On the Natures of Thermally Induced Ultrasonic Emission from Nanofilm

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Abstract. Thermo-acoustic (TA) ultrasound has lots of advantages over traditional electric-acoustic ultrasound. In this work, by using a full-field formulas derived for acoustic field of TA emission from arbitrary source based on a thermally-mechanically coupled model, the basic natures of TA emission from nanofilm are studied via carbon nanotube (CNT) film. It is found that the TA sound pressure level (SPL) is fluctuated in near field and attenuated in far field, the SPL fluctuation in near field results from the interference of TA waves emitted from every element of film, which directly leads to the existence of, in point of technique, the most important nature of TA wave--flat frequency response at certain condition, and in far field, all the sound-emitting films can be regarded as point sources. These researches are significant for understanding TA wave and developing a variety of TA devices.

1. Introduction

It has been found that thermo-acoustic (TA) ultrasound has lots of advantages over traditional electric-acoustic ultrasound since its emission from nanocrystalline silicon was reported by Shinoda et al. in *Nature*, 1999: larger frequency bandwidth and acoustic pressure, lesser reverberation and distortion, higher sensing accuracy and spatial resolution, easily integrated in MEMs and sound signal self-demodulation, and availability and controllability for finely structured phase arrays operation [1-6]. These are mainly due to its unique nature -- wideband flat frequency response. In 2008, Xiao et al. found that carbon nanotube (CNT) thin film sheet can also generate sound with wide frequency range, high sound pressure level (SPL), and low total harmonic distortion, thus could be a practical TA loudspeaker [7-8]. Many researchers have done a fair amount of work to investigate the performances of CNT-based TA projectors and revealed that the ultra small heat capacity of per unit area (HCPUA) is the key for CNT thin film being a good TA material [9-13]. Similarly, graphene membranes have attracted a lot of researchers also [15-25]. These nanofilms 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. Although there have been many investigations of nanofilm TA projectors, few focused on the basic natures of TA emission, so that it is still unclear that how might the most important TA nature, from the standpoint of technique, wideband flat frequency response has come about.

We have theoretically investigated the issue of wideband flat frequency response of TA emission by a one-dimensional TA model, and given the the conditions for existence of flat frequency response, the flat frequency response region, and the expression of flat frequency response [11]. Here, in this paper, by a three-dimensional expression of acoustic pressure field of TA emission taking advantage of the point sources superposition and the surface heat distribution factor, we explore furtherly the basic natures of TA sound based on CNT nanofilm. The behavior of TA wave in full-field is clarified, thus
the formation of wideband flat frequency response can be understood by combining quantitative and qualitative analysis. The illustration of nature of TA sound wave would be of guiding significance for developing new-type sound-emitting devices without magnets and moving parts.

2. 3D Full-Field TA Formulas

The schematic of TA emission from a suspended CNT thinfilm is shown in Fig. 1. A sinusoidal alternating current (AC) with direct current offset is used to excite a periodical heating current \( q = q_0(1 + e^{j\omega t}) \). A simplified expression of sound pressure of TA emission from a suspended thinfilm can be derived by the method of point-source superposition based on a fully coupled TA model as follow [14]

\[
p_{s} = \int_{\Omega} \frac{j\omega \gamma - 1}{2\pi r} \frac{e_\gamma}{v_\gamma^2} \frac{e_\gamma}{2e_\gamma + \sqrt{j\omega C_f}} \frac{q_0 e^{j\omega t}}{v_\gamma} d\Omega
\]

(1)

![Figure 1. Schematic of TA emission from a suspended CNT thinfilm](image)

Where \( q_0 \) is the intensity of heat flux density, \( \omega \) is the angle frequency of periodical heating, \( C_f = \rho_f c_f \delta_f \) is the HCPUA of thinfilm, where \( \rho_f \), \( c_f \), and \( \delta_f \) are the density, specific heat, and thickness of thinfilm, respectively. The other parameters are the sound velocity in gas \( v_\gamma = \sqrt{\frac{\gamma P_0}{\rho_f}} \), the thermal effusivity of gas \( e_\gamma = \sqrt{\kappa_g \rho_g c_p \rho_g} \), in which \( \kappa_g \), \( \rho_g \), and \( c_p \) are the thermal conductivity, density, and specific heat of ambient gas, \( \gamma \) is the specific heat ratio of gas, and \( P_0 \) is the ambient pressure. \( r \) is the distance between the measured point and a small area element \( d\Omega \) of thinfilm.

