

Multi-Physics Simulation of Ultra-Lightweight Carbon Nanotube Speakers

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ABSTRACT

Carbon Nanotube (CNT) thin film speakers produce sound with the thermoacoustic effect. Alternating current passes through the low heat capacity CNT thin film changing the surface temperature rapidly. CNT thin film does not vibrate; instead it heats and cools the air adjacent to the film, creating sound pressure waves. These speakers are inexpensive, transparent, stretchable, flexible, magnet-free, and lightweight. Because of their novelty, developing a model and better understanding the performance of CNT speakers is useful in technology development in applications that require ultra-lightweight sub-systems. The automotive industry is a prime example of where these speakers can be enabling technology for innovative new component design. Developing a multi-physics (Electrical-Thermal-Acoustical) FEA model, for planar CNT speakers is studied in this paper. The temperature variation on the CNT thin film is obtained by applying alternating electrical current to the CNT film. The surface temperature variation is then used to simulate the pressure distribution in the open medium. To validate the model, the results of simulation are compared to the experimental data and traditional lumped-parameter models. From the simulation results, the frequency response and directivity patterns for the CNT speakers are shown. The effects of thin film surface area and material properties of the medium are also discussed with respect to the output sound power.

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1. INTRODUCTION

Carbon nanotube (CNT) speakers are a new type of non-moving, ultra-light-weight, flexible, and stretchable thin-film loudspeaker that produce sound with the thermoacoustic effect. Alternating current passes through the electrodes to the low heat capacity CNT thin film changing the surface temperature rapidly. Then, the air adjacent to the CNT surface expands and contracts and the pressure waves are produced. In comparison, conventional loudspeakers that we use mostly have a permanent magnet and a voice coil attached to the cone. By applying the current to the voice coil, the movement of the voice coil and cone will produce the pressure waves that are propagated into the medium. The simple structure of CNT speakers includes only two electrodes and CNT thin film with the mass per unit area of $1.5 \mu\text{g}/\text{cm}^2$ [1]. The CNT speakers are pure resistance up to 10 kHz and can produce the pressure with the frequencies from zero up to 100 KHz. These speakers are useful in many applications in the automotive and aerospace industry where the lightweight subsystems are needed. Active exhaust noise cancellation is one of the applications where the high temperature environment inside the exhaust will not damage the CNT speakers. The current exhaust noise cancellation systems use different external conventional speakers to cancel out the noise of the exhaust. Based on the space limitations inside the exhaust tube, a specific size and shape of the lightweight CNT speaker can be used instead of using many conventional speakers. Crandall [2] studied the thermoacoustic effect and the thermophone as a source of sound theoretically and experimentally in 1917. At that time, they could not find appropriate material for the thin film to make sound in the human audible range. In 2006, Yu et al.

[3] found that a piece of CNT thin film can produce sound by applying a current across it at audio frequencies. Xiao et al [4] obtained the frequency dependent sound pressure level (SPL) and total harmonic distortion (THD) for different layers CNT loudspeaker. Also, the effect of different gases in the performance of the CNT speakers, was reported. Several studies have been reported experimentally the performance of the CNT speakers [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17].

To date, all modeling in the field of CNT speakers has focused on analytical 1-D lumped parameter estimations. Arnold and Crandall [2] obtained the temperature variation over the surface of the thermophone and pressure in the far field by applying the current through thermoacoustic source. They showed that the sound pressure increases as frequency increases. Also, the sound pressure is inversely related to heat capacity of the thin film. The model was modified by Xiao [1] by including the rate of heat loss per unit area of the thin film and the instantaneous heat exchange per unit area between the thin film and its surrounding air due to thermal conduction. In addition, the pressure in the far field and near field was obtained in [5] by Lim by solving the coupled thermal-mechanical equations. However, all of these researchers reported the sound pressure level at a single location and assumed the source velocity was uniformly zero across the area of the thin-film speaker and the sound pressure level was uniformly non-zero across the same area. It is shown by Barnard et al [6] that the temperature distribution on the thin film is non-uniform due to the heat sink effect at the copper electrodes and free convection of a vertical CNT speaker. This indicates that the acoustic properties are also non-uniform in a realistic CNT thin film speaker.

It is also, shown using near field acoustic holography (NAH) measurements in [7] by Asgarisabet et al that the sound pressure level distribution is not uniform on the CNT thin film, which is contrary with the assumption of uniform acoustic properties in the lumped parameter models. Lumped parameter models are also effective for small and flat acoustic sources. However, the main benefit of CNT speakers is that they can easily be manufactured as large sources and can be conformal to any geometry, not just a flat plate. When evaluating conformal CNT speakers the simple 1-D lumped parameter estimations are no longer sufficient for predicting and designing the thermal or acoustic characteristics.

