Study on the thermo-acoustic emission from a carbon nanotube stripe

D D Wang, H P Hu* and J H Wang

Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei, Anhui 230027, China

Corresponding author and e-mail: H P Hu, hphu@ustc.edu.cn

Abstract. Carbon nanotube (CNT) was demonstrated to show a great potential as a thermo-acoustic (TA) material. It can be used to fabricate novel TA loudspeaker free of magnets and moving parts, a promising device that directly converts thermal energy into acoustic energy. In this paper, the characteristics of TA emission from a CNT stripe are explored by means of parametric analysis. The impacts of the length of stripe, detecting distance and detecting angle on the sound pressure level (SPL) of emitted TA sound are discussed separately. In addition, the directivity of TA emission from stripe is also investigated. Hence, some phenomena and principles are found and summarized, which would be of guiding significance for the further invegation and development of nanothermophones.

1. Introduction

Thermally induced acoustic emission is a kind of new way of sound generation, which converts thermal energy into acoustic energy without need for vibration of sound source. In fact, thermo-acoustic (TA) phenomenon firstly reported can be trace to 1875 by W.H.Preece [1], who attached the alternating current to a metal wire, and then heared the sound around the energized wire. After that, Arnold and Crandall [2] further explored the TA mechanism using platinum strip as TA source in 1917. However, due to the larger heat capacity of used TA material and the lag of measuring apparatus, TA sound seemed too weak to arouse enough interest. It was not until 1999, H. Shinoda et al. [3] reported their finding of thermally induced ultrasonic emission from Nanocrystalline silicon in nature, that TA sound was once again getting interested. In recent years, with the development of nanomaterials and nanofabrication techniques, nanothermophones have received lots of attentions since Xiao et al. found that carbon nanotube (CNT) thin sheet could be a practical TA loudspeaker in 2008, which can generate sound with wide frequency range, high sound pressure level (SPL), and low total harmonic distortion[4]. The researches of nanothermophones open up a new direction for designing novel loudspeakers.

Thermophone essentially is a kind of device producing sound waves, and the type of sound sources can also be line, line arrays or thinfilm. A.O. Niskanen et al. [5, 6] reported the suspended Al wire array can produce thermoacoustically high-pressure ultrasound, and pointed out the strong dependence of its SPL on applied energy and frequency. H. Tian et al. [7] designed a sound-emitting device using silver nanowires. And gold nanowires are used for making thermophones by R. Dutta et al. [8]. CNT has attracted considerable attentions and has been regarded as ideal TA material due to its extremely small heat capacity per unit area[9]. M. E. Kozlov et al. [10] and A. E. Aliev et al. [11, 12] studied the...
usage of aligned arrays of multiwalled carbon nanotube forests and its solid drawn sheets to make thermally driven sound projectors. Using CNT thin yarn as the TA sound source has also been explored by Y. Wei et al. [13, 14].

However, most of researches relevant to TA emission focus on line arrays and films, the single line type as the acoustic source is relatively much less mentioned. And yet conventional line-source loudspeaker has a wide application because of its strong directivity [15]. It is frequently seen using the discrete point source to simulate a line source in gymnasium, auditorium and art square et al. Thermally driven line-source loudspeaker has not only the strong directivity of line sound source but also the unique advantages of TA sound, therefore, can be applied to acoustic local control, reducing the noise pollution to the surroundings, audio oriented communication, acoustic directivity weapon, guiding the blind, and so on. In this paper, the characteristics of TA emission from thermally driven line-source is studied in detail by using a suspended CNT stripe as TA material.

2. Model and theory formula

\[ p_g = \left( \frac{j \omega}{2 \pi r} \right) \left( \frac{\gamma - 1}{v_g^2} \right) \left( \frac{e_g}{2 v_e} + \frac{1}{v_e} \right) \left( \frac{-\alpha_e}{2 v_e} \right) \left( \frac{a_2^2 \gamma (\gamma - 1) \alpha_r}{a_2^2 \mu} \right) \left( \frac{2 a_2^2 \mu}{a_2^2 \mu} \right) \left( \frac{3 v_p^2}{3 v_p^2} \right) \int dl \]

Figure. 1 Schematic diagram of the TA emission from suspended CNT stripe.

Due to the width and thickness of CNT stripe are far less than its length, it can be regarded as a line-source thermophone. Figure 1 shows the schematic diagram of the TA emission from CNT stripe. It has length \( L \), and \( t \) is the distance from the measuring position to the midpoint of CNT stripe. \( \alpha \) is the angle between the bisector of CNT stripe and the line connecting the midpoint of CNT stripe and the measuring position. And we assumed that the device is placed in the air at normal atmospheric pressure and room temperature. Alternating current was applied to the stripe through an electrode, which induces periodic Joule heating to make the air expand and shrink, and then acoustic waves were generated. When the influence of gas viscosity was considered, the equation of TA emission from suspended CNT stripe can be presented as follows [16, 17]:
respectively, \( \rho_s \), \( c_s \), and \( \delta_s \) are the density, specific heat and thickness of stripe. And periodical line density of heat applied to stripe is \( q_t = q_0(1 + e^{\nu_t}) \).

