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Airborne Ultrasonic Transducers for Ultrasonic Transmission Tomography in Gaseous Media

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ABSTRACT

Ultrasonic transmission tomography is one of the measurement methods used for imaging of internal structure of various media. The method can be used in gaseous media, e.g. to identify the shape, size and location of objects, to determine the spatial distribution of temperature in a studied area (if here is a heterogeneous field of that quantity) and to determine concentration of components of selected binary gas mixtures. The non-invasive nature and short duration measurement process are the great advantages of this method. All applications of the method in gas media it is necessary to use suitable ultrasonic transducers intended for operation in a gaseous medium in the frequency band of 20 kHz – 100 kHz, that generate cylindrical wave.

The paper presents the designed ultrasonic transducers constructed using piezoelectric film. They are capable of generating cylindrical wave at the frequency f = 31.5 kHz, f = 63 kHz and f = 90 kHz and are intended to work in gaseous media. The focus is on electromechanical model of transmitting and receiving transducer and the properties of EMFi film and powering systems (using burst type signal) are taken into consideration. It also presents the results of measurements of characteristics of directivity of transmitting transducers and the results of measurements performed using those transducers operating as ultrasonic wave receivers. Additionally, examples of applications of ultrasonic transmission tomography in gaseous media are presented.

INTRODUCTION

Generation of ultrasonic waves in gaseous media requires the use of special ultrasonic transducers that guarantee sufficient level of generated signals when transmitting and proper voltage sensitivity when receiving. In low ultrasonic frequencies range (20 kHz ÷ 50 kHz), when generating high levels of pressure, a metal plate is usually used as a source for ultrasonic waves. The plate is transverse vibrated by means of a piezomagnetic transducer or a piezoelectric sandwich type one [1]. Those transducers are predominantly used as transmitters. In 50 kHz ÷ 100 kHz frequency range they are usually piezoceramic transducers using radial vibrations. On the flat surface of the transducers there is a layer matching high acoustic impedance of piezoelectric ceramics to low acoustic impedance of the gaseous medium [2]. The transducers generate a plane wave. In order to generate other types of waves (cylindrical, spherical) it is necessary to use sources that are designed to produce the required wave shape directly.

In ultrasonic transmission tomography used e.g. to identify the shape, size and location of objects [3] or to determine the spatial distribution of physical parameters of gases (temperature distribution, determining concentration of components of selected binary gas mixtures [4]) in divergent ray beam geometry it is best to use cylindrical wave.

PIEZOCERAMIC TRANSDUCERS FOR CYLINDRICAL WAVE GENERATION

One of the ways to generate cylindrical wave is to use radial vibrations of a thickness-polarized piezoceramic disc with a ring-shaped matching layer located on the side of the disc. This solution makes it possible to generate ultrasonic waves in the frequency range of 30 kHz ÷ 100 kHz. However, because there is a limit to how much the disc's thickness and consequently the emitting surface can be increased, it cannot be used when a large emitting surface is required. It is also possible to use a cylindrical piezoceramic transducer (ring-shaped) with a matching layer on the outside of the cylinder. This solution, however, is especially troublesome in higher ultrasonic frequency range, due to thin sides of piezoceramic material. A solution originating from hydroacoustics, where the piezoceramic ring is placed inside a metal ring [5,6,7] is not suitable for use in case of transducers operating in gaseous media.