In this study, our goal is to develop a coupled electrical-mechanical-thermal-acoustic 3-D model of the CNT speaker in COMSOL Multi-Physics software. Simulations reduce the development cost and time and allow to study the effect of different parameters in the performance of the system. A planar sample will be modeled, built, and validated to ensure the material properties are correct and the modeling method is viable. First, the current lumped parameter models studied by Xiao [1] and Lim [5] will be discussed in the modeling section. Then, the results of the simulation will be compared with the experimental data and theoretical models. The effects of thin film surface area and material properties of the medium are also discussed with respect to the output sound power.

2. DESCRIPTION OF THE CNT SPEAKER

Figure 1 shows the CNT speaker, which was made of the CNT forests. The CNT forests were grown by NanoWorld Laboratories at the University of Cincinnati using a chemical vapor deposition (CVD) technique¹⁴⁻¹⁵. To make the CNT speakers, the CNT forest was stretched and drawn over the copper electrodes in the dynamics systems laboratory at Michigan Tech. The speaker consists of seven ribbons of CNT, each overlaid with five layers of thin-film as shown in Fig 1.

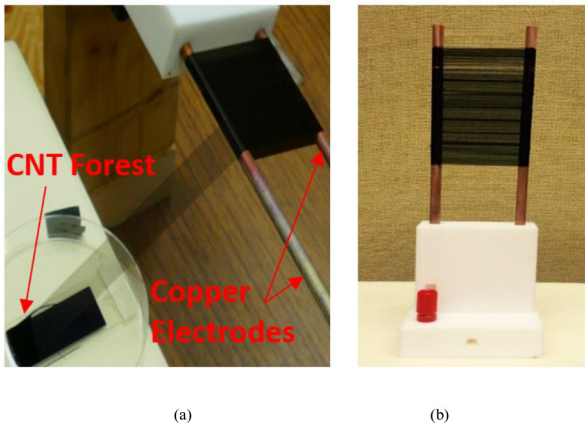


Figure 1. (a) CNT forest was expanded on to the copper electrodes (b) Picture of the CNT speaker

3. MODELING

3.1. Analytical Lumped Parameter Model

By applying a sinusoidal alternating current ($I \sin(\omega t)$) with the frequency of ω and the amplitude of I through the planar CNT thin film, the temperature on the thin film was obtained by Xiao et al [1],

$$T_f(t) = T_a + |\tilde{T}_f| \sin(2\omega t + \varphi') \quad (1)$$

where T_a is the surface average temperature and $|\tilde{T}_f|$ and φ' are the amplitude and phase of the varying temperature on the surface of thin film:

$$T_a = \frac{P_{input}}{4a\beta_0} \quad (2)$$

$$|\tilde{T}_f| = \frac{P_{input}}{4a\beta_0} \times \frac{1}{\sqrt{\left(1 + \sqrt{\frac{2\omega}{\omega_1}}\right)^2 + \left(\frac{2\omega}{\omega_2} + \sqrt{\frac{2\omega}{\omega_1}}\right)^2}} \quad (3)$$

$$\varphi' = \frac{3}{2}\pi - \tan^{-1} \left(\frac{\frac{2\omega}{\omega_2} + \sqrt{\frac{2\omega}{\omega_1}}}{1 + \sqrt{\frac{2\omega}{\omega_1}}} \right) \quad (4)$$

where a is the surface area of the thin film and the input power of P_{input} is the input power, which is defined as $R I^2$ where R is the resistance of the thin film. Also, β_0 is the rate of heat loss per unit area of the thin film due to conduction, convection and radiation. The parameters ω_1 and ω_2 can be expressed as:

$$\omega_1 = \frac{2\alpha\beta_0^2}{K^2}, \quad \omega_2 = \frac{2\beta_0}{c_s} \quad (5)$$

where α and K are the thermal diffusivity and conductivity of the gas, respectively and c_s is the heat capacity per unit area of the thin film.

In this model, the temperature on the thin film is only a function of time and uniform distribution of temperature over the thin film surface has been assumed. It is also shown that the frequency of the temperature is double the input frequency. Using the temperature and thermal expansion properties of the medium gas, the pressure in the far field at the distance of x was described as,

$$P_{rms} = P_{input} \times \frac{\rho_0 \sqrt{\alpha}}{4\sqrt{2}\pi c_s (T_a + T_0)} \times \frac{1}{x} \times \frac{\frac{2\omega}{\omega_2} \cdot \sqrt{2\omega}}{\sqrt{\left(1 + \sqrt{\frac{2\omega}{\omega_1}}\right)^2 + \left(\frac{2\omega}{\omega_2} + \sqrt{\frac{2\omega}{\omega_1}}\right)^2}} \quad (6)$$

where ρ_0 and T_0 are the density and the temperature of the gas, respectively. This shows that the acoustic pressure produced by the CNT speaker is proportional to the input power and increases as frequency increases. Also, it is shown that the heat capacity per unit area of the thin film and the pressure are inversely related. The heat capacity of the CNT thin film is orders of magnitude less than the platinum thin film used by Arnold and Crandall [2]. This makes these speakers practical to produce the high SPL in audio frequency range.

