The Influence of Temperature on the Frequency Dependent Directivity of Ultrasonic Transducers – An Indirect Acquisition Technique

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Abstract

Components of ultrasonic measurement devices suffer from exposition to temperature fluctuations, which influence both the speed of sound in the surrounding medium and the material properties of the ultrasonic transducer itself. A consequence may be deviations of the frequency response and the frequency dependent directivity pattern. This might have an undesirable impact, for instance, on the accuracy of flow metering devices. A conventional method for the determination of radiation patterns of water-coupled ultrasonic transducers is the scanning of the sound field with a hydrophone. Using this technique for the purpose of measuring influences of temperature would be challenging and time consuming. The required water basin, which represents a large thermal capacity, must be kept on stepwise constant temperatures. Furthermore, the hydrophone might not be designed for such conditions. The approach presented in this contribution exploits an indirect acquisition of the directivity. Instead of simulating the unknown ultrasonic transducer setup the normal velocity of the transducer surface is measured in air with a Laser-Scanning-Doppler-Vibrometer. In a second step, the acquired normal velocity serves as excitation signal for a finite-element simulation of the radiated sound field. The influence of temperature on the transducer is studied by recording the corresponding membrane vibrations while placing the transducer in a climatic chamber. The temperature dependent speed of sound of water is taken into account during simulation. For sake of validation, a comparison to hydrophone measurements at room temperature reveals good agreement of the frequency response at zero angle. The resulting directional patterns also exhibit distinctive similarities.

1 Introduction

Modern ultrasonic flow meters exhibit measurement inaccuracies lower than one percent. In order to meet the increasing accuracy requirements for the specified temperature range of $0 - 90\,^{\circ}\mathrm{C}$, efforts have been made to characterize the influences on the signal path [1]. Another important part of these sensors are the ultrasonic transducers. Their frequency dependent electrical and acoustic characteristics suffer from influences by varying temperature. Our main focus lies on the directivity pattern and the acoustic field radiated by the ultrasonic transducers. A common way of measuring the acoustic field is the utilisation of a hydrophone. Chen et al. presented an alternative non-invasive method by light refractive tomography for this task [2]. While there are many known ways to measure the acoustic field, it takes great effort to apply them to wide temperature ranges. The necessary water basin, which represents a large thermal capacity, must be kept on stepwise constant temperatures. Furthermore, a hydrophone might not be designed for such conditions.

Thus, it is desirable to develop an alternative method in order to get information on the influence of temperature variations on the frequency dependent directional pattern. The presented method is based on the temperature dependent, space and frequency resolved surface velocity measurement of the ultrasonic transducers by means of a Laser-Doppler-Vibrometry (LDV). The obtained data is used for numerical simulations based on the finite element method (FEM). Sapozhnikov et al. [3] presented an acoustic holography approach dealing with the inverse problem. Herewith, they characterized the transducer surface vibrations based on the measured sound pressure field.

After presenting our acquisition technique, we compare the results to data obtained by directly measuring the frequency dependent directional pattern with a hydrophone being immersed in a water basin. Finally, an analysis of the qualitative temperature influence on the acoustic field of the examined ultrasonic transducer is presented.

2 Indirect acquisition technique

Our approach is based on the calculation of the sound field that is radiated by an ultrasonic transducer. The analytical model of a piston type piezoelectric transducer rests on the assumption of an uniform normal surface velocity. For this simplified case, the sound pressure field can easily be calculated using Huygens' theorem by superimposing elementary waves excited from the transducer surface. Such a model is not appropriate for a real piezoelectric transducer due to the different mode structure of the excited modes of the piezoelectric disc [4]. A conceivable theoretical method for obtaining the surface velocities is a FEM-simulation of the whole transducer [5]. This was not possible in our case because the exact setup of the device was not known. Therefore, the surface velocities have to be obtained by measurement.

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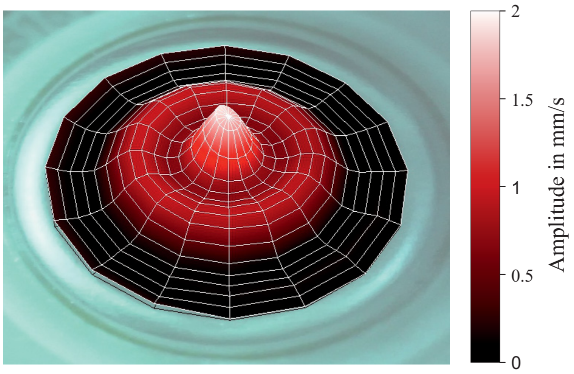

Figure 1 Magnitude of surface velocity of a piezoelectric ultrasound transducer at 1 MHz.

