VOLUMETRIC CHARACTERIZATION OF ULTRASONIC TRANSDUCERS FOR GAS FLOW METERING

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Abstract—**The design of ultrasonic gas flowmeters requires a thorough three dimensional characterization of the acoustic sound field. For large pipe flowmeters, such as used for flare gas metering, the transducers are operated at frequencies ranging from 20 kHz up to 150 kHz. Thus, in this work we use a commercially available calibrated 1/8-inch microphone, mounted on a 3D positioning system for performing volumetric measurements in a volume of up to 1x1x1 m. By using proper corrections in terms of angular and free-field response of the microphone, the measurement system is efficient and delivers around 30000 measurements in about only eight hours. The data then is visualized in form of 3D figures or various slices to extract all relevant information. The system has been used to identify non-uniform velocity profiles in capacitive micromachined ultrasonic transducers (CMUTs), operating in permanent contact mode. Further, the system can be used to investigate the effect of various acoustic boundary conditions the transducers are facing when mounted inside transducer port cavities and it can be used for general model validation purpose.**

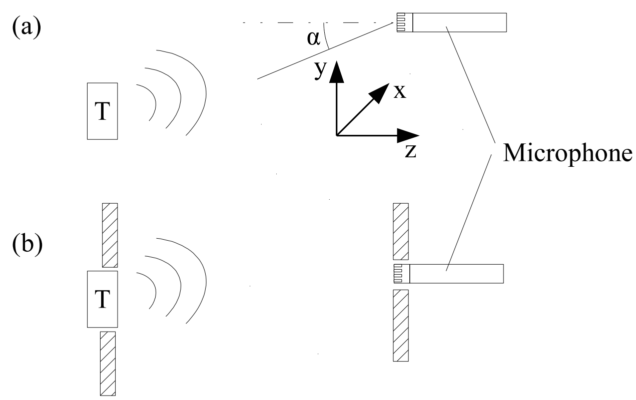

Fig. 1. Schematic of the volumetric measurement system. A microphone is used to sample a large volume in front of the transmitting transducer (T). The front face of the transmitting transducer and the microphone are kept in parallel. Depending on the acoustic boundary conditions, proper corrections about the microphone response must be applied for both (a) free-field measurements and (b) pressure response measurements with baffles.

I. INTRODUCTION

The exact knowledge of the acoustic pressure field in front of an ultrasonic transducer is essential for applications in both immersion and in air. In immersion, in addition to hydrophone measurements (see for example in [1]), various methods are available, such as light refractive tomography [2] or Schlieren-based systems [3], but these do not work in air.

Our main focus in this work is air-coupled ultrasonic transducers, such as capacitive micromachined ultrasonic transducers (CMUTs) operated in permanent contact mode [4]. Currently, CMUTs are entering the arena of gas flow metering. The optimum design of such ultrasonic gas flow meters requires exact knowledge of transducer performance in terms of acoustic beam characteristics. In particular, this is important for non-symmetric ultrasonic flowmeter configurations, as introduced in [5] and [6].

In data sheets of commercially available gas-coupled ultrasonic transducers, the information concerning the acoustic beam profile is often oversimplified. The usual method of performing these measurements is to position a microphone or a receiving transducer along a line or a few points on a semicircle at a fixed distance (far-field measurement). The result is a beam profile curve that is only valid in one plane. Certainly one can rotate the transmitter to obtain several planes to check whether the transducer features a beam profile that is axially symmetric, but this complicates the measurement procedure.

Therefore, instead of using such far-field measurements in one plane only to obtain acoustic beam profiles, we built a large 3D positioning system (Fig. 1), that allows to perform complete volumetric sound field measurements for characterizing air-coupled ultrasonic transducers. In comparison to work described in [7] and [8], our system benefits from the fact that we focus on air-coupled ultrasonic transducers in a frequency range not exceeding 140 kHz, which allows us to use a calibrated microphone, and, thus, to perform calibrated sound pressure level measurements. Further, at this frequency range the attenuation can be neglected. In comparison to [8] we also have the advantage that we only use burst signals, which allows us to calculate an expectation window for the arrival time of the main signal, and, thus, avoiding the need for an anechoic chamber.

After describing the details of the measurement system and the method we used to correct the data, we present the capability of this system by showing measurement results obtained from CMUTs, built for ultrasonic gas flow meters.

