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RESEARCH PAPER

Piezoceramic Element Design and Fabrication for Ultrasonic Transducer of Gas Meter

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Abstract

Ultrasonic transducers play a significant role in generating and receiving the acoustic waves in ultrasonic flowmeters. Depending on the required accuracy, the ultrasonic transducers can be installed either in one pair or more in an ultrasonic flowmeter. The main part of an ultrasonic transducer is its piezoceramic element. In this work, four piezoceramic elements with different diameter to thickness ratio were fabricated and one of them with center frequency of 200 kHz was selected for the numerical simulations. The piezoceramic element and its gaseous propagation environment were simulated numerically using the finite element method. Similar to the experiments, air was considered as the propagation medium and PZT-5H was used as the piezoceramic element. The results showed that the numerical simulation is in good agreement with the experimental data which indicates that numerical simulation could be an efficient alternative way to reduce trial and errors. It leads to good results if reasonable assumptions are used.

Keywords:
Experimental Fabrication,
PZT-5H Reactor,
Simulation,
Ultrasonic Flowmeter,
Ultrasonic Transducers

Introduction

Gas flow measurement has always been a key requirement in all industrial operations including natural gas distribution, compressed air systems, air conditioning, and process control. Ultrasonic flowmeters are one of the fast-growing technologies in these fields [1,2]. In ultrasonic flowmeters, acoustic waves would be used to determine the velocity, and consequently the flow rate of a fluid flowing in a pipe. Since the first multipath gas ultrasonic meters were introduced in the early 1990's, they have now become the preferred technology for most custody transfer and non-custody transfer installations on all 5 continents. These flowmeters feature high accuracy and reproducibility. Moreover, containing no moving parts, it does not create extra pressure drop and allows bi-direction measurement. Finally, this system can be conveniently maintained on-line without interrupting the fluid transport. Thus, the ultrasonic flowmeters have been more and more widely applied in the general field of process monitoring, measurement and control [3-5].

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The transit-time method can be divided into two techniques: invasive and non-invasive. In contrary with non-invasive measurement technique, the invasive measurement technique involves the use of transducers which are in contact with the flowing fluid, as shown in Fig. 1 [6]. Ultrasonic transducers are usually crucial parts of ultrasonic measurement instruments of any kind, therefore, the radiated sound field, response functions and vibration of such transducers are therefore important parameters in the design of ultrasonic measurements instruments [7].

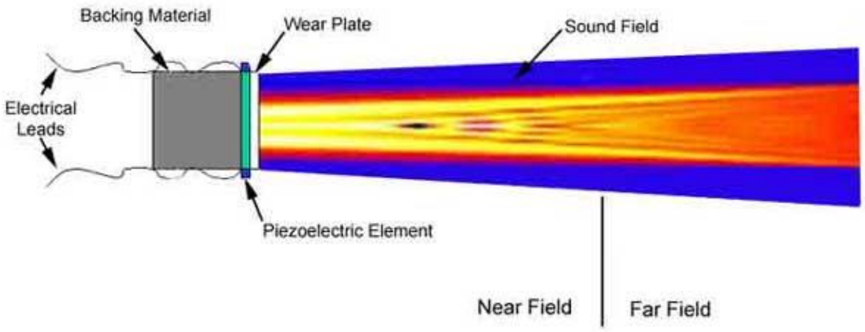

Fig. 1. The internal components of an ultrasonic transducer along with the generated wave [8]

Ultrasonic transducers play a significant role in generating the acoustic waves. The advances in numerical simulations, electronics, signal processing and ultrasonic meter software have made possible certain developments in ultrasonic transducers. This has shown that to optimize performance in all the different conditions where gas and liquid ultrasonic meters are now being applied, one transducer will no longer provide the industry with the best solutions to fit all applications.

An ultrasonic transducer represents a layered structure as shown in Fig 1. The basic component of a transducer is piezo crystal which converts the electrical energy into mechanical (acoustic) energy and vice versa. In order to support the piezo crystal, a backing plate is used at the back of the piezo crystal. One or more front layers can be used to improve the power transmission between the piezo crystal and the propagating fluid. These layers also act as wear protection plates for a piezo element.

