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Influence of thermodynamic properties of a thermo-acoustic emitter on the efficiency of thermal airborne ultrasound generation

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ABSTRACT

In this work we experimentally verify the theoretical prediction of the recently published Energy Density Fluctuation Model (EDF-model) of thermo-acoustic sound generation. Particularly, we investigate experimentally the influence of thermal inertia of an electrically conductive film on the efficiency of thermal airborne ultrasound generation predicted by the EDF-model. Unlike widely used theories, the EDF-model predicts that the thermal inertia of the electrically conductive film is a frequency-dependent parameter. Its influence grows non-linearly with the increase of excitation frequency and reduces the efficiency of the ultrasound generation. Thus, this parameter is the major limiting factor for the efficient thermal airborne ultrasound generation in the MHz-range. To verify this theoretical prediction experimentally, five thermo-acoustic emitter samples consisting of Indium-Tin-Oxide (ITO) coatings of different thicknesses (from 65 nm to 1.44 μm) on quartz glass substrates were tested for airborne ultrasound generation in a frequency range from 10 kHz to 800 kHz. For the measurement of thermally generated sound pressures a laser Doppler vibrometer combined with a 12 μm thin polyethylene foil was used as the sound pressure detector. All tested thermo-acoustic emitter samples showed a resonance-free frequency response in the entire tested frequency range. The thermal inertia of the heat producing film acts as a low-pass filter and reduces the generated sound pressure with the increasing excitation frequency and the ITO film thickness. The difference of generated sound pressure levels for samples with 65 nm and 1.44 μm thickness is in the order of about 6 dB at 50 kHz and of about 12 dB at 500 kHz. A comparison of sound pressure levels measured experimentally and those predicted by the EDF-model shows for all tested emitter samples a relative error of less than ±6%. Thus, experimental results confirm the prediction of the EDF-model and show that the model can be applied for design and optimization of thermo-acoustic airborne ultrasound emitters.

1. Introduction

Ultrasound-based methods for medical applications [1], non-destructive materials testing [2,3] and echolocation [4] have become an indispensable part of our lives. In particular, airborne ultrasound as a contact-free inspection method has been gaining in importance and has been increasingly applied in many technical fields including non-contact quality control and health monitoring of lightweight materials and safety-relevant components for automobile and aerospace applications [5–7] as well as parking assistant and blind-spot monitoring systems [8,9].

Currently, the most commonly used ultrasound transducers are piezoelectric or electrostatic transducers that are basically damped mass-spring systems. The influence of the sprung mass of a transducer is particularly strong in airborne ultrasound transducers and manifests itself in the post-ringing of the transducer and a "long" decay time (up to 200 μs) of the generated acoustic signal after a 500 ns impulse excitation [10]. Further disadvantages of the sprung mass include resonance frequencies and the resulting narrow bandwidth (±5–10% of the main frequency) of the conventional airborne ultrasound transducers. The resonances and the post-ringing of airborne ultrasound transducers make difficult the impulse-echo detection of the near-surface defects and limit the minimal distance of object localisation.

Thermo-acoustic emitters (TA-emitters), also called thermophones, generate sound without any macroscopic displacement of the surface and only generate heat if electric current is applied.

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They consist either of free hanging electrically conductive films or wires, or, for reasons of better mechanical stability, of electrically conductive films on solid or polymer substrates. The sound waves emerge due to thermally induced particle velocity of the adjacent gas particles away from the heated emitter surface. After switching off of the electric current, the emitter surface cools down and the velocity of the adjacent gas particles returns to that of the initial state. Therefore, a TA-emitter displays no post-oscillations and no resonances and can be applied as a broadband airborne ultrasound source in a frequency range from 20 kHz to 1 MHz and over [10].

Additionally, as was experimentally demonstrated [10] in a frequency range from 200 kHz to 1 MHz, TA-emitters reaches acoustical efficiencies comparable to those of conventional piezoelectric airborne ultrasound transducers generating sound pressure levels of about 140 dB at 6 cm distance from the emitter.

This suggests e.g. the possibility of non-destructive testing applications, where a "short" (500 ns – 1 µs) airborne ultrasound impulse length is the key for reliable impulse-echo detection of the near-surface defects.

Moreover, TA-emitters can be used for testing of transfer function of conventional acoustic sensors in the audio frequency range [11,12] and also as recently experimentally demonstrated for frequencies from 1 kHz to 1 MHz and in a dynamic range from µPa to kPa [13].

In addition, TA-emitters can also be applied in medical applications such as the study of the frequency dependant acoustic threshold of human hearing [14].

Besides resonance-free behavior TA-emitters do not need $\lambda/4$ matching layers or dampening bodies. Thus 20–30 nm thin and transparent airborne ultrasound emitters can be built and embedded in the screens of smart phones, tablets and other electronic devices [15].

