AIN SHAMS UNIVERSITY

FACULTY OF ENGINEERING

Mechatronics Engineering

Wave Propagation Control Using Active Acoustic Metamaterials

A Thesis submitted in partial fulfillment of the requirements of the degree of

Master of Science in Mechanical Engineering

(Mechatronics Engineering)

by

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Bachelor of Science in Mechanical Engineering

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Statement

This thesis is submitted as a partial fulfillment of Master of Science in Mechanical Engineering, Faculty of Engineering, Ain shams University. The author carried out the work included in this thesis, and no part of it has been submitted for a degree or a qualification at any other scientific entity.

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Summary

Acoustic metamaterials (AMM) are artificial materials with engineered sub-wavelength structures that possess acoustic material properties which are not readily available in nature. The material properties of AMMs can be manipulated by embedding active elements inside their structure (active AMMs). This manipulation of properties is done by an external voltage signal and is hardly available in any natural material.

In this work, existing designs for passive and active AMMs are reviewed and summarized. Existing homogenization techniques for the material properties of passive metamaterials are investigated and extended to be applied for active AMMs. Three new designs for active plate-type AMM with tunable density are proposed and verified analytically, numerically and experimentally.

The first design is a one dimensional (1D) AMM consisting of clamped piezoelectric disks in air. The effective density of the material is controlled by an external static electric voltage. An analytic model based on the acoustic two-port theory, the theory of piezoelectricity and the pre-stressed thin plate theory is developed to predict the behavior of the material. The results are verified using the finite element method. Excellent agreement is found between both models for the studied frequency and voltage ranges. The results show that the density is tunable within orders of magnitude relative to the uncontrolled case. This is done with a limited effect on the bulk modulus of the material. The results also suggest that simple controllers could be used to program the material density.

The first design was modified and extended to construct a two-dimensional AMM with controllable anisotropic density. The modified design consists of composite lead-lead zirconate titanate (PZT) plates clamped to an aluminum structure with air as the background fluid. The effective anisotropic density of the material is controlled, independently for two orthogonal directions, by means of an external static electric voltage signal. An analytic model based on the acoustic two-port theory, the theory of piezoelectricity, the laminated pre-stressed plate theory is developed to predict the behavior of the material. The results are verified also using the finite element method. Excellent agreement is found between both models for the studied frequency and voltage ranges. The results show that, below 1600 Hz, the density is controllable within orders of magnitude relative to the uncontrolled case. A reconfigurable wave guide was constructed using the developed material and its performance was evaluated numerically and analytically. The waveguide can control the direction of the acoustic waves propagating through it.

The results obtained from the previous models were used to construct and experimentally verify a third design with a fully real-time controllable effective density. The effective density of the AMM can be programmed and set to any value ranging from -100 kg/m^3 to 100 kg/m^3 passing by near zero density conditions. This is done through an interactive graphical user interface and is achievable for any frequency between 500 and 1500 Hz. The modified design consists of clamped composite piezoelectric diaphragms suspended in air. The dynamics of the diaphragms are controlled by connecting a closed feedback control loop between the piezoelectric layers of the diaphragm. The density of the material is adjustable through an outer adaptive feedback loop that is implemented by the real-time estimation of the density of the material using the 4-microphone technique. Applications for the new material include programmable active acoustic filters, non-symmetric acoustic transmission and programmable acoustic superlens.

Keywords: Acoustic metamaterials, Piezoelectric materials, Feedback control, Adaptive control

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