Traditionally, the design of an ultrasonic transducer is normally accomplished via established "rules of thumb" and fundamental theoretical understanding. Today, however, numerical simulations are used to design ultrasonic transducers.

It is a common practice to analyze the vibration characteristics of the piezoelectric disk through one-dimensional analytic models. These one-dimensional models assume that the piezoelectric disk vibrates in thickness extensional mode and behaves like the motion of a piston. They are applicable to a piezo disk with diameter to thickness (d/h) ratios greater than or around 20. This is due to the fact that under such geometrical constraint, the vibration characteristic related to the thickness extensional mode becomes dominant. However, many designers employ the disc with the d/h ratios much less than 20 due to the space limitations in their design. In these cases, the use of the finite element method to analyze the vibration characteristics of a piezoelectric disc becomes indispensable. It implies that the one-dimensional models are no longer adequate to completely analyze the performance of an ultrasonic transducer. It is, therefore, necessary to analyze the piezoelectric transducer using a complete three-dimensional model.

The finite element method (FEM) has a great flexibility to analyze the piezo element disc independently and with the layered structured inside an ultrasonic transducer. Concerning fluid-borne sound, Eccardt et al. [9], used FEM for simulating sound wave propagation in timeindependent mean flows. This finite-element formulation relies on the work of Pierce [10] who derived an approximate but concise wave equation for a moving in-homogeneous fluid with the flow that varies both in position and time. An alternative finite-element approach was demonstrated by Astley [11] for irrotational mean flows.

In this work, in order to compare the simulation results with corresponding experimental results, a piezoceramic element and its gaseous propagation environment was simulated numerically. The simulation includes electro-mechanical and acoustical simulations.

Fabrication of Piezoceramic

Four piezoceramic elements of PZT-5H with different diameter to thickness ratios of 1.38, 1.35, 122 and 0.98 were synthesized as the heart of the transducers. PZT-5H as a “soft” kind of piezoceramics possess high permittivity and electromechanical coupling factor [12].

At first PZT-5H powder was pressed to form raw piezoceramic elements with the different sizes. After that, they were sintered at up to 1150 °C. Fig. 2 shows the forming and sintering process for fabrication of piezoceramic element. The elements were formed using suitable molds and sintered using an electric furnace.