To the best of our knowledge, all up to now existing theoretical approaches for TA-emitters can be sub-divided into three categories:

- models for TA-emitters consisting of free hanging films and wirers [11,16–19],
- models for substrate-based TA-emitters [20–24] and
- a generalized model for thermal sound generation, the EDF-model [25].

Models falling into the first category consider only the thermal capacity of the heat producing film as a frequency independent constant and ignore the thermal effusivity of the adjacent gas.

Models of the second category consider only the thermal effusivities of the substrate and the adjacent gas and ignore the thermal inertia of the heat producing film.

The EDF-model predicts that the thermal inertia of an electrically conductive film is a frequency-dependent parameter. With the increase of the operation frequency, it has to act as a low-pass filter that reduces the generated sound pressure non-linearly.

Thus, the thermal inertia of electrically conductive film seems to be the major limiting factor for an efficient thermal airborne ultrasound generation in the MHz-range.

To the best of our knowledge there are up to now no published experimental examinations about the influence of electrically conductive films on the generated sound pressure for substrate-based TA-emitters.

Therefore, the main objective of this work is an experimental examination of the influence of thermodynamic properties of an electrically conductive film on the thermally generated sound pressure. Thus the theoretical prediction made by the EDF-model can be experimentally confirmed or refuted.

Below we describe the EDF-model for thermal sound generation in gases. Then, we analyse the influence of the thermodynamic properties of the electrically conductive film on the generated sound pressure and discus the requirements of an optimal TA-emitter material for airborne ultrasound applications. And finally, we experimentally examine the influence of the thermal inertia of the heat producing film on the generated sound pressure by testing five TA-emitters consisting of Indium-Tin-Oxide (ITO) coatings of different thicknesses (from 65 nm to 1.44 µm) on quartz glass substrates for airborne ultrasound generation in a frequency range from 10 to 800 kHz.

2. Theory

In a previous work [25] we introduced a novel theoretical model for thermal sound generation based on the kinetic theory of gases. Particularly, we consider thermally induced kinetic Energy Density Fluctuation (EDF) and its propagation in the adjacent gas. Using this energy-based approach we avoid the problems encountered by the analytical solution of a set of coupled nonlinear partial differential equations for temperature and pressure, and arrive at a full analytical solution for thermally generated sound pressure at each point of the adjacent gas. The derivation of the EDF-model can be found in [25].

Contrary to existing theoretical approaches [11,16–24] proposed EDF-model is applicable to free hanging as well as to substrate-based TA-emitters and comprise:

- thermodynamic properties of emitter materials including the thermal inertia of the heat producing film and the thermal effusivities of substrate and adjacent gas;
- shape and size of the emitter surface;
- and the distance and frequency dependant sound attenuation effects.

Thus, the EDF-model proposed seems to be applicable in the entire frequency range of airborne ultrasonic applications.

In the following, we consider a TA-emitter consisting of an electrically conductive film, a solid substrate and an infinitely extended adjacent gas volume.

The EDF-model predicts for the amplitude of sound pressure generated by a thermo-acoustic point source on a substrate for an arbitrary observation distance r in a gas at temperature T and pressure P that:

$$p_{point}(T,P,\bar{r},f_{th}) = \frac{3 \cdot P_{el\ eff} \cdot f_{th}}{2 \cdot \pi \cdot c^2_{sound\ gas}(T) \cdot |\bar{r}|} \cdot E_{gas}(T,P,f_{th}) \cdot \frac{F_{transl}}{F_{total}(T,P)} \cdot A_{gas}(T,P,\bar{r},f_{th}) \quad (1)$$

where $P_{el\ eff}$ is the effective value of the supplied electric power, f_{th} is the thermal excitation frequency and $c_{sound\ gas}(T)$ is the speed of sound in the gas.

The coefficient $E_{gas}(T, P, f_{th})$ gives the ratio of distribution of the released thermal energy between the heat producing film, the adjacent gas and the substrate and is given by

$$E_{gas}(T,P,f_{th}) = \frac{e_{gas}(T,P)}{e_{gas}(T,P) + e_{sub}(T,P) + I_{th\ film}(T,P,f_{th})} \quad (2)$$

with

$$e_{gas}(T,P) = \sqrt{\lambda_{gas}(T,P) \cdot \rho_{gas}(T,P) \cdot c_{v\ gas}(T,P)}, \quad (3)$$

$$e_{sub}(T,P) = \sqrt{\lambda_{sub}(T,P) \cdot \rho_{sub}(T,P) \cdot c_{psub}(T,P)} \quad (4)$$

and

$$I_{th\ film}(T,P,f_{th}) = d_{film}(T,P) \cdot \rho_{film}(T,P) \cdot c_{p\ film}(T,P) \cdot \sqrt{2 \cdot \pi \cdot f_{th}}, \quad (5)$$