In a similar study, Lim [5] used another approach by using the coupled mechanical-thermal equations and obtained the pressure distribution in both near and far fields. Following equations show the pressure in the near ($x \leq R_0$) and far ($x \geq R_0$) fields where R_0 is the Rayleigh distance and is defined as a/λ where λ is the acoustic wavelength:

$$P_{rms} = P_{input} \times \frac{(\gamma - 1)}{4ac_0} \times \frac{\sqrt{\frac{2\omega}{\omega_1}}}{\sqrt{\left(1 + \sqrt{\frac{2\omega}{\omega_1}}\right)^2 + \left(\frac{2\omega}{\omega_2} + \sqrt{\frac{2\omega}{\omega_1}}\right)^2}} \quad x \leq R_0 \quad (7)$$

$$P_{rms} = P_{input} \times \frac{(\gamma - 1)}{16\pi c_0^2} \times \frac{1}{x} \times \frac{2\omega \sqrt{\frac{2\omega}{\omega_1}}}{\sqrt{\left(1 + \sqrt{\frac{2\omega}{\omega_1}}\right)^2 + \left(\frac{2\omega}{\omega_2} + \sqrt{\frac{2\omega}{\omega_1}}\right)^2}} \quad x \geq R_0 \quad (8)$$

where γ is the heat ratio of the gas, c_0 is the isentropic sound velocity in the gas, which is 347 m/s for the air at 300 K. It was reported in [5] that the two models are in good correlation with the experimental results for small sources with small input power.

3.2. COMSOL Multi Physics Simulation

Our goal is to develop a coupled electrical-thermal-acoustic 3-D model of the CNT speaker in COMSOL. To simulate the CNT speaker, the AC/DC (Joule Heating), thermoviscous and pressure acoustic modules are used. In the AC/DC module, the Joule heating should be used to consider both Electric Current and Heat Transfer modules. The temperature variation on the CNT thin film is obtained by applying alternating electrical (AC) current to the CNT film in time domain. Then, the surface temperature is transformed to the frequency domain using the Time-to-Frequency study. Finally, the frequency dependent temperature variation on the surface is used to simulate the pressure distribution in the open medium using the thermoviscous and pressure acoustics modules. The results of simulation will be validated by analytical models and experimental results. All the material properties of the medium gas used in the simulation are shown in Table 1.

Table 1. Constant material properties of the gas (Air) at 300 K [5]

ρ_0 (kg/m ³)	1.16	K (W/m.K)	0.0262
γ	1.14	α (m ² /s)	2.25×10^{-5}

The material for the electrodes has been considered as copper and all material properties for the CNT thin film were obtained from the reported values in [1] and [5]. The most important material properties for the CNT thin film are the heat capacity c_s and rate of heat loss β_0 .

4. RESULTS AND DISCUSSION

The temperature distribution on the CNT thin film was obtained by applying the AC current between the electrodes at different frequencies. It is shown (Fig. 2) that the temperature distribution on the surface is not uniform and maximum in the centerline of the CNT thin film. This is due to the high thermal and electrical conductivity of the CNT thin film compared to the copper electrodes.

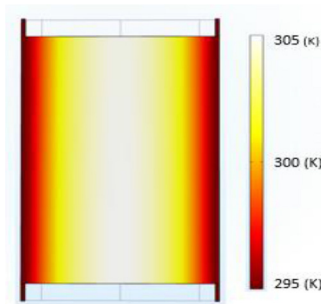


Figure 2. Temperature distribution on the CNT thin film

Also, the time variant temperature on the source surface for different input frequencies is shown in Fig 3. For each input frequency, the temperatures at different locations on the surface were obtained and then averaged over the surface. As shown, the output frequency of the temperature variation is double that of the input frequency, as discussed in the Eq. 1. In addition, the average temperature is not a function of frequency and is only related to the input power (Eq.2).

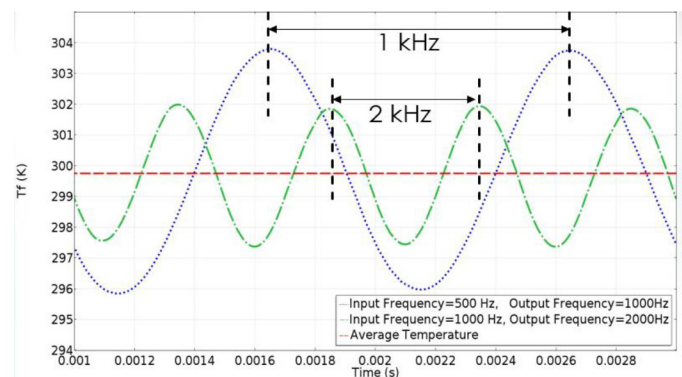


Figure 3. Time dependent average temperature on the CNT thin film for different frequencies