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A membrane-type acoustic metamaterial with adjustable acoustic properties

F. Langfeldt [a,*], J. Riecken [a], W. Gleine [a], O. von Estorff [b]

[a] *Department of Automotive and Aeronautical Engineering, Hamburg University of Applied Sciences, Berliner Tor 9, D–20099 Hamburg, Germany*
[b] *Institute of Modelling and Computation, Hamburg University of Technology, Denickestr. 17, D–21073 Hamburg, Germany*

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ABSTRACT

A new realization of a membrane-type acoustic metamaterial (MAM) with adjustable sound transmission properties is presented. The proposed design distinguishes itself from other realizations by a stacked arrangement of two MAMs which is inflated using pressurized air. The static pressurization leads to large nonlinear deformations and, consequently, geometrical stiffening of the MAMs which is exploited to adjust the eigenmodes and sound transmission loss of the structure. A theoretical analysis of the proposed inflatable MAM design using numerical and analytical models is performed in order to identify two important mechanisms, namely the shifting of the eigenfrequencies and modal residuals due to the pressurization, responsible for the transmission loss adjustment. Analytical formulas are provided for predicting the eigenmode shifting and normal incidence sound transmission loss of inflated single and double MAMs using the concept of effective mass. The investigations are concluded with results from a test sample measurement inside an impedance tube, which confirm the theoretical predictions.

1. Introduction

The so-called acoustic metamaterials have received much attention by researchers in physics and acoustical engineering during the last two decades. The term “metamaterial” has originally been coined in the late 1990s for composite materials specifically designed to yield physically unusual electromagnetic properties, such as negative permittivity and/or negative permeability [1]. Realizations of such extraordinary electromagnetic materials were proposed by Pendry et al. [2,3] and first experimental evidence of metamaterials with negative permittivity and permeability was later provided by Smith et al. [4] and Shelby et al. [5], 30 years after Veselago [6] studied theoretically the physical consequences of such materials, such as negative refraction and a reversed Doppler effect. These findings initiated the emergence of a variety of electromagnetic metamaterials with powerful applications, e.g. a perfect lens overcoming the diffraction limit [7] or electromagnetic cloaks [8].

Light and sound waves are both governed by the wave equation. Therefore, most concepts of electromagnetic metamaterials can be transferred to acoustical problems. Consequently, Liu et al. [9] presented the first acoustic metamaterial with sub-wavelength-sized periodically arranged rigid spheres coated by an elastic material. This so-called locally resonant sonic material exhibited low-frequency bands with strongly reduced transmission of sound, caused by the effective density

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[*] Corresponding author.
E-mail address: Felix.Langfeldt@haw-hamburg.de (F. Langfeldt).

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of the structure – i.e. the density "seen" by the acoustic wave passing through it – becoming negative in these band gaps [10]. Since then, many different types of acoustic metamaterials with negative density [11–16], negative bulk modulus [17–20], and double-negative properties [21–24] as well as various extraordinary applications of these metamaterials, like acoustic diodes [25], cloaks [26], near-unity absorbing surfaces [27], or acoustic superlenses [28], have been investigated.

From this wide range of different acoustic metamaterials developed by various research groups, the so-called membrane-type acoustic metamaterials (MAMs), originally proposed by Yang et al. [12], provide some features that are particularly useful in some engineering applications (e.g. aeronautical engineering), where lightweight structures and compact installation spaces are critical for the design of noise protection measures: MAMs are composed of thin pre-stressed membranes with one or more small rigid masses attached to the membrane material. These two-dimensional structures provide narrow frequency bands at low frequencies where the sound transmission through the MAM is reduced by several orders of magnitude below the corresponding mass-law [12,29]. These frequency bands can be tuned during manufacturing of the MAM structures by choosing suitable values for the membrane pre-stress [30,31], the magnitude of the added masses [12,30,31], the mass location [31–33], and the number of added masses [34,35].

