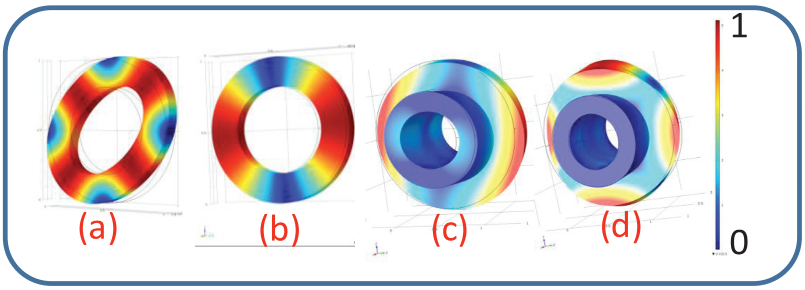

Figure 3: Displacement field profile of some selected modes in Fig. 2 of the hollow cylinder and the tubular phononic crystal.

3.2. FEM analysis

The typical computational domain used in COMSOL™ Multiphysics for our first studies consists specifically of the fluid domain, the solid tube domain and solid collar domain. The whole tubular structure is divided into elementary units. Periodic boundary conditions are applied along axis of the tube and cyclic boundary conditions are applied to the side surfaces. The outer surface is free. Three styles of the tubular bell are shown in Fig. 4. They feature all major aspects required for the perspective sensor application. Predominant out-of-plane displacement of the tube will address density and compressibility, i.e., speed of sound measurement of the liquid. We will focus on this measurement scheme due to the absence of any competing sensor and on undiscovered information behind volumetric property measurement. Sensitivity considering the frequency shift of the transmission peak related to the appropriate defect mode can compete with ultrasonic spectroscopy methods [7]. Predominant in-plane displacement recovers the measurement concept of microacoustic sensors and the physics behind including density viscosity measurement. The tube realization has been unexplored so far and justifies further investigations. Circumferential periodicity introduces another degree of freedom which may be needed to tune band gaps and modes of interest independently. Our sensor approach resumes especially a strongly localized high-*Q* liquid resonator with efficient confinement of acoustic energy wherein and therefore may require this tuning opportunity.

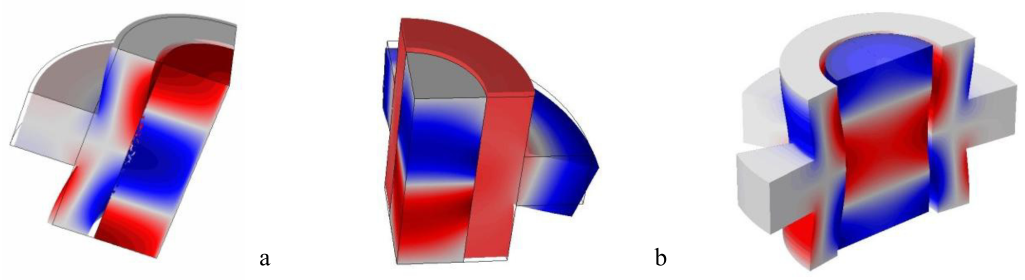

Figure 4: First eigenfrequency analyses of a tubular bell featuring major requirements of the proposed sensor. Colors (do not scale!) represent displacement (solid) or pressure (liquid) with white being a node line. Collar structure (a) realizes a predominant out-of-plane displacement profile at the inner tube surface, (b) a predominant in-plane displacement along the tube axis while the sectioned structure (c) executes both out-of-plane displacement and twisting. Illustrative animated graphics are available.

Acknowledgements

This contribution is the result of preliminary work in preparation of an ANR-DFG project proposal. First steps of sample fabrication of the proposed structure have been performed by F. Lucklum at the Institute for Microsensors, -actuators and –systems (IMSAS), University of Bremen, Germany.

References

[1] M.S. Kushwaha, P. Halevi, G. Martinez, L. Dobrzynski, B. Djafai-Rouhani, Theory of acoustic band structure of periodic composites, Phys. Rev. B 49 (1994), 2313-2322.
[2] Y. Pennec, B. Djafari-Rouhani, H. Larabi, J.O. Vasseur, A.C. Hladky-Hennion, Low-frequency gaps in a phononic crystal constituted of cylindrical dots deposited on a thin homogeneous plate, Phys. Rev. B 78 (2008), 104105.
[3] Y. Pennec, J.O. Vasseur, B. Djafari-Rouhani, L. Dobrzyński, P.A. Deymier, Two-dimensional phononic crystals: Examples and applications, Surface Science Reports 65 (2010), 229.
[4] R. Lucklum, M. Ke, M. Zubtsov, Two-dimensional phononic crystal sensor based on a cavity mode, Sens. Actuators B 171-172 (2012), 271-277.
[5] R. Lucklum J. Li, Phononic crystals for liquid sensor applications, Meas. Sci. Technol. 20 (2009), 124014.
[6] S. Amoudache, Y. Pennec, B. Djafari Rouhani, A. Khater, R. Lucklum, R. Tigrine, Simultaneous sensing of light and sound velocities of fluids in a two-dimensional phoXonic crystal with defects, J. Appl. Phys. 115 (72014), 134503.
[7] O. Tirosh, Y. Barenholz, J. Katzhendler, A. Priev, Hydration of Polyethylene Glycol-Grafted Liposomes, Biophysical J. 74 (1998), 1371-1379.