Focussed sound field of thermoacoustic transmitters

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Introduction

Ultrasonic testing of some lightweight components is performed using air-coupled transducers, to avoid damage from liquid couplants. Commercially available air-coupled transducers are based on piezoelectric materials and contain elaborate matching layers, so that they exhibit relative bandwidth below 30 % [1]. To increase the bandwidth, thermoacoustic transducers were introduced. The thermoacoustic effect offers a method for selectively exciting broadband and focused ultrasonic waves. Thermoacoustic transmitters are composed of an electrically conductive layer deposited on an insulating substrate [2, 3]. When electrical pulses are applied, the conductive layer heats, briefly warming the adjacent air and inducing thermal expansion, which generates an acoustic wave (Figure 1(a)). If the substrate is spherically curved, this acoustic wave forms a focused sound field with a significantly higher sound pressure in the focus area. In testing applications, the thermoacoustic transmitter is positioned at the focal distance to the structure under examination, where the resolution of the resulting ultrasonic image is influenced by the focus diameter.

To optimize imaging resolution, understanding the focusing characteristics of thermoacoustic transmitters is essential. In this study, thermoacoustic transmitters with an indium tin oxide (ITO) layer on a quartz glass substrate were developed [4]. Geometrical parameters, including substrate curvature and conductive layer thickness, along with electrical excitation parameters, were systematically varied to investigate their impact on the sound field up to approximately 1 MHz. The sound field was measured using an optical microphone based on Fabri-Perot etalon.

Experimental setup

Focused thermoacoustic transmitters were developed for this study. They consist of a thin layer of indium tin oxide (ITO) and a curved substrate made of quartz glass. The electrical voltage is applied through copper electrodes coated on the edges of the quadratically shaped aperture, which was 17x17 mm. Figure 1(b) shows a prototype with electrodes positioned at the upper and lower side of the aperture.

Effects of various parameters on sound field focusing of substrate-based thermoacoustic transmitters were studied. The transmitters were excited using rectangular burst signals. The independent variables of the experiments included: pulse width, number of pulses in a burst, ITO coating thickness, and curvature radius. The influence of these factors was examined on these dependent variables: focal distance, focal zone length, sound pressure at focus, spectrum, and bandwidth. These parameters were determined using an automatized measurement system consisting of the air-coupled ultrasonic testing device USPC 4000 AirTech from Hillger NDT GmbH paired with the mechanical manipulator Aerotech Npaq A3200.

Two different optical microphones from XARION Laser Acoustics GmbH, Austria, were utilized for sound field measurements, namely Eta 450 Ultra and Eta 100 Ultra [5]. Due to the structure of the sensor head, the sensitivity is directional and the opening should be normal to the incident wave for optimal sensitivity.

We performed two main experiments with 2D sound field measurements: (1) the influence of the excitation parameters, and (2) the influence of the transmitter parameters. These setups are described in the following.

(1) We examined the influence of the pulse width and of the number of pulses in the burst. The voltage of power supply was kept 150 V. These tests were performed on the same transmitter with 200 nm ITO and 69 mm curvature. There were four levels for pulse width, namely 0.5, 1, 2 and 4 µs, and two levels for the number of pulses, namely 1 and 2 pulses. The duty cycle was 1:2. To reach a better SNR, the measurements were performed using ETA 450 Ultra.

(2) We studied the influence of the thickness of the conducting layer and of the substrate curvature. Nine transmitters were studied with ITO thicknesses of 100, 200 and 300 nm and curvature radii of 23, 69 and 114 mm. The voltage was 200 V and the excitation signal a rectangular pulse of 1 µs width. Due to high sound pressures, the microphone ETA 100 Ultra was used, which is less sensitive than ETA 450 Ultra.

The sound field measurements were performed according to guidelines published in [6].