CYLINDRICAL TRANSDUCERS CONSTRUCTED USING PVDF PIEZOELECTRIC FILM

Transducers constructed using PVDF film are commonly used both in audible frequency range and ultrasonic frequency band [8]. PVDF film can be formed freely – it is also possible to produce a source generating cylindrical wave by attaching the film correctly to a round core. Since PVDF film is characterised by a high temperature coefficient ($103 \cdot 10^{-6}$

$^{o}C^{-1}$), it cannot be permanently fixed (e.g. glued) to the surface of the core. Temperature increase would cause its deformation. Additionally, if the film is exposed to an external electric field, the vector of which is normal to surface plane, its length changes. If the film is glued to some parts of the surface (e.g. edges), the radius of the cylinder made of the film will change, after it is exposed to electric field. The film will acts as an membrane radiating energy in radial direction. As the film has certain mass and mechanical susceptibility, a mechanical setup is created, the resonant frequency of which depends on film thickness, radius and height of the cylinder [8]. Since radius value is similar to the length of the wave in resonance, radius increase can have various phase for various distances from the source (film acts as a membrane). Therefore the signal coming from the cylinder will be much shorter than in the case when the film's length does not increase.

TRANSDUCERS CONSTRUCTED USING EMFI FILM

EMFi piezoelectric film was used to construct a transducer generating cylindrical wave. This film has a cellular structure: the internal part of the film has porous structure consisting of a lot of layers of polypropylene with air between them [9]. This structure results in the film's low acoustic impedance, which makes it a very good material for construction of ultrasonic transducers intended for operation in a gaseous environments. The electromechanical film model presented in works [10,11] can be used to determine both effectiveness and sensitivity parameter of the film. In an electromechanical model of a transducer acting as a transmitter it was assumed that the transducer is operating using thickness vibrations; a change in film thickness Δx caused by external voltage ΔU is the source of vibration of a arrangement consisting of a lot of layers of polypropylene and air. If changes in the thickness of individual layers is taken into consideration (assuming for purposes of simplification that the layers are identical), the effectiveness of the transmitting transducer S_T is determined by the following dependence [10]:

$$S_T = \frac{\Delta x}{\Delta U} = \frac{x_0}{Y} \frac{B - \varepsilon_p (\sum_{j=1}^{n} x_{ij}\sigma_{ij} \sum_{j=1}^{n+1} x_{pj})(\sum_{j=1}^{n} x_{ij})^{-1}}{(\sum_{j=1}^{n+1} x_{pj} + \varepsilon_p \sum_{j=1}^{n} x_{ij})^2} , \qquad (1)$$

$$B = \varepsilon_0 \varepsilon_p^2 U + \varepsilon_p x_{pp1} \sigma_{p1} + \varepsilon_p x_{pp2} \sigma_{p2} , \qquad (2)$$

gdzie: x_0 – initial thickness of the film,
Y – Young's modulus,
ε_0 – vacuum permittivity,
ε_p – permittivity of polypropylene,
ε_g – permittivity of gas,
σ_{ij} – charge density on individual layers,
σ_{p1}, σ_{p2} – charge density on the surface of the film,
x_{ij} – thickness of individual layers,
x_{pp1} , x_{pp2} – average depths for surface charge.

A model of a transmitting transducer with numerous layers of gas can be substituted with a model with one gas layer, the total thickness of which is equal to the thickness of the multilayer model. Effective charge density σ_{eff} is charge density in the position where polypropylene and gas meet. Equations for the effectiveness of a transmitting transducer and the sensitivity of a receiving one are identical, which points to linear relation between both models [10].

THE STRUCTURE OF A SENDING-RECEIVING TRANSDUCER MADE OF EMFI FILM

Figure 1 shows the structure of a transducer generating cylindrical wave.

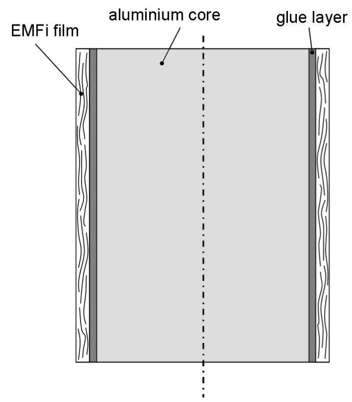

Figure 1. The structure of a sending-receiving transducer

The transducers were constructed using EMFi film made by EMFi Ltd. The film, covered with aluminium on one side, was glued with a conductive adhesive to a cylinder shaped aluminium core on the side that has no metal plating. Displacement Δx depends on the number of layers and the volume of the air accumulated between them.