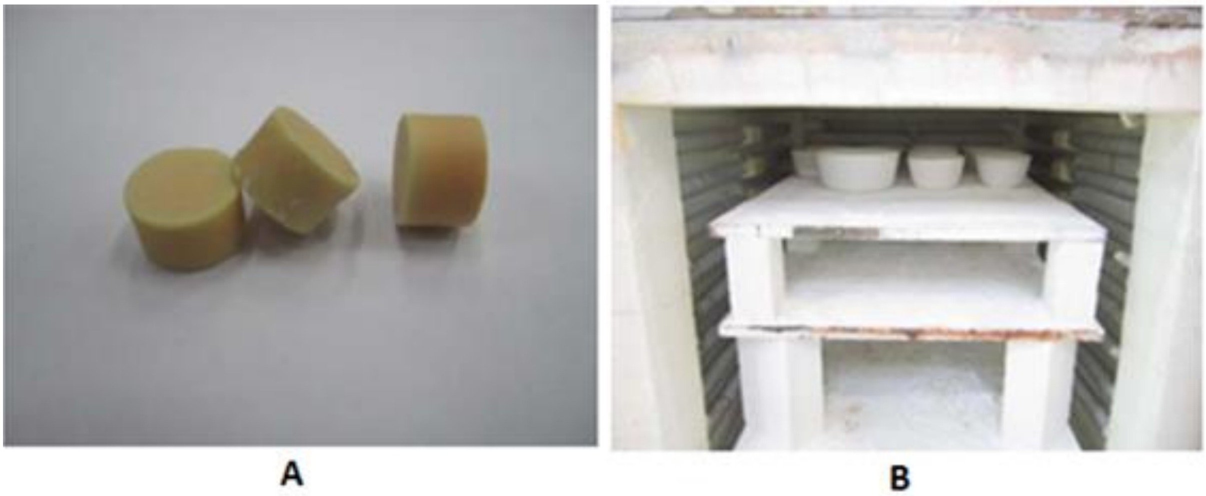

Fig. 2. A) Forming and B) sintering process for the piezoceramic elements

Furthermore, the sintered piezoceramic elements were polished to gain the exact size and flat surface. Finally, the two surfaces of the piezoceramic element were silver coated, to be their electrodes.

In order to measure electrical impedance-frequency curves of the piezoceramic elements and ultrasonic transducers, Wayne Kerr ZGA5920-Impedance/Gain-Phase Analyzer were used. Also, a PM3500 d33 meter was used to measure constants for the piezoceramic elements. Fig. 3 shows the setup for measurement of a piezoceramic constants.

Mathematical Modeling

The modeling procedure is divided into two stages: 1) solid mechanics modeling, 2) pressure acoustics modeling. The first stage was modeled using electromechanical modeling of linear piezoelectric material and the second stage was modeled using wave equation in a gaseous medium.

Solid Mechanics Modeling

The dynamics of the piezoelectric and linear elastic materials are determined from Newton's second law:

$$\rho \frac{\partial^2 u}{\partial t^2} = \nabla \cdot S \tag{1}$$

where ρ the mass density of the piezoelectric material and S is is the strain tensor. With the assumption of small deformations, the mechanical properties of a piezoelectric can be described as a linear-elastic material. The stress-charge form of the electromechanical constitutive equations for linear piezoelectricity are given as follows [13,14]:

$$T = c_E S - eE \tag{2}$$

$$D = e^T S + \varepsilon_S E \tag{3}$$

flux density vector, E is the electric field vector, c_E is the elasticity matrix (evaluated at a constant electric field), e is the piezoelectric stress matrix and ε_S is the dielectric matrix (evaluated at constant mechanical strain).

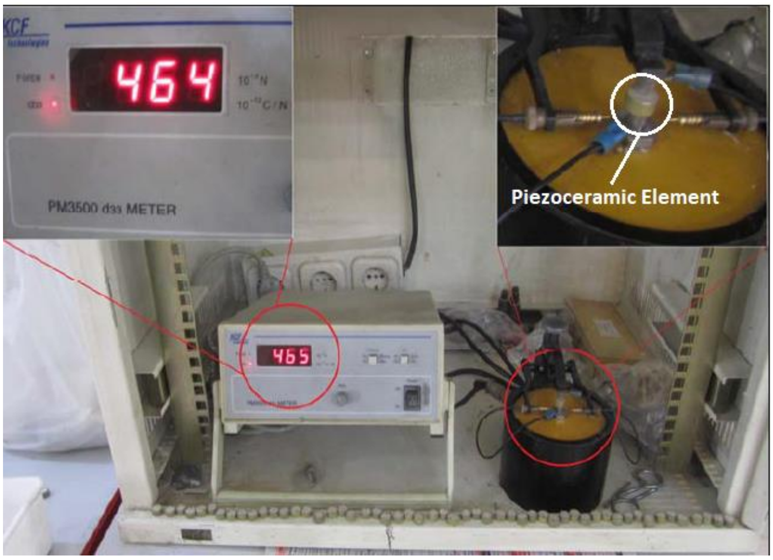

Fig. 3. Test setup for electrical impedance measurements

Pressure Acoustics Modeling

In a compressible lossless medium (isothermal condition and fluid are assumed to be ideal), continuity and momentum equations are given by [15,16]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \tag{4}$$

$$\frac{\partial u}{\partial t} + (u \cdot \nabla) u = -\frac{1}{\rho} \nabla p \tag{5}$$

where ρ is density, p is pressure, and u is the velocity field. When a fluid experiences a small-amplitude disturbance produced by an ultrasonic transducer, its ambient physical variables are modified:

$$p = p_0 + \acute{p} \tag{6}$$

$$\rho = \rho_0 + \acute{\rho} \tag{7}$$

$$u = u_0 + \acute{u} \tag{8}$$

where p_0, ρ_0 and u_0 are pressure, density and the steady mean flow velocity, and the primed variables are the small-amplitude disturbance caused by ultrasonic wave propagation. Finally, the wave equation for sound waves in a lossless medium can be written as:

$$\frac{1}{\rho c^2}\frac{\partial^2 p}{\partial t^2} + \nabla \cdot \left(-\frac{1}{\rho}(\nabla p - q_d)\right) = Q_m \tag{9}$$

where c is the speed of sound, q_d is the dipole source term, and Q_m is the monopole source term. When molecular relaxation loss effect is considered, there are viscous and thermally conducting losses. Therefore, Eq. 9 can be modified to:

$$\frac{1}{\rho c^2}\frac{\partial^2 p}{\partial t^2} + \nabla \cdot \left(-\frac{1}{\rho}(\nabla p - q_d) + \frac{1}{\rho c^2}\left(\frac{4\mu}{3} + \mu_B + \frac{(\gamma - 1)k}{C_p}\right)\frac{\partial \nabla p_t}{\partial t}\right) = Q_m \tag{10}$$

where μ is the dynamic viscosity and μ_B is the bulk viscosity, γ is the ratio of specific heats, C_p is the specific heat at constant pressure, and k is the thermal conductivity.

At the interface between the gas and the solid domain, the normal component of the structural acceleration of the solid boundary is used to drive the gas domain. This is described by the following equation:

$$n \cdot \left(\frac{1}{\rho_0}(\nabla p)\right) = a_n \tag{11}$$

where a_n is the normal acceleration. The above equations were solved using Finite Element Method (FEM).

Results and Discussion

Experimental Results

Fig. 4 shows impedance-frequency curves for the four piezoceramic elements. According to the figure, the resonance frequency of the elements decreases by decreasing the ratio of diameter to thickness of the elements. Also, at diameter to thickness ratio of 1.38, the resonance frequency is 200 kHz. This is the desired working frequency for ultrasonic transducers of gas meters. Table 1 shows all the data obtained from the measurements for the four piezoceramic elements.

Table 1. Results from measurements for the four different D/t ratios of the synthesized piezoceramic elements

D/t	f_r (kHz)	f_a (kHz)	Phase (deg.)	Z_m (Ω)	Tgδ (%)	d_{33} (pC/N)	C (pF)
0.98	160	201	-0.47	575	1.9	400±10	120±5
1.22	185	227	-1.8	370	2	400±10	157±5
1.35	195	232	-13	275	2	400±10	176±5
1.38	200	235	-0.2	340	1.8	400±10	168±5

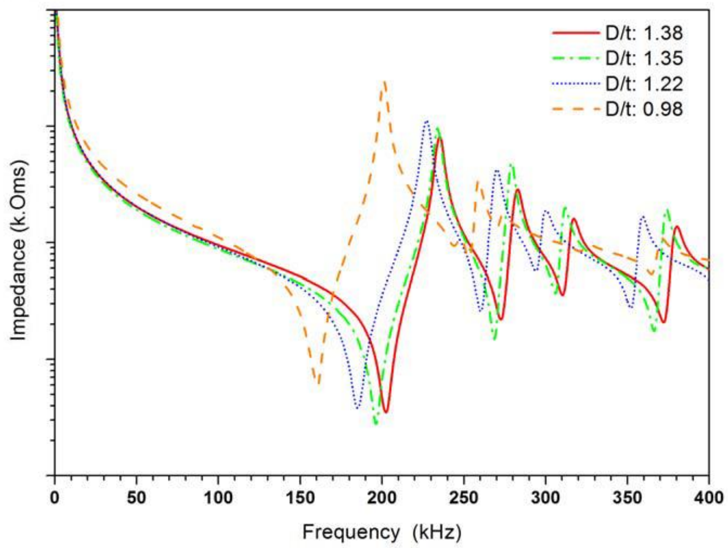

Fig. 4. Impedance-frequency curves for the four different synthesized piezoceramic elements

Numerical Simulation Results

The numerical simulations including electro-mechanical and acoustical simulations were performed using frequency-domain solver. Air was considered as propagation medium and also PZT-5H was used as piezoceramic element. Due to the gas environment, considering the experimental results, the operating frequency was considered to be 200 kHz, approximately.

