Journal of Engineering Sciences and Information Technology
Volume (6), Issue (2): 30 Mar 2022
P: 136 - 147

ISSN: 2522- 3321

مجلة العلوم الهندسية وتكنولوجيا المعلومات
المجلد (6)، العدد (2): 30 مارس 2022م
ص: 136 - 147

# Improving the performance of ultrasound transducer using simulation and modeling

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**Abstract:** Improving medical imaging using ultrasound is important in order to get a high- resolution medical image, this research aims to achieve a physical modeling and simulation of an ultrasound transducer (UT) showing the electrical impedance of the piezoelectric material, in order to increase the transducer performance at both high and low frequencies by choosing a suitable piezoelectric material with good impedance. we adopted in this research Lead Zirconate Titanate material (PZT4), and performed modeling using mathematical equations that describe the actual physical behavior in the transducer structure and made a graphic user interface (GUI) using Matlab environment that demonstrate it, and display the electrical impedance of the piezoelectric material. As well as using Simulation by Finite Elements Methods (FEM) using On Scale environment and comparing the results in both of them. The results matched at a certain frequency, to give a clear image in the deep areas of the body. This later enables us to make modifications to the transducer structure and add backing layer and matching layer for the piezoelectric material.

**Keywords:** Medical imaging, Electrical impedance, Piezoelectric Material, Lead Zirconate Titanate (PZT4), Graphic user interface (GUI), Finite Elements Method (FEM).

# تحسين أداء محول طاقة الأمواج فوق الصوتية باستخدام المحاكاة والنمذجة

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**المستخلص:** يعتبر تحسين الصورة الطبية الناتجة من التصوير باستخدام الأمواج فوق الصوتية أمر ضروري للحصول على صورة ذات دقة عالية، يهدف البحث إلى عمل نمذجة فيزيائية ومحاكاة لمحول طاقة الأمواج فوق الصوتية تظهر الممانعة الكهربائية للمادة البيزوكهربائية، وذلك من أجل مراقبة وتحسين أداء عمل محول الطاقة في كلا الترددات العالية والمنخفضة من خلال اختيار مادة بيزو كهربائية مناسبة ذات ممانعة جيدة. حيث اعتمدنا في البحث مادة زيركونيت تيتانيت الرصاص Lead Zirconate Titanate (PZT4)، وقمنا بعمل نمذجة باستخدام معادلات رياضيات تصف السلوك الفيزيائي الفعلي في بنية محول الطاقة وعمل واجهة مستخدم رسومية Graphic User Interface(GUI) باستخدام بيئة الماتلاب Matlab توضح ذلك، وتظهر الممانعة الكهربائية للمادة البيزوكهربائية. وكذلك باستخدام المحاكاة بطريقة تحليل العناصر المنتهية Finite Elements Method (FEM)، باستخدام بيئة أون سكيل OnScale ومقارنة النتائج بينهما. وتحقق التطابق بين النتائج عند تردد معين، لإعطاء صورة واضحة في المناطق العميقة من الجسم. وهذا يمكننا لاحقاً من إضافة تعديلات على بنية محول الطاقة وإضافة طبقة داعمة وطبقة ملائمة للمادة البيزو كهربائية.

**الكلمات المفتاحية:** التصوير الطبي، ممانعة كهربائية، مادة بيزو كهربائية، زيركونيت تيتانيت الرصاص، واجهة مستخدم رسومية، تحليل العناصر المنتهية.

## 1. Introduction.

Based on mathematical equations that were deduced in a previous research mentioned by (Estanbouli *et al*, 2004) and to complement this research an ultrasound transducer (UT) modeling was developed. We used these mathematical equations to make physical modeling of the (UT) and observe the effect of output changes represented by electrical impedance, through the use of several piezoelectric materials (PZT4, PZT5H, LiNbO3, PVDF, BaTiO3, PMN- PT), In this research, we have adopted the piezoelectric material PZT4, because it is considered the most common in power transformers as in (Deangelis *et al*, 2016), and its values are more accurate than other materials, using Matlab environment, and compare the impedance represented output results, with the impedance results generated by FEM simulation using OnScale environment.

Medical ultrasound imaging for diagnostics has advantages, such as reasonable cost, real- time imaging, portability and harmless effect. The ultrasound imaging system consists of (UT) and an imaging system. The imaging system controls the (UT) in order to transmit and receive ultrasound, and creates an ultrasound image with a set of data from the transducer. Depending on the type of transducer and imaging system, the images may be either two- dimensional (2D) or three- dimensional (3D). Ultrasound imaging technology has benefited from increasingly sophisticated computer technology, and system integration has ensured better image quality, data acquisition, analysis, and display, as in (Lee and Roh, 2017). Medical (UT)s work by piezoelectric material as mentioned in (Roy, 2015). When an electric voltage is applied across a piezoelectric crystal or ceramic material causes it to deform physically, producing sound. Conversely, these materials produce an oscillating voltage potential. When deformed by an incoming sound pulse. The transducer structure consists of the backing layer located behind the piezoelectric material, piezoelectric material layer and matching layer, as shown in Figure (1), Ultrasound is generated when an alternating voltage is applied across the piezoelectric material, the alternating voltage drives the oscillation of the piezoelectric material.

