

Acoustic Nanowave Absorption through Clustered Carbon Nanotubes Conveying Fluid^{**}



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ABSTRACT Absorption of acoustic nanowave in specific frequency region is important for the design of acoustic filter. This paper puts forward a meta material model made up of fluid-conveying carbon nanotubes (CNT), which can absorb acoustic nanowave in a given frequency range by adjusting the lengths and fluid velocities of themselves. Absorption coefficients are calculated out through the combination of the finite element method with the theoretical model, which are 0.4~0.55 relating to different fluid velocities for the crossing-distributed model. Comparisons are made between the crossed model and the aligned one, which prove that the CNT forest with crossed distribution is more effective in acoustic wave absorption.

KEY WORDS acoustic nanowave, absorption, meta-material, clustered carbon nanotubes

I. Introduction

Nano phononics is a promising field with a wealth of potential applications, such as implementations of phononic memories and computers, thermal diode and transistor^[1-9], heat pump^[10-14], and thermal rectifier^[9,15]. As a fundamental aspect in nano phononics, the propagation of acoustic nanowaves with terahertz or sub terahertz frequencies has attracted considerable interest. Nanowaves have been generated through several techniques. Juve and Crutet^[16] employed surface-controlled Pt nanoparticles as terahertz acoustic resonators to generate nanowaves. Walker and Kent^[17] generated terahertz acoustic wave through stimulating phonon emission in an optically pumped super lattice. On another aspect, owing to its tiny wavelength, nanowave has often been used in probe micro- or nano-instruments^[18], and has also been applied to detecting DNA in genetic engineering^[19].

The transmission characteristics of nanowave have been studied widely in recent time. The transmission of nanowaves in semiconductor superlattice has been demonstrated experimentally and theoretically (See Refs.[20,21]). Ahn et al.^[22] carried out a study on interesting equipment which presents the fluorescence of acoustic nanowave in a semiconductor. Reed et al.^[23] presented the acoustic radiation as terahertz strain wave traveled past the interface between materials with different piezoelectric coefficients. Armstrong et al.^[24] observed the coherent radiation nanowaves generated by acoustic waves travelling in semiconductor materials. Meanwhile, nanophonon with terahertz frequency has also shown a widespread utilization on controlling the thermal conduction processes at nanoscale^[11,25]. In recent times, heat pumps and rectifiers have been fabricated in laboratory serially based on manipulating the

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acoustic nanowaves^[9, 12, 14, 15, 26]; and oriented heat transportation has been observed in superlattice coherent with nanophonon^[25].

These practical applications cannot be achieved without appropriate manipulations of acoustic nanowaves. Lanzillotti-Kimura et al.^[27, 28] reported a control technique of nanowaves, based on which they fabricated different forms of acoustic filters. O'Connell et al.^[29] carried out a technique to realize the quantum ground state and obtained a single phonon of terahertz frequency. Baldi et al.^[30] showed the nanowave attenuation in vitreous silica. Notwithstanding these, there has been a lack of instrument which can absorb terahertz acoustic wave and change the acoustic energy into another type of energy efficiently, just as the sound absorption material usually used in the audio frequency domain, which precludes the application of terahertz acoustic wave in practice.

Nanowave cannot be dissipated inconspicuously in usual transformation media because of its high energy density, which is the main limitation for the normal material. However, researchers have proved that the nano-instruments can be easily driven by the sub terahertz waves^[27, 31, 32]. As a simple one-dimensional nanostructure, the carbon nanotube (CNT) can be easily stimulated by terahertz acoustic waves^[22]. The free vibration of cantilevered fluid-conveying CNT has been researched by Yoon et al.^[33]. In his research, the fluid-conveying CNT was modeled as a nanopipe. It illustrated the instability of the fluid-conveying CNT, apart from a lack of consideration for the small scale coefficient. To illustrate more detailed dynamic characteristics of fluid-conveying CNTs, the nonlocal continuum theory was developed to derive the governing equations of the system^[33, 34]. Wang developed the nonlocal continuum elastic theory during the research of fluid conveying carbon nanotubes^[33]. In this research, the nonlocal strain-gradient theory was mentioned and combined with inertia gradients for dynamic applications of fluid-conveying CNTs, then an equation with two small-scale coefficients was derived. Following Wang's research, Zhang et al. calculated the free vibration of fluid-conveying CNT with the wave method^[35]. By using the stress gradient theory, the governing equation was derived in another study of Zhang et al., which contained only one small scale coefficient^[36]. These studies have proven that resonance and flutter would occur in nanotubes under certain inspirations of sub terahertz or terahertz waves. In the converse view, CNTs could absorb the energy of acoustic waves in this vibration procedure and the energy might thus be efficiently dissipated through damping.

On the other hand, fluid conveyed in certain CNTs with minute diameters has been demonstrated to be 'single-file-chain', which presents as molecular chain rather than the bulk flow in macrotubes^[37, 38]. Thus, the fluid molecules in vibrating CNTs are accelerated by the vibration, and this vibrating energy directly transforms into the thermal motion of the molecules rather than the material motion usually occurs in the macro scale. Based on these theorems, this paper presents clustered cantilevered fluid-conveying CNTs embedded in water, which performs as a resonance absorption device. The energy of acoustic nanowave would be absorbed by those vibrating nanotubes and transformed into the thermodynamic energy of the fluid. Meanwhile, the eigen-frequencies of CNTs vary with the inner fluid velocities, and thus the absorbed wave frequency band can be adjusted by adjusting the velocity of fluid in the CNTs.

Paragraphs are structured as follows. In §II, the vibration characteristics of fluid-conveying CNTs are analyzed using the nonlocal gradient stress theory. The heat generation and transformation are also demonstrated statistically in this section. §III investigates the absorption theorem of clustered CNTs conveying fluid. Distributions and heights of the clustered CNTs are designed in this section. §IV presents the calculation results which prove the absorption effect of the model. To validate the theorem and the model, the finite element analysis is conducted in this section and comparisons are made between two different models. At last, several conclusions are obtained in §V. This research provides a reference for the reverse design of acoustic meta-material which has potentials in hypersonic cloaking, heat pump, phononic computers and many other fields.

II. Kinetic Energy Increase of the Fluid Molecules Caused by CNT Vibration

2.1. Stimulated vibrations of fluid-conveying CNT

The model of the entire system is sketched in Fig.1, in which the highly concentrated fluid and low concentrated fluid are separated by a semipermeable membrane. Acoustic wave propagates in the fluid, and clustered CNTs are fixed on the surface of the semipermeable membrane using epoxy resin polymers. These CNTs are modeled cantilevered because their lengths are different. Driven by the osmotic pressure,

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