The three types of transducers varying in height and diameter were constructed. The dimensions of individual cores, to which the film was glued, are shown in Table 1.

Table 1. The dimensions of aluminium cores

Core number	Core diameter [mm]	Core height [mm]
1 and 2	22	27
3 and 4	30	20
5 and 6	50	12

The diameters and heights of the cores were suitably selected to allow experimental verification of the theory presented in study [12].

Figure 2 shows the constructed transducers.

Figure 2. Transducers constructed using EMFi film

The transducers are powered by a voltage amplifier, the frequency characteristics of which are shown in Figure 3.

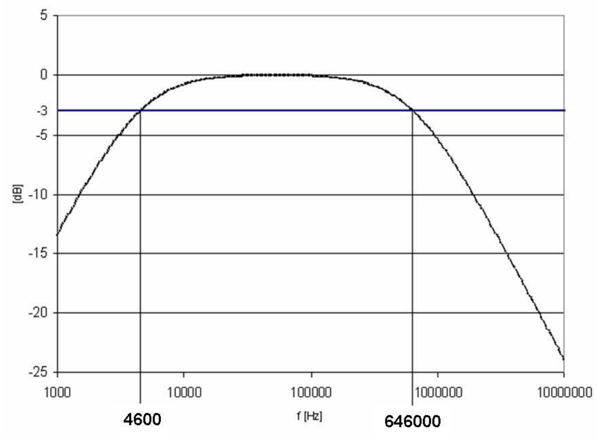

Figure 3. Frequency characteristics of a voltage amplifier

The measurements of acoustic pressure in the function of the distance from the transducer were performed by activating the transducer with a burst type signal with U = 300 V_{pp}, t = 160 µs duration and 2 ms intervals between the pulses. Figure 4 shows an example of characteristics of pressure level in the function of distance from the transducers operating at f = 63 kHz frequency.

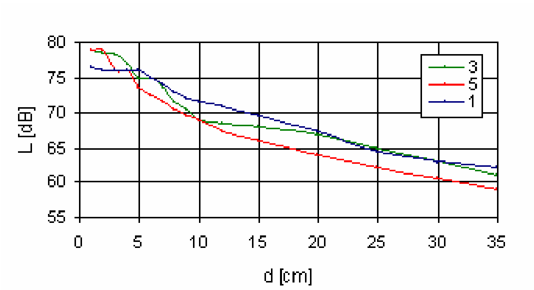

Figure 4. Characteristics of pressure level in the function of distance for f = 63 kHz

Figure 5 shows frequency characteristics of the designed transducers in 30 kHz ÷ 90 kHz frequency range.

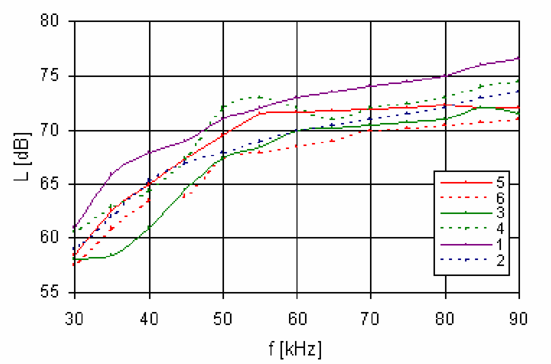

Figure 5. Frequency characteristics of the designed transducers

Figures 6 ÷ 8 show voltage characteristics of transducers No.2, No.4 and No.6 operating at f = 31.5 kHz, f = 63 kHz and f = 90 kHz frequencies.

