# 2P3-2

# Design of a Piezoelectric Multilayered Structure for Ultrasound Sensors using the Equivalent Circuit Method

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## 1. Introduction

Ultrasonic sensors are widely used in wide range of applications of the modern-day systems. Ultrasonic sensors in the air are used in various applications like automobiles, robots, and consumer electronics [1]. The ultrasonic sensor using piezoceramics has typically a multilayered structure and its performance is highly dependent on dimensions, boundary conditions, and material properties of each layer. In order to develop a good sensor, the performance characteristics of the multilayered structure should be analyzed meticulously. The acoustical characteristics of a piezoelectric multilayered structure have been commonly analyzed by simplified theoretical equations or time-consuming numerical methods [2]. In this work, we have developed an electroacoustic equivalent circuit for more efficient and reliable estimation of the characteristics of the piezoelectric multilayered structure as an in-air ultrasonic sensor. Using the equivalent circuit, we analyzed the effects of various structural parameters on the acoustic properties of the structure such as resonant frequency and electromechanical impedance. Acoustical radiation pattern of the structure is also derived on the basis of the equivalent circuit analysis results.

## 2. Electromechanical characteristic analysis of a piezoelectric multilayered structure

**Fig. 1** shows a simplified view of a typical ultrasonic sensor comprised of a piezoelectric ceramic disk, a vibrational metallic plate, a bonding layer and a backing layer subjected to a uniform pressure *P* and an applied voltage *V*. In order to analyze the axisymmetric composite structure of Fig. 1, the classical laminated plate theory was adopted to derive the equations of motion for the composite structure comprising the multiple layers [3]. The z-axis is in a perpendicular direction to the plane of vibration whereas $r$ and $\theta$ correspond to the radial and circumferential coordinates of the multilayered structure. The multilayered structure consists of two regions, inner region containing the composite layers ($0 \le r \le R_p$) and annular region containing only the metallic plate ($R_p \le r \le R_m$).

The equilibrium equations of the composite structure were solved by combining the piezoelectric constitutive equations with external forces and moments to obtain the governing differential equations in terms of radial displacement u(r) and slope θ(r). Subsequently, the governing equations were solved to derive the vertical deflection of the whole system as a function of the applied voltage, geometry, and anisotropic material properties of the constituent layers using the boundary conditions and interface matching conditions between the multiple layers.

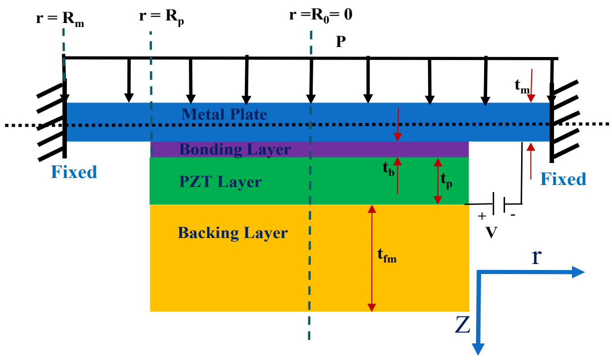


Fig. 1 A simplified view of the multilayered structure of an ultrasonic sensor.

## 3. Equivalent circuit analysis of the piezoelectric multilayered structure

The equivalent circuit of the axisymmetric multilayered composite structure of Fig. 1 is shown in Fig. 2.

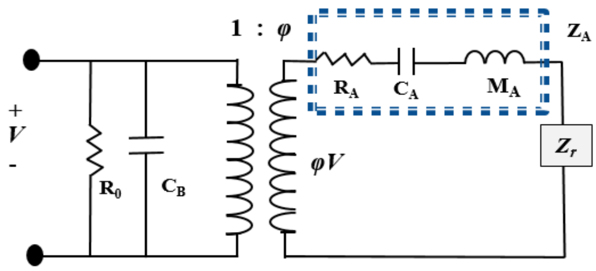


Fig. 2 Equivalent circuit of the multilayered composite structure.