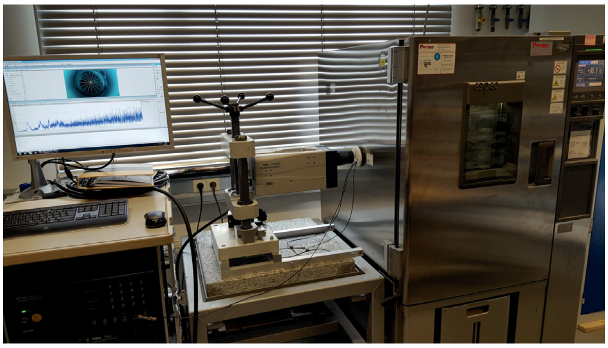

Figure 2 Picture of the measurement setup: Signal processing unit (left), scanning head (middle) and climate chamber (right).

2.1 Measurement of temperature dependent surface velocities

For the acquisition of the surface velocities, a Laser-Scanning-Vibrometer (LSV) *PSV-500 (Polytec, Germany)* was utilized. With this measurement device, it is possible to scan the active surface of the transducer in order to determine the surface normal velocity $\underline{v}_n(r, \vartheta, f)$ in the frequency-domain. The obtained values depend on the location in cylidrical coordinates r and ϑ and on the frequency f. By acquiring complex values, the phase information is preserved. The chosen setup results in a focal point with 19 µm diameter and 430 µm depth. The transducer was excited by a linear frequency-sweep using the function generator provided by the LSV. **Figure 1** visualizes the magnitude of the surface vibration of the examinated transducer for a frequency of 1 MHz.

This work intends to study the influence of temperature. Therefore, the tested transducer was placed inside a climatic chamber. By inserting a window, which was highly transparent for the wavelength of the vibrometer laser, into the housing of the climatic chamber, reasonable signal levels of the laser could be obtained while keeping the LSV outside the chamber. The temperature was brought stepwise to measuring points between 0 – 100 °C, while keeping dry conditions inside the chamber. The measurement setup consisting of the LSV and the climatic chamber containing the device under test is shown in **Figure 2**.

Attention should be payed to the fact that the described setup, measuring the surface velocities in air, does not match the conditions of a immersed transducer. The surface load differs significantly due to the constraining acoustic impedance of water and air. The model represents a weak coupling between structural vibrations and the acoustic field. We expect, however, a representative behavior regarding temperature changes. This assumption will be supported by a comparison to a conventional measurement and allows qualitative conclusions.

2.2 Calculation of the directivity pattern

A numerical finite element simulation is set up for the calculation of the radiated sound field. The model for the tested transducer is 2D axially symmetric. This assumption can be made because geometry and the measured mechanical vibrations of the transducer surface (compare **Figure 1**) exhibit this same symmetry. In order to be able to use the measured velocities as excitation for the model, the dimension of the data has to be reduced. For this purpose, the normal velocities are averaged over the angle coordinates ϑ. In discrete form, this gives

$$\bar{\underline{v}}_n = \frac{1}{N}\left(\sum_{i=1}^{N} \mathrm{Re}\,\underline{v}_n(\vartheta_i) + \mathrm{i}\sum_{i=1}^{N} \mathrm{Im}\,\underline{v}_n(\vartheta_i)\right) \qquad i = 1,\dots,N. \tag{1}$$

One boundary line of the FE-model corresponds to the transducer active area, to which the averaged velocities are remapped. The measured values are assigned as an inhomogenous Neumann-boundary condition to the nodes of this meshed line. All other transducer surfaces are defined as acoustically hard boundary conditions. The meshed area is a quadrant with the radius exceeding the near sound field range. All boundaries other than that related to the transducer are set to absorbing boundary conditions in order to model free-field media. Hence, only the surrounding water is modeled by the simulated domain.

For this acoustic simulation, the only necessary material properties are the density and the longitudinal sound velocity of water. The second parameter varies significantly with temperature and is adjusted according to [7]

$$c(T_W) = 1402.736 + 5.03358\,\mathrm{T}_W - 0.0579506\,\mathrm{T}_W^2. \tag{2}$$

Harmonic simulations are performed for a frequency range of 0.5 – 3 MHz and for the temperature range of 0 – 100 °C. As our main focus is on the directivity pattern, only sound pressure values $\underline{p}$ on an arc with radius greater than the near sound field range and centered over the active surface are saved as output of each simulation step. From these gained sound pressure values, the spectral power density S

$$S = \frac{1}{f_s N}\left|\underline{p}\right|^2 \tag{3}$$

with the sampling rate f_s and the number of samples N is calculated. This spectral power density is determined for each angle and each temperature. **Figure 3** displays the colour coded spectral density resulting from simulations for the temperature $T = 20\,°\mathrm{C}$.