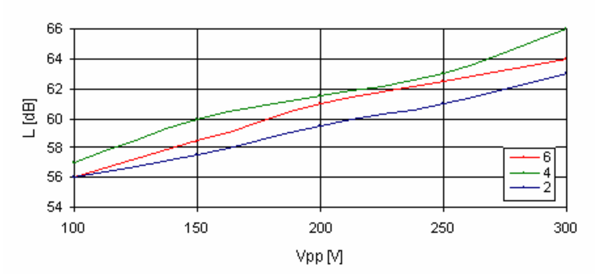

Figure 6. Voltage characteristics of the transducers for f = 31.5 kHz

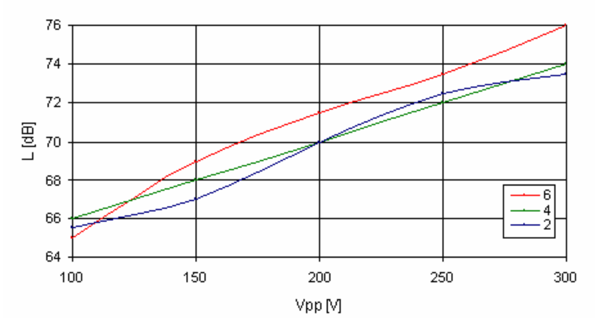

Figure 7. Voltage characteristics of the transducers for f = 63 kHz

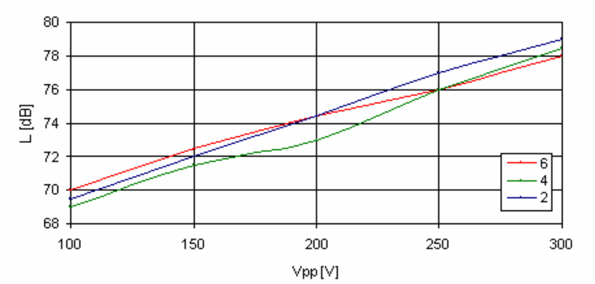

Figure 8. Voltage characteristics of the transducers for f = 90 kHz

The measurements of directivity characteristics were preformed for the voltage of U = 300 V_{pp} and three types of transducer activating signals:

- burst type signal with f = 31.5 kHz frequency and t = 320 µs pulse duration,
- burst type signal with f = 63 kHz frequency and t = 160 µs pulse duration,
- burst type signal with f = 90 kHz frequency and t = 100 µs pulse duration.

Examples of directivity characteristics of transducer No.1 for the above mentioned parameters have been shown in Figures 9 ÷ 11.

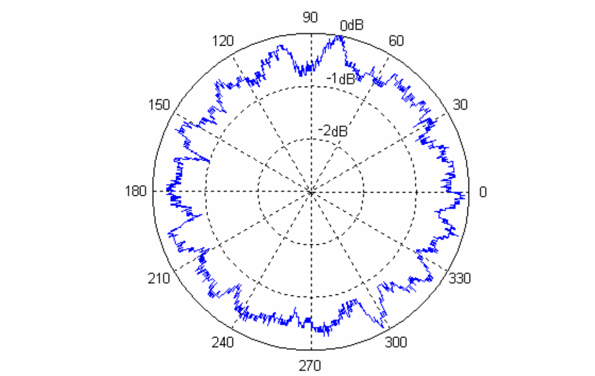

Figure 9. Directivity characteristics of transducer No.1 for f = 31.5 kHz frequency

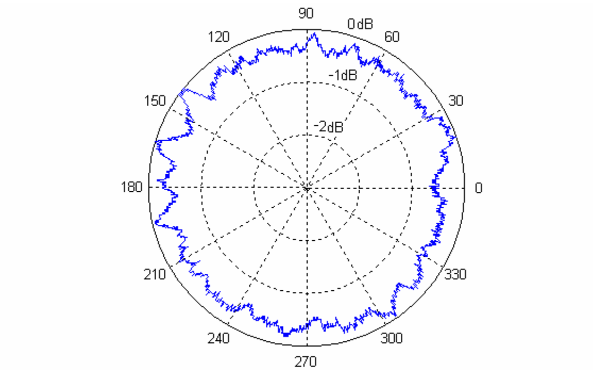

Figure 10. Directivity characteristics of transducer No.1 for f = 63 kHz frequency