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The main parameters of the electroacoustic circuit including acoustic compliance ($C_A$), acoustic mass ($M_A$), piezoelectric coefficient ($d_A$), acoustic resistance ($R_A$) were first evaluated using derived functional forms of the deflection. Then the remaining circuit parameters such as radiation impedance ($Z_r$), coupling factor ($k$), free electrical capacitance ($C_0$), blocked electrical capacitance ($C_B$), and turning ratio ($\varphi$) were calculated. After calculating all the circuit parameters, performance characteristics of the ultrasonic sensor such as the resonance frequency, the input electrical impedance, and the radiated ultrasound pressure were calculated.

## 4. Characteristic analysis and experimental measurement

The effects of structural parameters on the acoustic characteristics of the piezoelectric multilayered structure were analyzed and validity of the equivalent circuit method was verified by comparing the results with those from the finite element analysis (FEA) of the same structure. In comparison with the other structural parameters, the effect of the vibrational plate radius and thickness was found most significant as illustrated in **Fig.3**.

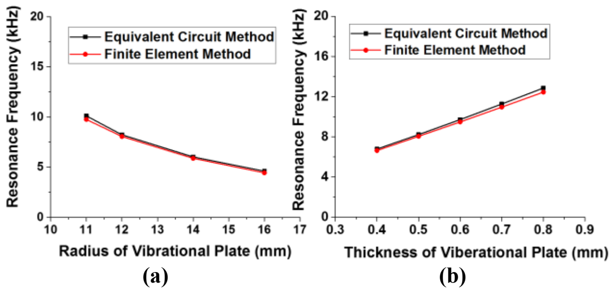


Fig. 3 Effect of the vibrational plate dimensions on the resonance frequency: (a) radius variation and (b) thickness variation.

In order to compare the equivalent circuit results more realistically, impedance spectrum and radiation pattern of an actual ultrasonic sensor in air were measured experimentally and compared with those calculated analytically as shown in **Figs. 4** and **5**, respectively. The resonance frequency from the measured impedance spectrum was 47.5 kHz whereas that from the equivalent circuit analysis was 48.2 kHz. The beam widths from the analysis with the circuit and that measured experimentally are 58° and 61°, respectively. Thus the comparison of acoustic characteristics using equivalent circuit method and experimental measurement shows that the performance of the ultrasonic sensor can be predicted with good accuracy using the equivalent circuit method.

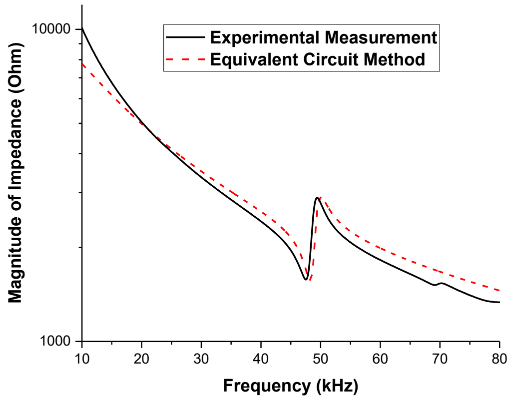


Fig. 4 Magnitude of impedance comparison of the ultrasonic sensor.

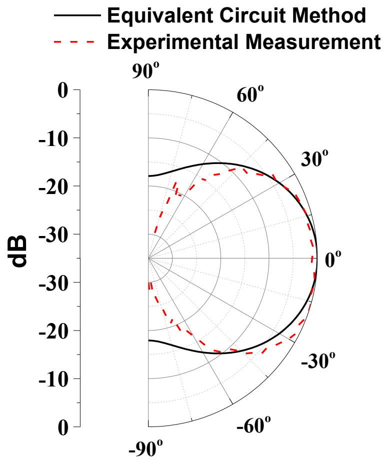


Fig. 5 Radiation pattern comparison of the ultrasonic sensor.

## 5. Conclusion

Equivalent circuit analysis to investigate the electroacoustic behavior of a circular piezoelectric ultrasonic structure was carried out in this study. The validity of the equivalent circuit method was verified initially by comparing the results with those from the finite element analysis of the same structure. Furthermore, the experimental testing of the performance of an actual ultrasonic sensor was carried out to verify the efficacy of the equivalent circuit method.

## References

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