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Thermo-acoustics generated by periodically heated thin line array

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ABSTRACT

A theoretical model for the generation of thermo-acoustic waves from a heated point source in a free-space and a half-space is proposed, where the source is suspended over a substrate. By directly applying the analytical results of a point source to a thin line thermo-acoustic speaker, the acoustic pressure field generated by the periodically heated thin line can be derived using a mathematical integration technique. To further generalize the results from a thin line speaker to a thin line array, the acoustic pressure response generated by the line array speaker can also be implemented in both free- and half-spaces. In this work, the characteristics of pressure fields generated by the thin line array are investigated in detail. The established model is well validated by comparing with the existing experimental results. The present findings not only can be extended to investigate thermo-acoustic responses generated by arbitrary sources, and also it can provide important design guidelines for the manipulation and optimization of thin line array thermo-acoustic devices.

1. Introduction

Thermo-acoustic (TA) transducers have attracted more research attention in recent years due to their superior properties of light weight and broadband response. The generation mechanism of TA devices is completely different with that of conventional mechanically driven loudspeakers. On the basis of this thermal principle, acoustic waves can be efficiently generated from the expansion and contraction of a medium that is heated periodically by applying an alternating current on a thin conductor [1]. However, the development of TA devices has remained stagnant for more than eighty years since it was first introduced by Arnold and Crandall [2], which is mainly attributed to the lack of innovative technology on the fabrication of smart materials. With the advancement of nanomaterials and nanotechnology at a rapid pace, it sheds light on the breakthrough technology of TA devices. The first efficient thermal ultrasound emitter was proposed by Shinoda et al. [3] in 1999, in which a patterned thin aluminum film was directly placed on a microporous silicon layer to serve as a major component for sound generation. An improved electrical power to sound power conversion efficiency was demonstrated by the experimental observation, which is beneficial from the low heat capacity per unit area (HCPUA) of a 30-nm aluminum film

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used as a thermal ultrasound emitter. To compare with conventional mechanically driven speakers, the conversion efficiency is still low due to the significant thermal leakage into the substrate. Nevertheless, it has been demonstrated that TA transducers can exhibit broadband responses, but conventional loudspeakers do not possess this feature [4]. Hence, it is highly desired to explore potential applications in the technological development of TA loudspeakers and transducers [5].

To enhance the conversion efficiency of TA devices, Xiao and his co-workers [6] proposed a newly-fabricated carbon nanotube (CNT) thinfilm [7,8], which can be drawn from nano-materials composed of a super-aligned CNT array as a thermal source. CNT thinfilms are able to generate considerable acoustic signals by feeding an alternating current onto it [6]. The high electrical power to sound power conversion efficiency of CNT thinfilm TA devices is mainly come from two sides. One is from its extremely small HCPUA and the other one is due to the suspension structure. Unlike the TA device designed by Shinoda et al. [3], a non-substrated structure TA transducer introduced by Xiao et al. [6] enables most of the thermal energy to heat the surrounding medium (fluidic or gaseous medium), resulting in a higher energy conversion. In pursuit of alternative forms, multiple types of TA devices were subsequently reported, including CNT assemblies [9], metallic wire arrays and metallic thinfilms [10–14], graphene-on-paper [15], CNT yarn array suspended on a substrate [5], carbon fiber array encapulated in a planar enclosure [16], carbonized electrospun nanofiber sheets [17] and even individual CNTs [18,19].

In the literature, the performance of TA devices in both gaseous and fluidic media was extensively investigated. Aliev et al. [20] reported an experimental study for the investigation of TA responses in water, ethanol and methanol. A higher pressure in water can be produced due to the hydrophobicity of the CNT sheets. In addition, Xiao et al. [21] and Aliev et al. [22] also investigated the performance of TA devices immersed in various gaseous media for the frequency spectrum analysis of TA signals. They found that there is a dominant effect for the thermal properties of surrounding gaseous media on the generation of acoustic pressure fields. In addition, the experimental results also showed that the performance of TA devices is completely different in closed systems and open spaces.

Nevertheless, there are few theoretical works attempted on the investigation of TA responses. Hu et al. [23] considered a set of coupled thermal-mechanical equations to study the ultrasound effect generated by an aluminum-porous silicon TA device. Xiao et al. [6] constructed a piston model to explain the importance of the HCPUA on the thermal-acoustic generation efficiency. To improve the piston model of Xiao et al. [6], an accurate analytical model was proposed by Lim et al. [24] to show an excellent agreement with the experimental results. Besides, Vesterinen et al. [11] theoretically investigated the efficiency of TA devices made of aluminum wire arrays. The influence of the appearance of substrates on the generation of acoustic waves was also demonstrated. Asadzadeh et al. [25] derived a formula for sound generation of small TA sound sources using two alternative forms of energy in terms of energy conducted to the fluid. To study acoustic pressure in the near-field region, a 3-dimensional governing equation was formulated and solved using the finite difference method. Tong and his associates [26,27] constructed two theoretical models to study the acoustic fields generated by specific types of TA devices, i.e., encapsulated TA transducers and gap-separation TA devices. Subsequently, acoustic field responses to various broadband input signals applied to both free-standing and nano-thinfilm-substrate TA devices were also investigated [4]. More recently, an electrical-thermal-acoustical model was constructed by Asgarisabet and Barnard [28] for the simulation of pressure distribution in an open medium by feeding an electric current into a CNT film. The influence of material properties in the surrounding medium on the output sound pressure was also discussed.

Although an industrial revolution in the fabrication of nanomaterials has significantly advanced the technology of TA devices to improve our daily audio experience, the weak structure form of free-standing CNT sheets [5] and the low energy conversion efficiency of film-substrate structures are still difficult to realize its practical applications. Consider the fascinating and promising applications of thin nano-structures on the design of TA devices, an improvement on the structure strength is highly demanded. Wei et al. [5] took advantage of the high mechanical strength of CNT thin line array to manufacture a suspended TA device, which can tactfully solve the weak structure problem involved in fresh CNT films. As the thin line array is suspended over a silicon substrate with a gap separation that can efficiently reduce the thermal leakage into the substrate, leading to a higher efficiency. However, Wei et al. [5] only presented a qualitative analysis on the experimental observation according to the model proposed by Xiao et al. [6]. Based on the previous study [5], Tong et al. [27] further developed an accurate approximate model to account for the acoustic pressure response of nano-film-substrate TA devices. In order to substantially investigate the performance of TA effect, a rigorous theoretical model is greatly desired for further design and optimization of thin line array TA devices.

Presented herein is a rigorous model to investigate the acoustic pressure response of thin line TA devices. Consider that receiving points are mostly within the far-field region, acoustic pressure responses in the far-field region are of great interest and thus it is the major scope of the present work. Both frequency- and power-dependent pressure responses are compared with the available experimental results to validate the accuracy of this analytical model. The characteristics of pressure distribution in a semi-space are also investigated. By increasing frequency results in the appearance of the principal maxima and the side-lobes due to the strong interference effect. Furthermore, a phased array TA emission by feeding an alternating current with different phase shifts onto the TA device is studied. The characteristics of the angular distribution of acoustic pressure is also presented.

2. Theory and analytical models

Consider a thin line array TA device that is made of a series of parallel thin lines as shown in Fig. 1. By superposing all acoustic pressure fields generated by these thin lines, we can obtain a total acoustic pressure field produced by the thin line