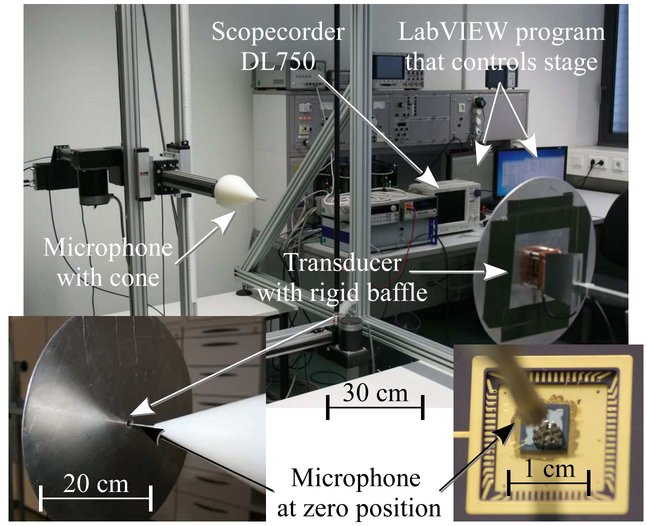

Fig. 2. Photograph of the measurement system, when configured to perform free-field measurements of a CMUT (bottom right) that operates in a rigid baffle (bottom left). The white cone has an angle of 12° and reduces standing waves between the stage and the rigid baffle.

II. Experimental Setup and Methods

The measurement system (Fig. 2) consists of high-quality components (BAHR Modultechnik, Luhden, Germany and Phytron-Elektronik GmbH, Gröbenzell, Germany). It is efficient and accurate enough to characterize a complete measurement volume (up to $1\,\mathrm{m}^3$) in front of the transmitting transducer with a spatial resolution of $50\,\mu\mathrm{m}$ in every direction.

The stage simply moves a calibrated 1/8-inch microphone unit combined with a pre-amplifier (B&K Type 4138, Skodsborgvej, Denmark) in front of the transmitter [Fig. 1(a)].

The system allows us to reproduce various cases in terms of the acoustic boundary conditions relevant for an ultrasonic flowmeter. We can add a rigid baffle or a transducer port cavity, which is typical for a ultrasonic flow meter, to the transmitting transducer. If desired, we can also add a rigid baffle to the microphone, as indicated in [Fig. 1(b)]. For the case in which we add the rigid baffle to the microphone, we measure the pressure response [9]. The microphone and pre-amplifier are calibrated to the pressure field response for the frequency range from 20 Hz up to 140 kHz. However, to eliminate any influence of ambient pressure fluctuations and audible signals we use a passive high-pass filter to suppress signals below 20 kHz. For the case without any rigid baffle at the microphone side, we can measure the free-field response, assuming the proper corrections are performed [9]. The correction concerning the free-field response is required because the microphone disturbs the sound pressure field just because of its existence in the pressure field.

Note that in our system the front face of the transmitting transducer and the microphone are kept in parallel at every location, which ensures a time efficient measurement over a large volume. However, at higher frequencies the wavelength is in the range of the aperture size of the microphone (3 mm), which requires additional correction to the data depending on the angle α (see Fig. 1) in terms of the angular response of the microphone [9].

We performed our own angular response measurements of the microphone, which were in excellent agreement with the data provided by the microphone manufacturer. Then we created a correction table for free-field response measurements, which has two input parameters – frequency and the angle α. After adding the calibration information and proper interpolation of the data, the correcting data used in our system can be visualized (Fig. 3).

The microphone signals are gathered by a digital oscilloscope (Scopecorder DL750 equipped with a high resolution module 701251, Yokogawa Electric Corporation, Tokyo, Japan). It features a sampling frequency of 1 MSa/s with a sufficient bandwidth of 200 kHz at a resolution of 16 bits at the smallest measurement division (10 mV). The measured noise level of our entire system is $75\,\mu\mathrm{V}_{\mathrm{pp}}$ without any averaging. This corresponds to a minimum sound pressure level of 73 dB SPL. The sensitivity of the microphone is 0.548 mV/Pa and the maximum possible sound pressure level that we can measure is 178 dB SPL.

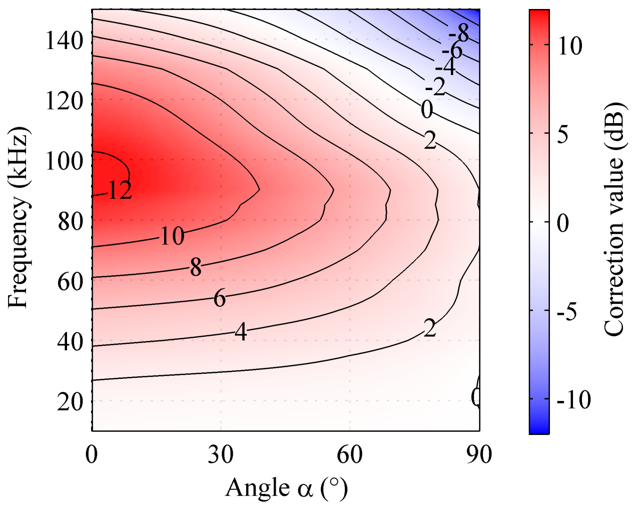

Fig. 3. Visualization of the total correction for free-field measurements. Shown is the ratio in dB between the measured pressure-response to free-field response for the B&K microphone (Type 4138).