In order to reduce computation time, 2D-axisymmetric simulations were considered. Fig. 5 represents the considered geometry for the simulations. In order to solve the problem, almost 6 elements per wavelength were considered for meshing the geometry. Fig. 6 represents acoustic pressure propagation in medium (A), formation of the main beam and side-lobes and also their strengths (B). As one can see, near field and far field of acoustic propagation are obvious. Due to the acoustic attenuation in the medium, acoustic pressure in the far field zone is decreasing.

Fig. 7 shows displacement of different points of the piezoceramic at center frequency of 200 kHz. It shows that the maximum displacement is about 0.12 µm at the center of piezoceramic element’s surface.

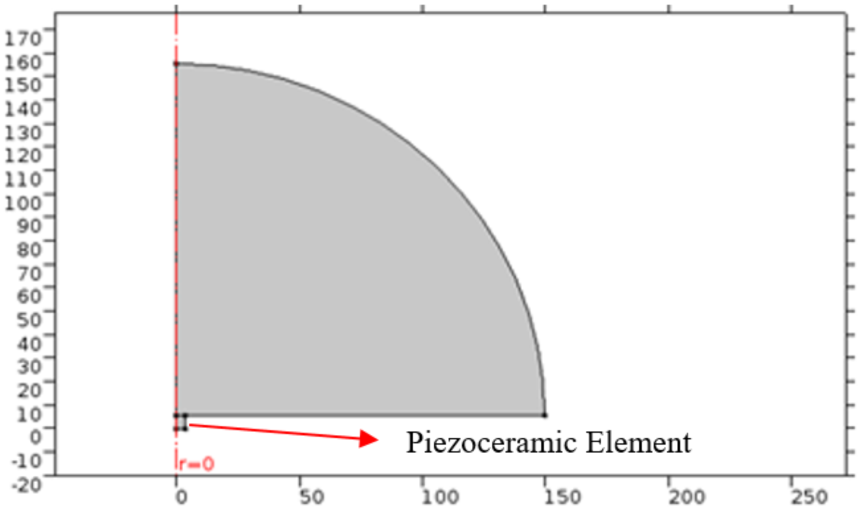

Fig. 5. The considered geometry for the simulations

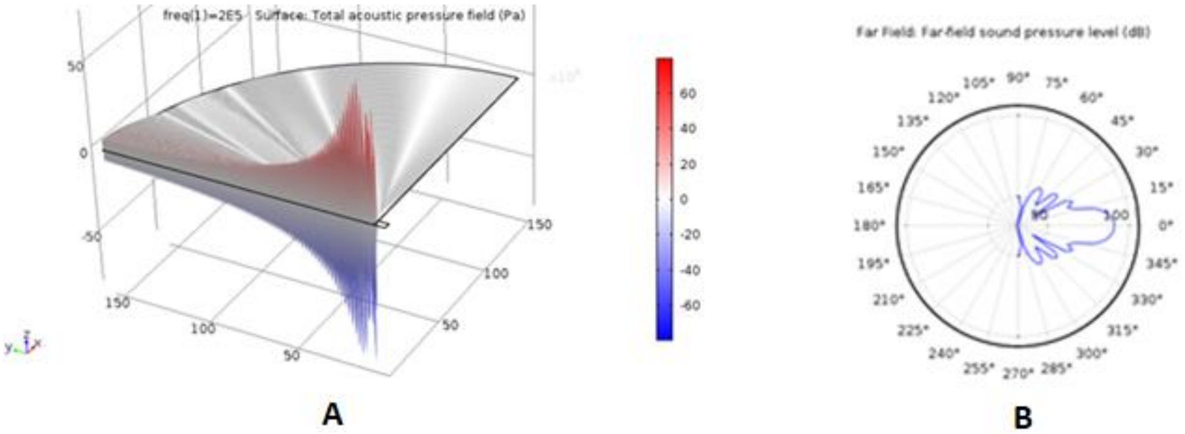

Fig. 6. A) Acoustic pressure propagation in medium, (B) formation of the main beam, side-lobes and their strengths