Once these parameters have been determined and the MAMs have been manufactured, however, it is not possible to re-tune the location of the high transmission loss frequency bands to account for shifting tonal components inside the spectrum of the noise source during operation (e.g. different rotational speeds of a propeller engine) or changes of the membrane pre-stress due to temperature changes or aging effects. There have been several efforts to increase the high transmission loss bandwidth using passive assemblies of MAMs: it is possible to stack multiple layers with differently tuned MAMs to achieve a broadband MAM panel with a high transmission loss over a wide frequency range that is more robust to changes in the operational conditions or material parameters [29,36]. This, however, leads to a heavier structure requiring more installation space which might not be available in some applications. Alternatively, a single MAM layer with multiple MAM cells in a parallel arrangement and different added masses in each cell can be used to introduce multiple transmission loss peaks without increasing the size and weight of the MAM structure significantly [37,38]. Nevertheless, this design also introduces additional resonances inside the frequency range of interest that may reduce the noise shielding capability of such a structure.

A substantially different approach to overcome the problematic narrow band characteristics of MAMs is to use active methods to adjust the MAM properties during operation. Active acoustic metamaterials have first been investigated by Baz [39,40] and Akl and Baz [41,42], who used piezoelectric materials to tune the effective density and bulk modulus of acoustic metamaterials. On this basis, Popa et al. [43] developed a tunable active acoustic metamaterial with effective properties that can be adjusted over a wide range of values, which was later extended to realize an active acoustic diode [44]. Chen et al. [45] applied the principles of active acoustic metamaterials to MAMs by using a magnetorheological membrane material and an external gradient magnetic field to control the pre-stress inside the membrane material. This enables the shifting of the membrane eigenfrequencies during operation by selecting appropriate external magnetic field gradients. However, in the experiments by Chen et al. [45] a large permanent magnet was used to generate the required magnetic field, which greatly increases the overall mass and size of this active membrane-type metamaterial (AMAM). A different realization of an AMAM was recently proposed by Xiao et al. [46], who used a setup similar to that of a condenser microphone with an acoustically transparent fishnet electrode and the added mass on the MAM acting as the counter electrode. By applying an external DC voltage the eigenfrequency of the MAM could be decreased due to the additional attractive force between the electrodes. This new design requires the supply of a constant voltage in every unit cell of the AMAM. For possible fields of application, where a big surface needs to be covered with such AMAMs, large amounts of wiring are required for providing each unit cell with the suitable amount of voltage, thus increasing the mass and installation effort of the AMAM structures. Furthermore, in some cases it might be infeasible to use electrical wirings inside noise protection devices due to safety regulations.

To overcome the limitations of these designs, a new realization of an AMAM, that employs a centralized actuation principle for adjusting the dynamic MAM properties without requiring individual electrical circuits in each MAM unit cell, is presented in this contribution. The unit cell of the proposed AMAM is shown in Fig. 1. It consists of two vertically stacked MAMs that are mounted onto a frame. The MAMs investigated here have a square shape with one circular mass attached in the center of each membrane layer. However, the basic principle of the proposed design can readily be applied to different MAM geometries (e.g. circular) and mass configurations (e.g. multiple masses per membrane layer). The materials of the membrane and the frame need to be airtight so that the air volume between the MAMs and the frame can be pressurized with a static differential pressure Δp_0 using an external source of pressurized air connected to the MAM by tubings or channels inside the frame. Pressurized air is usually readily available in passenger transport vehicles with air conditioning, such as trains or airplanes, which makes this concept particularly applicable to such fields of engineering. If Δp_0 is large enough, the deflection characteristic of the membranes due to the applied pressure difference becomes geometrically nonlinear and the stiffness of the membranes increases [47,48]. This geometrical stiffening leads to an increase of the eigenfrequencies, which can be exploited to tune the acoustic properties of the double MAM element.

The present contribution is structured as follows: First, a theoretical analysis of the proposed AMAM based upon analytical and numerical models is presented to investigate the effect of the static inflation on the eigenfrequencies and, consequently, the normal incidence sound transmission loss (TL) of the structure. Then, the results of an experimental investigation of the proposed AMAMs inside an impedance tube are presented in order to validate the theoretical predictions made in the first part of the paper.