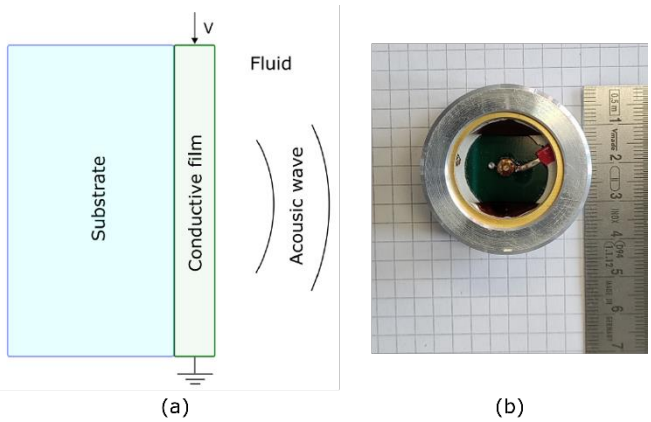

Figure 1. Substrate-based thermoacoustic transmitter, (a) schematic representation, (b) prototype.

Results and discussion

Influence of the excitation parameters

As expected, the properties of the sound field strongly depend on the excitation signal. Figure 2 shows the distribution of sound pressure level along the acoustic axis when the transmitter is excited with single square pulses with a varying length. The signal height increases with the increasing pulse length. The influence on the focal distance, which is the position of the maximum of each curve, is rather small. Focal zone length, which is measured as the range in which the signal drops by less than -3 dB, extends slightly when the pulse length is increased.

The frequency spectra of the same transducer and the same excitation parameters measured in the focus using microphone ETA 450 Ultra are presented in Figure 3. The first striking feature is the major drop of the signal at around 120 kHz. Comparative measurements with a different microphone, ETA 100 Ultra, do not exhibit this drop, and they also have a different distribution of maxima, so that we conclude that the drop and some other sound pressure variations are a property of the microphone rather than of the themoacoustic source. Particularly the standing waves resulting from the geometrical conditions of the sensor head might be the source of deviations from a uniform spectrum. Additional measurements using a laser vibrometer (not presented here) confirmed that the spectrum of the thermoacoustic source is rather continuous and has only one local maximum. Nevertheless, the measurements with the optical microphone still show clearly that shorter pulses produce a spectrum with a maximum at higher frequencies, as expected.

Measurements with a burst consisting of two pulses were performed. We expected a slightly narrower spectrum, but this effect was not observed, most likely because of the irregularities in the spectrum of the microphone.

The sound field in a plane containing the acoustical axis presented in Figure 4 shows the effect of the excitation on the sound field. For piezoelectric transducers, a commonly used approximation is that the position of the sound field maximum is also the position on the acoustical axes where the sound beam width has its minimum [7]. This position is called focus. However, this is a valid approximation only for transducers based on piezoelectricity. Thermoacoustic transducers have a significantly larger bandwidth, so that the narrowest position of the sound beam is considerably further from the transducer than the position of the maximum of the sound field. In this publication we use the word “focus” to refer to the position of the maximum sound pressure.

The sound field was recorded at the focal distance in the plane perpendicular to the acoustical axis. The focus diameter (-3 dB values) ranged between 2.5 and 4 mm for all analysed pulse lengths and bursts, as shown in Table 1. The results suggest that the shorter pulses lead to a smaller focus diameter, but the difference is not statistically significant.

Influence of the transmitter parameters

The measured sound field and the focussing properties strongly depend on the substrate curvature. Figure 5 demonstrates this dependency on the example of transmitters with

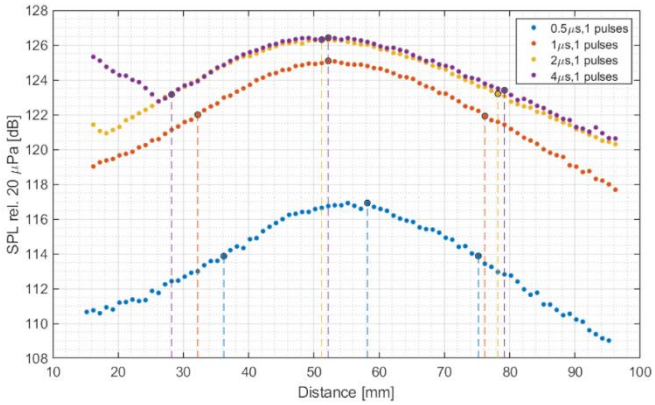

Figure 2. Sound pressure level recorded on the acoustical axis of a thermoacoustic transmitter with 200 nm ITO and 69 mm curvature. The transmitter was excited with a single square pulse with a varying length between 0.5 and 4 µs.

