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Experimental and numerical analysis of membrane-patterned meta-materials

1.EMMANUEL AYORINDE
Advanced Composites and
Nondestructive Evaluation Laboratories
Mechanical Engineering Department
Wayne State University
Detroit, MI 48202

2.MOHAMMAD AL-ZUBI
Advanced Composites and
Nondestructive Evaluation Laboratories
Mechanical Engineering Department
Wayne State University
Detroit, MI 48202

3. AKIF DUNDAR
Advanced Composites and
Nondestructive Evaluation Laboratories
Mechanical Engineering Department
Wayne State University
Detroit, MI 48202

4.GARY WITUS
Advanced Composites and
Nondestructive Evaluation Laboratories
Mechanical Engineering Department
Wayne State University
Detroit, MI 48202

ABSTRACT

Meta-materials show unconventional properties by virtue of their construction which normally includes physically-periodic formations. Various responses of these materials manifest frequency-dependent occurrences of significantly-enhanced and significantly-attenuated values, thus facilitating a wealth of design possibilities. The analysis of these structures presents non-trivial challenges, hence only very simple types are presently under analytical study. In this paper, a formation which includes patterned membrane fillings is explored experimentally and numerically to see if and how well such a construction may be utilized for meta-material applications.

Keywords: lexan, vibration, meta-material, membrane, periodic

INTRODUCTION

Meta-materials are widely known as those materials that manifest unusual behaviors which are not normally found in nature, but which derive from their construction. From the work of Brillouin [1] on wave motion in periodic structures, through the speculations of Veselago [2] on materials with negative electric permittivity and negative magnetic permeability, and ensuing works of numerous authors including those of Pendry [3] on lenses and Genella and Ruzzene [4] on mathematical treatment of periodic structures, there has been an abundance of literature on the conceptual, experimental and analytical aspects of periodic constructions and meta-materials. Very many styles of construction that permit local resonance in the developed structures have been adopted, and continue to be adopted in these efforts. However, the treatment of circular constructions of such structures has been quite little by comparison, although in real life there are many situations when circular profiles will serve best. In this work, a circular profile of a disk with an array of circular membranes has therefore been briefly examined as to its possible application for acoustic meta-material purposes.

ACOUSTIC METAMATERIALS

Liu et al. [5] examined the sound propagation and signal blocking properties of a block meta-material, and Sun et al. [6,7] and Islam and Newaz [8] have looked at the vibration and sound propagation analysis of acoustic meta-materials. Whereas many meta-materials for magnetic and electrical applications tend to involve micro and nano-sized components, acoustic meta-materials have been successfully manufactured with larger components [6-8].

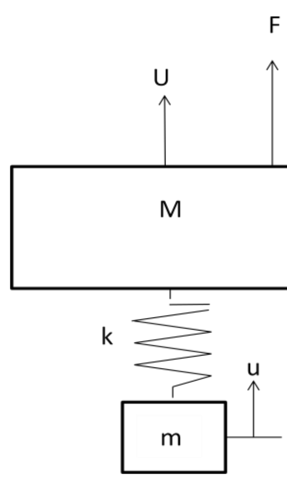

Fig.1. Basic mass-in-mass model of acoustic metamaterial [6,7]. It is assumed that the applied harmonic force results in harmonic displacements for both masses such that the amplitudes of applied force, main mass and locally-resonant mass are F_0, A, and a respectively, and that the undamped natural frequencies of these masses are Ω and ω respectively while the applied force has a frequency w. The undamped natural frequencies of the local resonator and main mass are

$$\omega = \sqrt{\frac{k}{m}},\ \Omega = \sqrt{\frac{K}{M}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

respectively. From the transfer functions of the system equations, for the case of n resonators, it is straightforward to obtain the effective mass of the system, $M_{eff,}$ [6-8] as

$$M_{eff=\frac{F}{\ddot{U}}=M+nm/\{1-(w/\omega)^2\}} \quad \ldots\ldots\ldots\ldots\ldots..(2)$$

From its structure, if excitation freq, w = ω, a = $-F_0/k$ = $-F_0/mw^2$, then a increases when m decreases. When w > ω, and $m/(w^2/\omega^2 - 1) > M$, the effective mass is negative

Fig.2. Model of lexan with membranes (oblique view)

