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Theory of suspended carbon nanotube thinfilm as a thermal-acoustic source

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ABSTRACT

Accurate analytical solutions for thermal-acoustic radiation from a suspended carbon nanotube (CNT) thinfilm is obtained for near- and far-fields by constructing a coupled thermal–mechanical CNT model and solving for the thermally induced acoustic response. The analytical approximate acoustic pressure is expressed in a brief and concise form after proper approximation within a certain frequency range. An example using CNT-thinfilm is presented and compared with experimental measurement in order to verify the theoretical model and analytical prediction. It is concluded that the approximate analytical solution obtained agrees well with experimental results. The heat capacity per unit area significantly influences the acoustic pressure and a CNT-thinfilm with a small heat capacity per unit area improves acoustic pressure. Acoustic wave radiating from a CNT-thinfilm is a plane wave in a near-field and it transforms into a spherical wave in a far-field. Acoustic wave at higher frequency remains as a plane wave for a longer distance. In addition, it is concluded that acoustic pressure undergoes a wideband constant (flat) amplitude–frequency response in a near-field.

1. Introduction

Since its first proposal by Arnold and Crandall [1] almost a century ago, thermo-acoustics recently again attracts wide research attention due to the advent of nanotechnology and the discovery of carbon nanotubes. Owing to the rapid advancement and availability of nanomaterials in recent years, the application of such new materials in thermo-acoustics will undoubtedly progress in a fast pace [2]. In 2008, it was reported by Xiao et al. [3] that a carbon nanotube (CNT)-thinfilm is capable of emitting acoustic wave in the air when an alternating current (ac) is applied. Aliev et al. [4] conducted the same experiment as Xiao et al. [3] but with the carbon nanotube emitter immersed in water. Kozlov et al. [5] found that dense alignments and arrays of multiwalled carbon nanotubes can be viewed as a thermo-acoustic source when an alternating current is applied to the system. In 2011, the graphene-on-paper thermo-acoustic source was fabricated and tested by Tian and his associated [6].

Besides carbon nanotube CNT-thinfilm and graphene, it was demonstrated that a suspended metal wire array is also capable of emitting considerable acoustic wave when an alternating current is applied [7–9]. The efficiency of a nano–thermo-phone was discussed by Vesterinen et al. [9]. It was recorded that the pressure level can be more than 100 dB when the input electrical power

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is 17 W for a 20 KHz frequency at a distance of 7 cm [2]. The acoustic wave generated by a thermo-acoustic device shows some different characteristics and its acoustic pressure is dependent on the frequency and the input power [3,6]. Both Xiao et al. [3] and Tian et al. [6] concluded that the acoustic pressure is proportional to input power and it is exponential to frequency when the thinfilm is suspended. In addition, Xiao et al. [10] also tested the thermo-acoustic response in different gaseous mediums and concluded that higher acoustic pressure level could be achieved in a gaseous medium with a smaller heat capacity. The thermo-phone also could be used to generate ultrasound with a higher pressure level and a wider bandwidth than a traditional piezoelectric transducer [7]. All of these thermo-phones possess a common feature, i.e. small heat capacity per unit area for the thermo-acoustic source [8]. In addition, the mechanism of acoustic generation that underlies aforementioned sources is unlike that of conventional electro-acoustic devices in which sound is produced by the mechanical vibration [2,11–15]. Thermo-acoustic is generated by the temperature variations in air or other medium surrounding the sources. These temperature variations are induced by the Joule heating produced by the device which is applied alternating current.

Although many experiments have been conducted and some scattering pieces of theoretical analyses reported, the development of a rigorous theoretical study on nanotechnological thermo-acoustics has been lacking. In Arnold and Crandall [1], they did not consider the effect of the heat capacity per unit area of the CNT-thinfilm. Xiao et al. [3] revised Arnold and Crandall's model but his was only suitable for far-field response. Taking advantage of Green's function formalism, Vesterinen et al. [9] presented an acoustic pressure expression which considered the effect of a heat-absorbing substrate. Hu et al. [16] explained experimental results of Shinoda et al. [7] by solving a set of coupled thermal–mechanical equations. However the heat capacity per unit area was not taken into consideration in Hu et al. [16] and, in addition, the model was not suitable for a fully suspended CNT-thinfilm. Although Tian et al. [6] introduced heat capacity into his model, the model was again not valid for a fully suspended CNT-thinfilm.

In this paper, a new theoretical model for a fully suspended CNT-thinfilm as a thermoacoustic source is first proposed and a new set of coupled thermal–mechanical equations is solved. In this model, the heat capacity per unit area omitted in Hu et al. [16] is considered. By solving the thermal–mechanical differential equations using the appropriate boundary conditions, an analytical and explicit expression for the acoustic pressure amplitude is first presented. Subsequently, considering a moderately high frequency range, the acoustic pressure can be analytically expressed in a brief form after proper approximation and simplification. Comparing with Xiao et al. [10], who presented an analytical prediction which is valid only for far-field response, the new analytical solution presented here is capable of predicting accurate near-field acoustic pressure response. In addition, by converting the plane wave into spherical wave, a comparison of the theoretical results with experimental data is presented. The acoustic pressure response for different heat capacities per unit area and varying distances away from the CNT-thinfilm are also derived discussed. Finally, the validity and applicability of the approximate analytical solution are elaborated in detail.

2. Near-field thermoacoustic theory for carbon nanotube (CNT) thinfilms

The schematic of a suspended CNT-thinfilm which acts as a thermoacoustic source is shown in Fig. 1. When a sinusoidal alternating current with frequency and amplitude $\omega/2$ and I, respectively, is applied, the electrical power generated by the CNT-thinfilm is given by

$$\left(I\,\sin\frac{1}{2}\omega t\right)^2 R = P_{in}(1-\cos\,\omega t) \tag{1}$$

where R is the resistance of CNT-thinfilm, $P_{in}=(I^2R)/2$ is the input power and t is time. The power generation can also be expressed in complex variables as

$$P_{in}(1-\cos\,\omega t) = P_{in} - P_{in}e^{j\omega t} \tag{2}$$

where $j=\sqrt{-1}$.

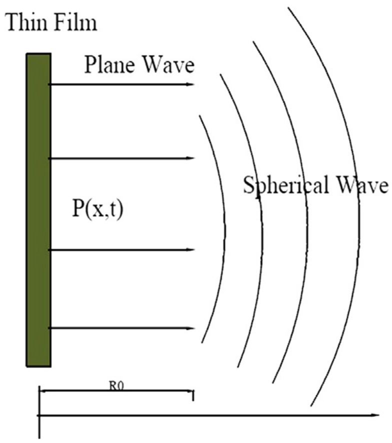

Fig. 1. A suspended CNT-thinfilm as a thermoacoustic source.