The 3D stage is controlled by a LabView program (National Instruments, Austin, TX, USA). For every location of the volume the system requires about 1 s.

First, the DL750 is armed by a trigger signal and then the stage moves to the xyz-location. A sinusoidal burst signal from a function generator (Agilent 33120A, Menlo Park, CA, USA) is applied to the transducer and at the same time it triggers the waveform collection. Depending on the measured amplitude of the signal a rescaling of the voltage division is performed. The entire measurement process is optimized in terms of time (including using a double meander trajectory used to sample the entire volume) and vibrations of the stage.

The post processing and visualization are done in Matlab (Mathworks Inc., Natick, MA, USA). First, the measured peak-to-peak values are sorted into a grid. Then the free-field correction table (Fig. 3) can be applied to this grid, by using the known excitation frequency and location of the microphone. In the last step the sound pressure values in dB SPL can be calculated and the grid resolution can be increased by interpolation (we used an interpolation factor of four) and visualized as desired (2D-slices and 3D with a cut-off section, as shown in this work, 3D isosurfaces, etc.).

All figures presented in the next section (Fig. 4) consist of 29989 measurements locations, evenly distributed over a volume of $(92 \times 92 \times 109)\,\mathrm{cm}^3$. Every measurement runs completely autonomous overnight and takes approximately 7.5 h. At the moment the total measurement uncertainty of our system is below ±2 dB SPL.

III. Results

We used a single-cell CMUT in permanent contact mode [4], mounted on an IC-package embedded in a rigid baffle to demonstrate the capability of our volumetric measurement system (Fig. 2). This device is designed for a large ambient pressure range and the operation frequency is 108 kHz. The circular aperture size is 4 mm, resulting in an axially symmetric beam profile [Figs. 4(a, c)] with an impressive maximum sound pressure level of 126 dB SPL. Note that the a.c. excitation signal was only $10\,\mathrm{V_{pp}}$.

However, for this CMUT our volumetric measurement system revealed that when the device is pushed in terms of excitation signal amplitude and dc bias voltage, one can excite non-symmetric plate modes as well. This results in an acoustic beam profile with a maximum sound pressure level of 129 dB SPL, as shown in Figs. 4(b, d).

IV. Conclusion

These first measurement results obtained from CMUTs designed for ultrasonic gas flow meters are a good illustration why a volumetric measurement system is essential for air-coupled ultrasonic transducer characterization. This is valid for many other applications as well, such as gas-coupled phased arrays, range finding, gesture sensing, anemometers, and ultrasonic communication systems, to name a few. Another example for which this measurement system has already been proven to be very useful is the model validation of diffraction loss calculations between non-coaxial ultrasonic transducer configurations. For more details see [10]. In terms of testing the influence of the acoustic boundary conditions on both the transmit and receive side, two consecutive measurements without and with the acoustic boundary modification can be performed and then one can visualize the difference only. This will guide the procedure of designing and optimizing the transducer housings, protection grids, and the shape and depth of the transducer port cavities inside the pipe of the gas flow meter.