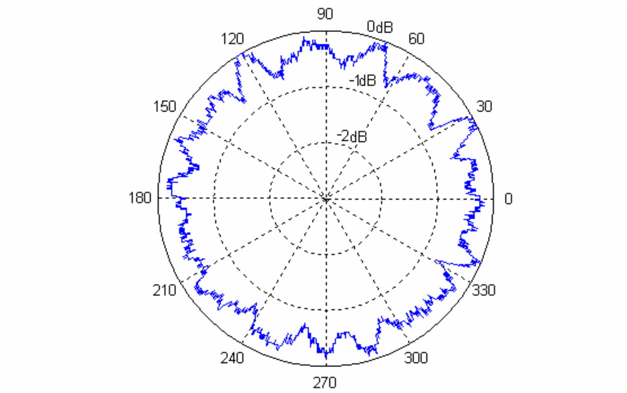

Figure 11. Directivity characteristics of transducer No.1 for f = 90 kHz frequency

To check sensitivity of the transducers acting as receivers the autors measured the level of pressure for the studied transducers related to the level of voltage on a standard microphone in accordance with the following dependence:

$$\Delta L = L - L_{mic} \ , \qquad (3)$$

where L is the level of pressure dBu for the studied transducers and L_{mic} is the level of voltage dBu on the standard microphone. Figure 12 shows the difference of voltage levels on the output of the standard microphone and transducers No.1, No.3 and No.5 at the distance of 10 cm from the source in the function of amplitude of sinusoidal voltage (continuous wave) U_{sup} powering the source, which is operating in air environment at 37.55 kHz frequency.

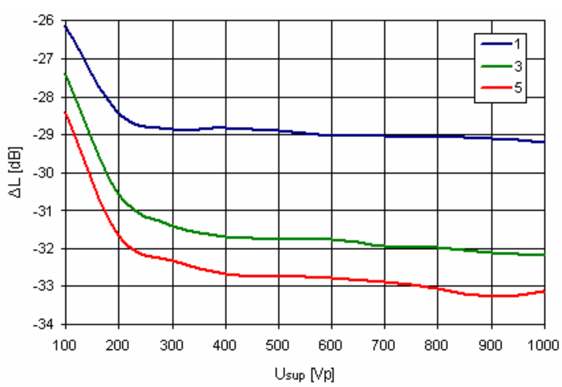

Figure 12. Relative difference of the levels of voltages of transducers (No.1, No.3 and No.5) and a standard microphone in the function of amplitude of sinusoidal voltage powering the source.

AN EXAMPLE OF USING TRANSDUCERS IN ULTRASONIC TRANSMISSION TOMOGRAPHY

As mentioned at the beginning of this work, in most applications of ultrasonic transmission tomography in visualisation of the distribution of certain physical parameters it is the best practice to use cylindrical wave. Figure 13 shows an example of using the designed transducers in a transmission tomograph setup to visualise the distribution of the flow of the mixture of air and helium in a duct [13]. A similar tomograph setup was used to measure the distribution of the flow of hot air in an axisymmetrical duct [4].