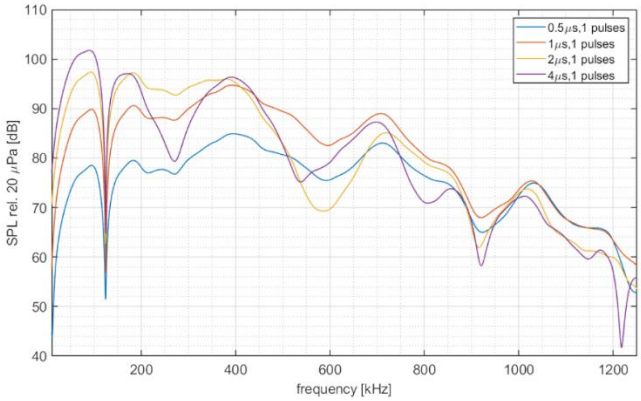

Figure 3. Spectra for lengths of the excitation pulse between 0.5 and 4 µs, measured in the focus of a thermoacoustic transmitter with 200 nm ITO and 69 mm curvature.

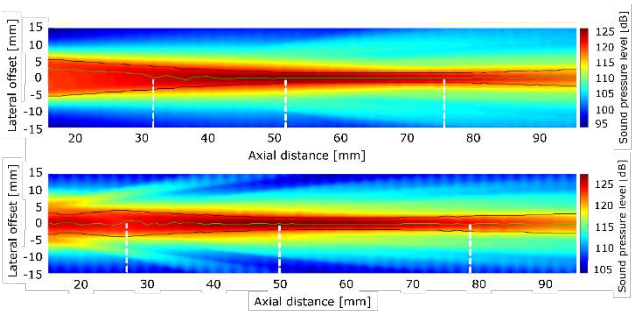

Figure 4. Sound field of a thermoacoustic transmitter with 200 nm ITO and 69 mm curvature. (a) Excitation with a single 1 µs pulse, (b) with two 4 µs pulses. The focus and the focal zone are indicated with white dashed lines.

Table 1. Focus diameter depending on the excitation. Measurements were performed on a thermoacoustic transmitter with 200 nm ITO and 69 mm curvature.

		Focus diameter (mm) for 1 pulse	Focus diameter (mm) for 2 pulses
Pulse width (µs)	0.5	3	2.5
	1	3	3
	2	4	4
	4	3.5	4

300 nm thick ITO layers. Complete results for all ITO thicknesses are shown in Table 2. The thickness of the ITO layer does not have any detectable influence on the focal distance, nor on the spectrum, as demonstrated in Figure 6.

The sound field was recorded at the focal distance in the plane perpendicular to the acoustical axis. The focus diameter ranged between 1.5 mm for the curvature radius 23 mm and 5.8 mm for the curvature radius 114 mm and it was independent on the thickness of the ITO layer. The complete results are shown in Table 3.

Discussion and conclusions

The sound field of thermoacoustic sources with different radii of curvature and ITO coating thicknesses were measured in 2D planes along and perpendicular to their acoustic axes. The study was divided into two main parts: 1. effects of excitation signals, 2. effects of curvature radius and ITO thickness, on the geometrical properties of sound fields and frequency response of transmitters.

In the first set of experiments, a transducer with a fixed curvature radius and ITO layer thickness was excited by 8 different rectangular burst signals. The sound fields were measured using Eta 450 Ultra optical microphone. The results showed that the excitation signal has a minimal effect on the geometrical characteristics of the sound e.g., focal distance, beam radius, etc., at least for the selected excitation signal. The sensitivity on the other hand is largely influenced by the pulse width due to higher thermal energy generation and hence higher achievable pressure levels. Effect of number of pulses on the pressure amplitudes was shown to be relatively small. The study of the resulted acoustic time signals and frequency spectra showed deviations from what was expected. Some of these deviations were proven to be caused by the microphone.

In the second experiment, the effects of transducer curvature radius and ITO thickness were studied. The measurements were carried out using a different optical microphone, Eta 100 Ultra. The curvature was demonstrated to be the dominant factor as expected, changing the geometry of the sound field considerably. It was also shown that the influence of both factors on the frequency spectra of the acoustic signals is relatively small.