If the influence of thermal diffusion and viscous dissipation of ambient gas, as well as the heat convection between ambient gas and thinfilm are taken into account, the acoustic pressure of TA emission from the suspended thinfilm can be further modified on the basis of Eq. (1) as [26]

\[
p_{s} = \int_{\Omega} \frac{j\omega \gamma - 1}{2\pi r} \frac{e_\gamma}{v_\gamma^2} \frac{e_\gamma}{2e_\gamma + \sqrt{j\omega C_f}} \frac{2h}{\sqrt{j\omega}} q_0 e^{j\omega t} \left[ \frac{-j\omega}{v_\gamma} \frac{(\gamma-1)\alpha_g}{2v_\gamma^2} \frac{2\alpha_g \rho_g}{3\kappa_g \rho_g} \right] d\Omega
\]

(2)
Where $\alpha_g$ is the thermal diffusivity of gas, $\mu_g$ is the dynamic viscosity of gas, and $h$ is the convective heat-transfer coefficient between ambient gas and thinfilm. This is a 3D full-field formula for calculating TA emission from nanofilm.

Therefore, the TA sound pressure in the central vertical line of a suspended square thinfilm shown in Fig. 1 can be expressed as

$$p_g = \iint_{-a/2 \leq x, y \leq a/2} \frac{j\omega \gamma - 1}{2\pi \sqrt{x^2 + y^2 + t^2}} \frac{e_g}{v_g} \frac{e_g}{2} \sqrt{\int_{-j\omega C_s + \frac{2h}{\sqrt{j\omega}}}^{+j\omega C_s + \frac{2h}{\sqrt{j\omega}}} dx} dxdy$$

Where $a$ is the side length of the square thinfilm and $t$ is the distance from the measured point to the thinfilm.

In following theoretical study of the TA emission from a suspended CNT thinfilm, the ambient gas of thinfilm is taken as air at normal atmospheric pressure and room temperature.

3. Results and Discussion

Rayleigh distance $R_0 = \frac{S}{\lambda} = \frac{Sf/\nu_g}{\lambda}$ is usually used to divide near-field and far-field, where $S$ is the area of film and $\lambda$ is the acoustic wavelength. It is showed that the TA sound pressure level (SPL) is fluctuated with distance and frequency in near field and attenuated in far field. For TA emission both from a larger area of film and at a higher frequency, its nearfield is greatly enlarged due to having much larger Rayleigh distance, hence, by Eq. (3), TA wave could also suffer severe damping induced by high frequency and large distance in near field (see Fig. 2 and 3).

The SPL fluctuation in near field results from the interference of TA waves emitted from every element of film. Since this interference is related to phase shift $\frac{\omega x}{v_g}$, by Eq. (2). The SPL of TA wave fluctuates with either frequency or distance in near field, while in far field, the TA wave emitted from a film is close to that from a point TA source (see below). The SPL fluctuation of TA wave with frequency in near field directly leads to the existence of the most important nature of TA wave—flat frequency response at certain condition (see Fig. 3). As is shown in Fig. 2 of Ref. 14, the larger the ratio $S/t^2$ is, the smaller the SPL fluctuation is, the more flat the TA frequency response would be.

![Figure 2](image-url)
Figure 3 describes the frequency responses of TA wave at various distances from the CNT film (ignoring convection). It is shown that the SPL of TA wave, basically, linearly increases with increasing logarithmic frequency at lower frequency, reaches its maximum value at a higher frequency, then goes down. It is seen that the SPL fluctuation with frequency of TA wave in near field weakens with increasing distance.

Generally, $f_{ms}$, the frequency corresponding to the maximum SPL, is related to both the distance from film $t$ and the area of film $S$. Detailed calculation indicates that, for any size of $S$, $f_{ms}$ increases first with the increasing $t$, and achieves its maximum $f_{ms, max}$ at about $t = \frac{2}{3} R_h$, then decreases gradually with the increase of $t$, as shown in Fig. 3. But, when $t \geq \frac{3}{2} R_h$, there’s almost no effect of film area $S$ on $f_{ms}$ and

$$f_{ms} \approx \frac{173}{\sqrt{t}} \text{ (kHz)}$$  \hspace{1cm} (4)

In the normal atmosphere, which agrees well with the results by using the solution of point source TA emission in Ref. 14 (see Fig. 4), that is, all the sound-emitting films here can be regarded as point sources.
Figure 4. Comparison of $f_{ms}$ between the result from the fitting formula of calculation data and that from point-source TA formula

4. Conclusion

In this work, the natures of TA sound wave are investigated furtherly by using a TA full-field formula to calculate TA emission from CNT nanofilm. The behaviors of TA wave in from near-field to far-field are clarified. It is found that TA sound pressure fluctuates in near-field with frequency and distance, while decays in far-field. SPL increases linearly with logarithmic frequency in far-field and decays with distance, similar to the sound field of point source. The unique nature of TA emission—flat frequency response results from the sound pressure fluctuation in near-field.

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6. References

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