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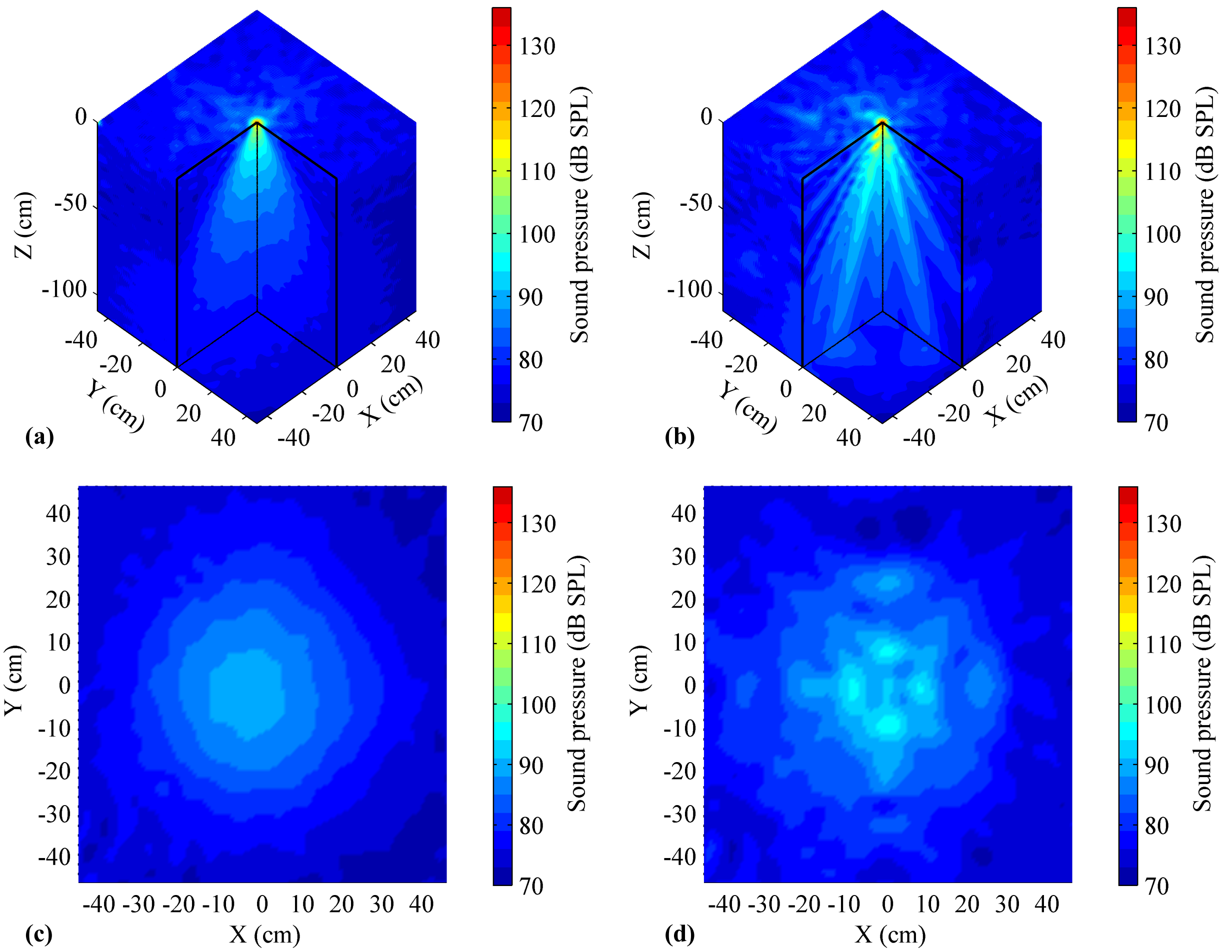

Fig. 4. Volumetric sound pressure fields (free-field, 3D with a cut-off section and 2D slices at a distance of 43 cm) produced by a CMUT in permanent contact mode mounted on an IC-package embedded in a rigid baffle. The two columns show two different measurement results corresponding to two operation modes for the CMUT. The right figure indicates a non-axial-symmetric velocity profile along the CMUT plate.

supporting us in terms of information concerning the components of the 3D system. We also thank Fluenta AS and Texas Instruments for financial support.

References

[1] M. Lenz N. Gust, M. Wolf, E. Kühnicke and T. Rödig, "Transducer characterization by sound field measurements," in *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 60, no. 5, pp. 998–1009, 2013.

[2] L. Bahr and R. Lerch, "Beam profile measurements using light refractive tomography," in *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 55, no. 2, pp. 405–414, 2008.

[3] B. Henning, J. Rautenberg, C. Unverzagt, A. Schröder, and S. Olfert, "Computer-assisted design of transducers for ultrasonic sensor systems," in *Measurement Science and Technology*, vol. 20, no. 12, pp. 1–11, 2009.

[4] M.-C. Ho, M. Kupnik, and B. T. Khuri-Yakub, "FEA of CMUTs suitable for wide gas pressure range applications," in *Proc. IEEE Ultrasonics Symposium*, pp. 1234–1237, 2010.

[5] K. S. Mylvaganam, "High-rangeability ultrasonic gas flowmeter for monitoring flare gas," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 36, no. 2, pp. 144–149, 1989.

[6] M. Kupnik, A. Schröder and M. Gröschl, "Adaptive asymmetric double-path ultrasonic transit-time gas flowmeter," in *Proc. IEEE Ultrasonics Symposium*, vol. 36, no. 2, pp. 2429–2432, 2006.

[7] J. Song and D. E. Chimenti, "Design, fabrication and characterization of a spherically focused capacitive air-coupled ultrasonic transducer," in *Int. J. Appl. Sci. Eng.*, vol. 4, no. 1, pp. 1-19, 2006.

[8] G. Benny, G. Hayward, and R. Chapman, "Beam profile measurements and simulations for ultrasonic transducers operating in air," *Journal of Acoustical Society of America*, vol. 107, no. 4, pp. 2089–2100, 2000.

[9] Brüel & Kjær, "Microphone Handbook Vol. 1," Brüel & Kjær A/S, Nærum, Denmark, 1996.

[10] R. Golinkse, M. Hoffmann, A. Gupta, and M. Kupnik, "Calculation of diffraction loss between non-co-axial ultrasonic transducer configurations," to appear in *Proc. IEEE Ultrasonics Symposium*, 2013.