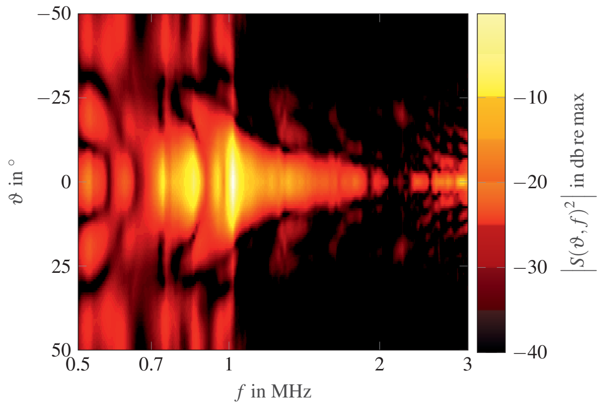

Figure 3 Simulated spectral power density S over frequency f and angle ϑ in logarithmic presentation with respect to the absolut maximum at $T = 20\,°\mathrm{C}$.

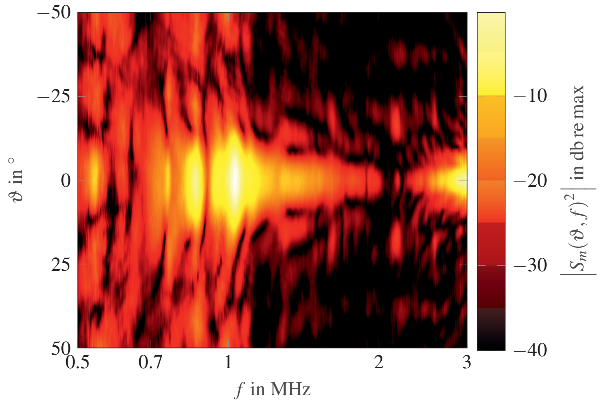

Figure 4 Measured spectral power density S_m over frequency f and angle ϑ in logarithmic presentation with respect to the absolut maximum at room temperature ($T \approx 20\,°\mathrm{C}$).

3 Comparison of the indirect acqusition against a conventional method

For the verification of the presented method, we examined the same ultrasonic transducer by conventional methods at room temperature. For this purpose, a hydrophone *HGL-400 (Onda, USA)* was fixed in a basin filled with pure water. The piezoelectric transducer was mounted to a traversing unit in order to align its symmetry axis with the sensing surface of the hydrophone. The distance between hydrophone and transducer was ensured to be greater than the near sound field range. An additional turning unit was used to rotate the piezoelectric transducer around its active surface.

The transducer was excited by a function generator with the same frequency sweep as for the measurement of surface velocities. An oscilloscope *DPO 7104C (Tektronix, USA)* was used to capture the amplified hydrophone signal. By scanning angles in the range of $\pm 50°$ in steps of $1°$, we obtained sound pressure data for the calculation of the

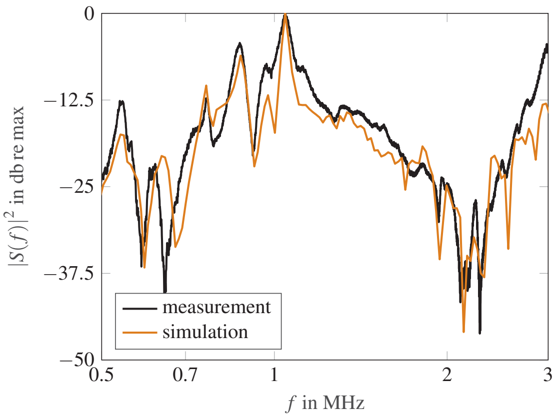

Figure 5 Comparison between the spectral power density of the simulation and a measurement by hydrophone for $\vartheta = 0°$ and $T \approx 20\,°\mathrm{C}$. Each graph is normalized to its maximum.

directivity pattern. After Fourier transform and applying Eq. 3, the measured spectral power density S_m is attained. For a visual comparison to S shown in **Figure 3** S_m is presented alike in **Figure 4**.

As the comparison of these two figures demonstrates, many details from the hydrophone measurement can also be found in the indirectly acquired picture. Nevertheless, differences begin to grow with increasing angles. Additionaly, the measured data is more noisy.

By comparing the spectral power densities at room temperature and $\vartheta = 0°$ (see **Figure 5**), the two graphs fit quite well for frequencies less than 2.5 MHz. However, the main resonance at 1 MHz is noticeable more narrowband for the simulation. This might be an effect of the dry measurement of the surface velocities.

4 Results

Indirect acquisition of the frequency dependent directivity pattern for a set of temperatures leads to a three dimensional data set for the sound pressure $\underline{p}(\vartheta, f, T)$. The results exemplified here refer to the main resonance at 1 MHz for the specific studied piezoelectric transducer. Other devices may exhibit a totally different behavior. Therefore, we keep our results briefly.