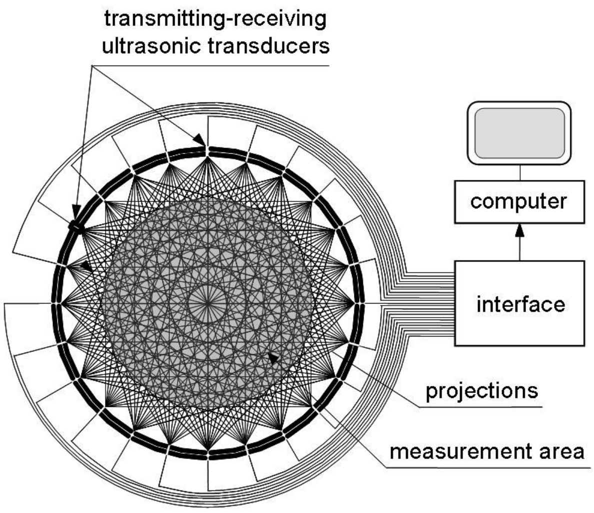

Figure 13. Ultrasonic transmission tomograph measurement setup

The measurement component of the tomograph consists of 24 ultrasonic transducers operating at f = 90 kHz frequency and situated on the perimeter of a circular duct. The transducers are a source of cylindrical wave when transmitting and ultrasonic signal detectors when receiving. Due to large differences in propagation velocity of ultrasonic wave in helium and air (sound velocity in 0 ^{o}C in helium is c = 965 m/s and in air it is c = 331 m/s) it is possible to detect even small amounts of this gas in air. By measuring local changes of the values of one or more parameters of ultrasonic wave in the area between the sending and receiving transducers located on the perimeter of the measurement duct it is possible to obtain a spatial distribution of those parameters in the studied area. The measurements of ultrasonic wave propagation velocity in homogeneous mixture of air and helium for 21 ^{o}C showed that even comparatively low volume fraction of helium in air results in easily noticeable changes of velocity in the mixture.

Figure 14 graphically presents the results of reconstruction of an image obtained as a result of a measurement of local values of sound velocity on a path between individual transducers on the whole surface of the measuring duct. The dark area on the 2D image and the highest point on the 3D image correspond to the measured maximum sound velocity value c_{max} = 891 m/s; this velocity is reflected by the volume fraction of helium in air, which is about 95 % [13].

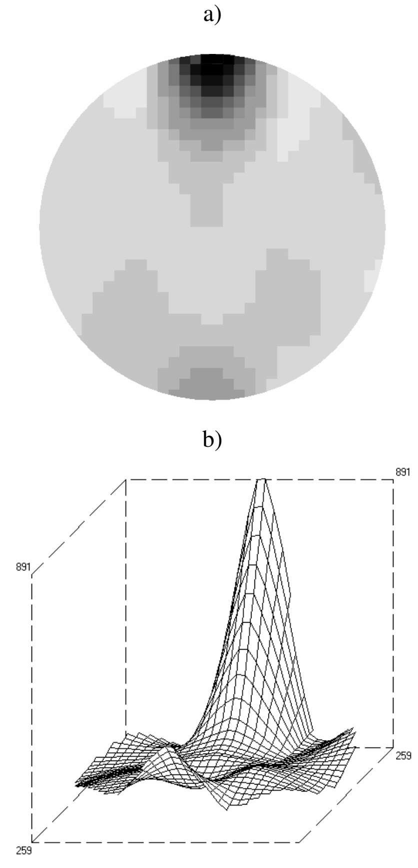

Figure 14. Reconstruction of the image of the flow of helium in a duct [13]: a) in grey scale, b) in pseudo-3D

CONCLUSIONS

The designed transducers made of EMFi film are characterised by regular distribution of pressure level around the transducers operating in 30 kHz ÷ 90 kHz frequency band. The maximum difference in pressure levels in $0^o \div 360^o$ angular range is not higher than 1 dB and may result from unevenness of the adhesive layer between the film and the metal core. The obtained pressure levels at the voltage power of $U = 300\ V_{pp}$ are definitely satisfying. According to the information provided by the manufacturer of EMFi film, voltage of up to 600 V_{pp} will not cause damage to the film, which means it is possible to obtain much higher pressure levels.

During fabrication of the transducers, gluing the film to the aluminium core evenly was the most problematic aspect. The quality of this glue joint affects both the shape of directivity characteristics and the regularity of sensitivity on the whole cylindrical surface of the transducer.

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