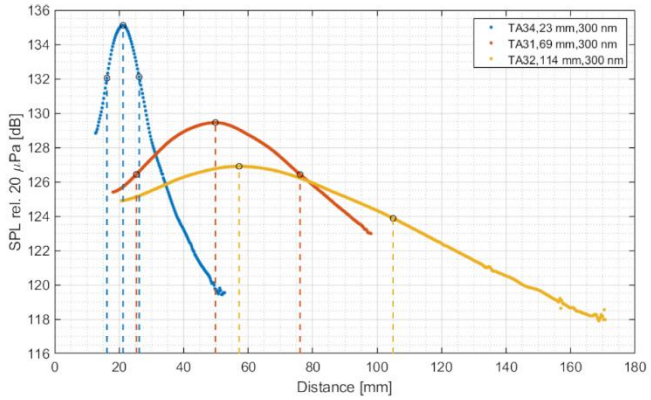

Figure 5. Sound pressure level recorded on the acoustical axis of focussed thermoacoustic transmitters with 300 nm ITO and curvature radii 23 mm (blue), 69 mm (red) and 114 mm (yellow). The transmitter was excited with a single square pulse with 1 µs width.

Table 2. Focal distance depending on the substrate curvature and thickness of the ITO layer.

		Focal distance (mm) for curvature radius 23 mm	Focal distance (mm) for curvature radius 69 mm	Focal distance (mm) for curvature radius 114 mm
ITO thickness (nm)	100	21.4	48.1	63.5
	200	21.3	48.5	62.6
	300	21.2	49.9	57.2

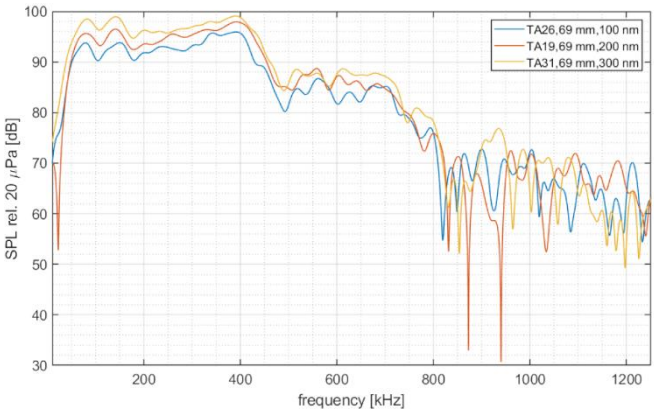

Figure 6. Spectra of the sound pressure measured in the focus of transmitters with curvature radius 69 mm and varying ITO layer thickness: 100 (blue), 200 (red) and 300 nm (yellow). The excitation pulse was a square pulse 1 µs wide.

Table 3. Focus diameter depending on the substrate curvature and thickness of the ITO layer.

		Focus diameter (mm) for curvature radius 23 mm	Focus diameter (mm) for curvature radius 69 mm	Focus diameter (mm) for curvature radius 114 mm
ITO thickness (nm)	100	1.5	3.75	5.5
	200	1.75	3.75	5.75
	300	1.5	4	6

The measurements of the focus diameter with the transmitter with 200 nm ITO, 69 mm curvature, excited with 1 pulse with 1 µs width were performed twice: Once as a part of the study of the influence of the excitation and once as a part of the study of the transducer parameters. These two measurements gave different results for the focus diameter: 3 and 3.75 mm respectively. This difference can be attributed to the use of different microphones: While the first study was performed with ETA 450 Ultra, the second one was performed with ETA 100 Ultra. This indicates how the choice of the microphone can influence the result. Further studies should be performed to systematically study other possible causes for the observed variation.

One of the main applications for thermoacoustic transmitters is the characterization of ultrasonic receivers, such as conventional transducers and condenser microphones. However, knowing the exact transfer function of the thermoacoustic transmitter is the main prerequisite for that. Unfortunately, determining the frequency response of the transducers using the implemented optical microphones alone is not possible. Moreover, the spectral characteristics of the optical microphones influence the measured sound fields and thus their computed geometrical properties. The results emphasize the lack of a proper ultrasonic receiver in the submegahertz range.

Furthermore, focussed thermoacoustic transmitters open new possibilities in contact-free ultrasonic material testing and characterisation due to their high bandwidth and good focusing, which enables their use in localized ultrasonic spectroscopy and detection of defect resonances.

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