An interesting issue was the temperature dependency of the resonance. Hence, we examined the frequency and amplitude of the maximum at the named resonance. A decreases by 15 kHz over the whole temperature range was observable. The amplitude at this resonance also exhibits a temperature dependency. It has its maximum at 30 °C. For higher as well as lower temperatures, the amplitude is decreased at most by 50 %.

Another considerable effect is the dependency of the directivity pattern on temperature. **Figure 6** depicts this for the main resonance. The directivity pattern is plotted over the y-axis, the x-axis corresponds to the temperature. The sound pressure amplitude is scaled by its maximum for each temperature step and is displayed in logarithmic scale.

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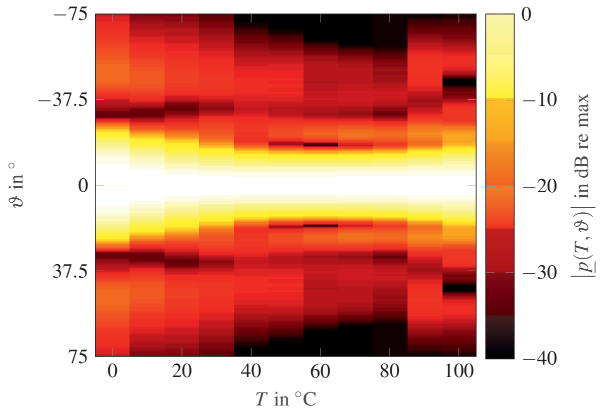

Figure 6 Influence of temperature on the directivity pattern for the main resonance $f = 1\,\text{MHz}$.

Evidently, the main lobe as well as the sidelobes become more narrow for rising temperatures until about 70 °C.

5 Conclusion

The presented method for the acquisition of the frequency dependent directivity pattern was motivated by the need to investigate the influence of temperature deviation. Measuring the surface normal velocities of the active membrane of the investigated transducer is crucial for this approach. We described a corresponding experimental setup under temperature influence. This data is used for numerical simulations of the acoustic field. We compared the results of the calculated frequency dependent directivity pattern to common measurements at room temperature and briefly presented results for the tested ultrasonic transducer.

The indirect acquisition technique is capable of providing qualitative statements of the temperature dependent directivity pattern, but could not bear the quantitative comparison with a direct hydrophone measurement in case of the tested ultrasonic transducer. Sources of error are the measurement of surface velocities under dry conditions, which causes a differing acoustic impedance and the assumption of axial symmetry of the surface vibration. Nevertheless the presented technique is able to provide qualitative information about temperature dependencies where the appliance of common methods is challenging. Other examples for use cases may be transducers employed in adverse media like oil or acid, which do not allow the use of hydrophones.

An additional benefit is the short time needed to measure the surface velocity by means of laser scanning vibrometry compared to measuring the directivity pattern utilizing a hydrophone, turning the transducer mechanically. This might be especially advantageous for air coupled ultrasound transducers as the error of measuring under altered conditions is elimated in this case.

6 Literature

[1] Bezdek, M.: A boundary integral method for modeling sound waves in moving media and its application to ultrasonic flowmeters, phdthesis, Friedrich-Alexander-University Erlangen-Nuremberg, 2006

[2] Chen, L. , Rupitsch, S. J., Lerch, R.: Application of light refractive tomography for reconstructing ultrasound fields in various media, tm-Technisches Messen Plattform für Methoden, Systeme und Anwendungen der Messtechnik 79.10 2012, pp. 459-463

[3] Sapozhnikov, O. A., Morozov, A. V. and Cathignol, D.: Piezoelectric transducer surface vibration characterization using acoustic holography and laser vibrometry, IEEE Ultrasonics Symposium, 2004, pp. 161-164 Vol.1.

[4] Delannoy, B., Bruneel, C., Haine F. and Torguet, R.: Anomalous behavior in the radiation pattern of piezoelectric transducers induced by parasitic Lamb wave generation, J. Appl. Phys., vol. 51, no. 7, 1980, pp. 3942-3948

[5] Kaltenbacher, M.: Numerical simulation of mechatronic sensors and actuators. Finite elements for computational multiphysics. 3rd ed., Heidelberg, New York, Dordrecht, London: Springer, 2015

[6] Krautkrämer, J., Krautkrämer H.: Werkstoffprüfung mit Ultraschall, 5th ed., Springer, Berlin, Heidelberg, 1986

[7] Marczak, W.: Water as a standard in the measurements of speed of sound in liquids, J. Acoust. Soc. Am. 102(5), 1997, pp. 2776-2779