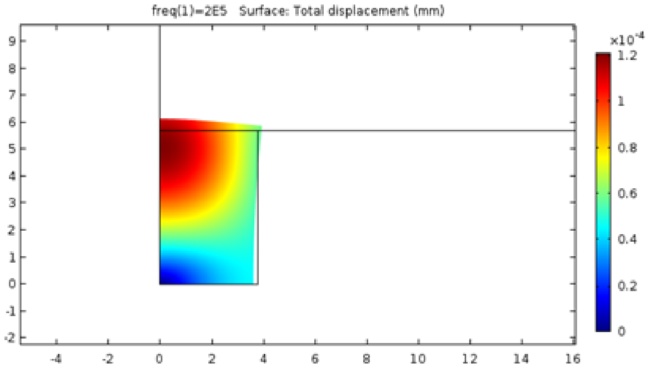

Fig. 7. Displacement of different points of the piezoceramic at center frequency of 200 kHz

Validation of the Results

Fig. 8 shows the comparison between experimental and numerical simulation results of impedance-frequency curve for the piezoceramic elements that were obtained from the previous sections. In Fig. 8, the behavior of the two curves (red and blue) is almost the same at different frequencies. The first resonant and anti-resonant points of two methods are the same, approximately. This means that the numerical simulation provides a good estimation of the behavior of the piezoceramic element. Moreover, the mismatch between impedance values at the resonant and anti-resonant points is due to not considering the environmental losses of the wave.

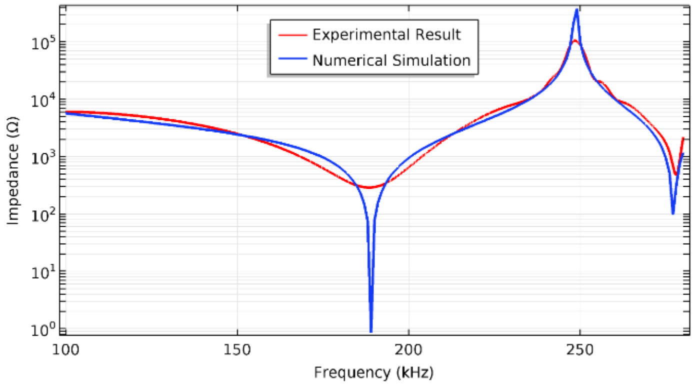

Fig. 8. Comparison between the experimental and the numerical simulation results of impedance-frequency curve for the piezoceramic elements

Conclusions

- There are a lot of factors that lead to a good signal strength. So, designing an efficient transducer needs try and error.
- An efficient alternative way to reduce try and errors is numerical simulation. It leads to good results if reasonable assumptions are used.
- In this work, a 200 kHz piezoceramic element was fabricated and it was numerically simulated. The experimental and simulation results showed a good agreement.
- The agreement between the experimental and simulation results shows the possibility of numerical simulation for designing ultrasonic transducers.
- More complicated numerical simulations needed to simulate behavior of the total ultrasonic transducer in a gaseous medium.

Nomenclature

a_n	Normal acceleration
c_E	Elasticity matrix at constant electric field
e	Piezoelectric stress matrix
f	Frequency
f_r	Resonance frequency
f_a	Anti-resonance frequency
k	Thermal conductivity
p	Pressure
q_d	Dipole source term
t	Time
u	Velocity field

Greek symbols

ρ	Density
ε_S	Dielectric matrix at constant mechanical strain
μ	Dynamic viscosity
μ_B	Bulk viscosity
λ	Wavelength in a given material

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