3. Results and discussion

3.1. The impact of the length of CNT stripe on TA emission

The viewing of TA emission from stripe can be in either on-axis direction (\( \alpha = 0^\circ \)) or off-axis direction (\( \alpha \neq 0^\circ \)). Figure 2(a) and (b) show respectively the on-axis and off-axis frequency response of TA emission changing with the length of CNT stripe. It is found that, when at lower frequency, the SPL of both on-axis and off-axis TA emission linearly increase with the logarithmic frequency due to in far field, and the longer the stripe, the higher the SPL for given density of heat flow and distance from the centre of stripe, then with the increase of frequency, both appear fluctuation due to the near-field effect, and the longer the stripe, the lower the start frequency and the wider the frequency region of fluctuation but with lower amplitude and smaller period. But, on-axis SPLs with different lengths of stripe oscillate upward around the same average, then decay synchronously at a higher frequency, while the off-axis SPL is declining overall compared to on-axis SPL and the average of fluctuation shifts downward and decay frequency decreases with the shortening of stripe length.

![Figure 2. The dependence of TA frequency response on the length of CNT stripes (q_0=5w/m).](image)

3.2. The impact of detecting distance on TA emission from CNT stripe

Figure 3(a) and (b) present the on-axis and off-axis TA frequency responses of CNT stripe. It is seen that the curve of on-axis SPL moves down by increasing the detecting distance \( t \) and tends to that of point TA source described by the Eq. (9) in Ref.15. That is, when the measure position is far enough, a line sound source can be regarded as a point source. With an increase in measuring distance, the off-axis SPL is also lowered, but its fluctuation with frequency in near field is growing significantly and the frequency cycles tend to the same. For example, the frequency cycle \( \Delta f=4870 \) Hz at \( t=0.2m \), \( \Delta f=4660 \) Hz at \( t=0.5m \) and \( \Delta f=4640 \) Hz at \( t=1m \) (see Figure 3 (c)).
Figure 3. On-axis and off-axis SPL frequency response changing with distance ($L=150\text{mm}$ $q_0=5\text{w/m}$).

3.3. The impact of detecting angle on TA emission from CNT stripe

Figure 4. SPL frequency response changing with angle ($L=150\text{mm}$, $q_0=5\text{w/m}$).
The effects of measuring angles on SPL of TA emission from CNT stripe are presented in Figure 4(a) and (b). It shows that when at low frequency, i.e. in far field, the SPLs for any angle are basically same and keep linear increase with frequency, while increasing frequency so that entering the near field, the SPLs are all waved. The bigger the measure angle of avertence and the farther the measuring distance, the lower the SPL and the fierce the fluctuation.

3.4. The directivity of TA emission from CNT stripe

![Figure 5](image)

**Figure 5.** Sound pressure polar response of a CNT stripe TA source.

As seen in Figure 5., various ratio between wavelength $\lambda$ and stripe length $L$ of TA source are taken into consideration to explore the directivity of CNT line-source. It shows that when $\lambda/L \geq 2$, there are no sidelobes, and the mainlobes cover a big range. TA emission from CNT stripe displays poor directivity. While $\lambda=L$, the sidelobes begin to appear, directivity is relatively apparent. Then, with the increasing of frequency, $\lambda/L$ decreases continuously, and while there are increasing numbers of sidelobes, the directivity becomes better and better, the energy distribution gets more concentrated. Therefore, TA emission from CNT stripe have a strong directivity at high frequency.

![Figure 6](image)

**Figure 6.** TA acoustic field of CNT stripe ($L=150\text{mm}$, $q_0=5\text{w/m}$).

The TA acoustic field distribution of CNT stripe is shown in Figure 6, from which we can see that when $f = 1 \text{kHz}$, the acoustic wave presents like spherical wave, but when $f = 20\text{kHz}$, the acoustic field of CNT stripe shows a strong directivity and multiple sidelobes.
4. Conclusions
In this paper, the features of TA sound emitted from a CNT stripe is explored, which is in either perpendicular or sloping direction. It is found that the higher acoustic pressure can be achieved with a small size of CNT stripe due to its lower heat capacity. There exists a critical distance where periodically heated CNT stripe can be regarded as point TA source. The SPL of CNT stripe is falling and its fluctuation with frequency in near field is growing with the increasing of measured distance and incline angle. TA emission from CNT stripe also shows a strong directivity. The higher the frequency is, the stronger the directivity. These studies should be helpful for further investigating and developing novel nanothermophones.

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