MATERIALS & METHOD

The primary, 100mm diameter disk is made of lexan, while the membranes are of silicon-based material. The material and geometrical properties are $E_{membrane}$ = 190 GPa, ρ_{mem} = 2.3 g/cc, ν_{mem} = 0.28, E_{lexan} = 2300 MPa, ρ_{lex} = 1.19 g/cc, ν_{lex} = 0.375., Following previous analysis [9,10]],

$$\omega = \frac{10.22}{a^2\sqrt{\rho t/D}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [3]$$

This gives the first natural flexural frequency of the circular membrane as 11450.1 Hz. The first natural frequency of the plate minus membranes, Ω = 256 Hz. The fundamental frequency of the membrane plate is 290 Hz. The equivalent mass of the circular plate considered is approximately [9,10]

$$m = 1.84\pi a^2 t\rho \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [4]$$

The mass ratio between the membrane and hard plate remainder is 0.01264.

RESULTS & DISCUSSION

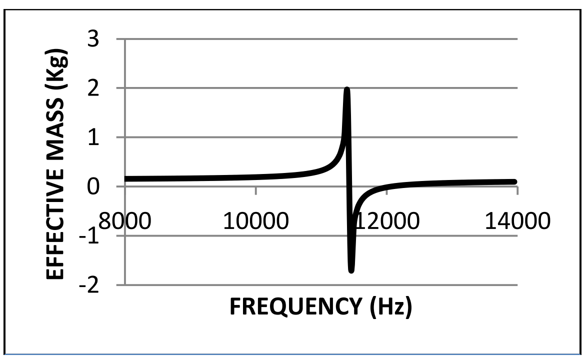

Fig.3. Effective mass of system versus frequency for lexan membrane system.

Fig. 3 is plotted from Equation (2). It is clear that around the resonance frequency of the local resonator, the effective mass of the system becomes negative, as expected. Similarly, from computations based on the dynamic behavior of the equivalent two-degree-of-freedom system, the normalized displacement of the primary mass, proportional to the system transmission, is shown in Fig. 4, which also shows a transmission dip around the same local resonator frequency. These two phenomena are characteristic of meta-materials for vibration and sound applications.

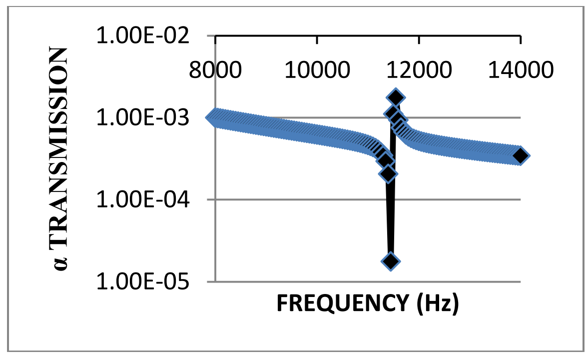

Fig. 4. Displacement Transmission

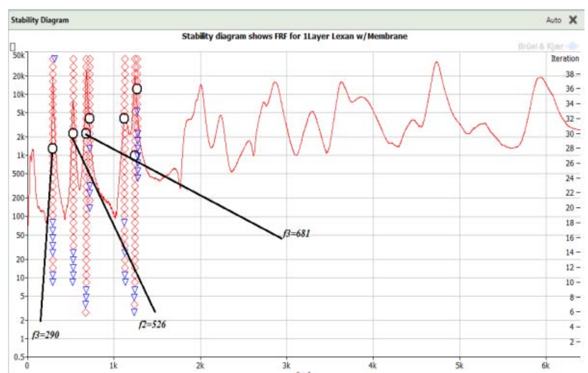

Fig.5: Detailed FRF of membraned lexan plate, illustrating the first several bending natural frequencies (0-6 kHz range)

Fig. 5 shows the most accurate experimental values obtained by the Pulse Reflex™ system from Bruel & Kjaer. The Finite Element computation yielded the fundamental frequency as 322 Hertz, which is considered reasonable considering factors of experiment and inexactitude of properties utilized.

CONCLUSIONS

This investigatory exercise appears to have shown that a simple structure with periodically arranged membrane units can function as an acoustic meta-material. The next thing to do is to progress the study further to examine more details of geometry, materials and architecture, in order to ascertain the best combination needed to tune the frequency bands of effectiveness as may be desired in particular cases.

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