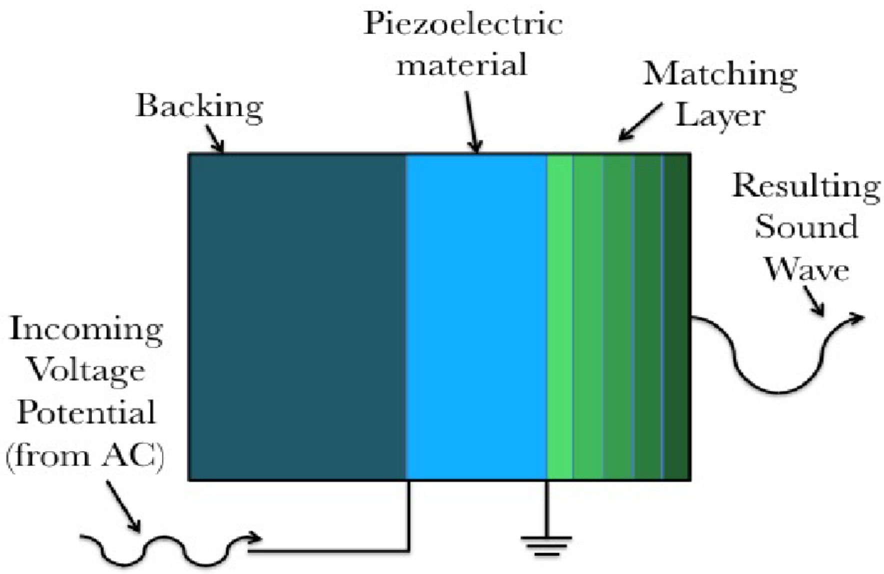


**Figure (1) Ultrasound transducer structure.**

As reported by (Fang et al, 2016) researchers, among the efforts to improve transducer's performance at both high and low frequencies is choosing an active piezoelectric material with high electromechanical coupling factor (higher than 0.5).

## 2. Research problem:

Improving the medical image and obtaining high accuracy by using ultrasound is an important matter, and given that we cannot obtain the piezoelectric material in our country and thus the difficulty of obtaining experimental results, the research aims to make physical modeling and simulation of the ultrasound transducer to clarify the environment and the way it works, In order to convey information to the user (i.e: scientific laboratories, medical clinics ) in a simple way demonstrating the functioning of the ultrasound transducer in a clear and easy way. The objective is to monitor and improve the working performance of the transducer at both high and low frequencies by selecting a suitable piezoelectric material with good impedance.

## 3. Reference studies:

In this section, we provide an overview of the most important studies conducted on ultrasound transducers and their comparison, with the aim of improving the image of ultrasound by improving the internal design of the transducer. The effect of bonding Delaminations on the performance of a single-element ultrasound transducer was investigated in the study of (Ding *et al,* 2021), which consists of a piezo- electric disc, a backing layer and matching. The performance of the transducer can be significantly degraded due to the loss of adhesion between some of its component elements. The single- component transducer structure was studied and FEM simulation was used and verified experimentally. We note that the resonance frequency was achieved between simulation and experimental with a slight shift of less than 0.5% between the frequency value in the 2D and 3D design, at a frequency of 1.4MHZ, which is a Low Frequency (LF), which helps to give a clear image in the deep areas of the body.

The researchers in the study (Ziarati *et al*, 2020), analyzed in detail the ultrasound transducer equivalent circuits of two popular models developed by KLM and Leach for piezoelectric cubes, and built a 3D model using FEM and compared the results with Equivalent circuit modeling (ECM). A piezoelectric cube model was developed in the FEM program assuming the presence of a PZT- 4A material with three different thicknesses. The results from the FEM model showed that ECM methods become more accurate when the transducer is thin, which at high frequencies (HF), and the values of the results varied between LF and HF, these models are far from accurate and need to be modified. And this help us to give a clearer picture for the surface areas of the body. And in a study (Xu *et al*,2020) the authors used an effective method to significantly improve transducer performance by alternating current polarization (ACP) of PMN- 0.25PT single piezoelectric crystals. A 2D transducer architecture was designed for FEM simulation using PZflex, using multi layers, two layers matching, piezoelectric material layer and backing layer for FEM simulation. And then compare the results between the experimental simulation and FEM and verify it, at a frequency of 4MHz, which LF, and it gives a clear picture in the deep areas.

Complementing the study (Estanbouli *et al*,2004) in which the researchers provided basic physical modeling by creating a model of the "inverse layer" transducer in thickness mode comprising oppositely polarized piezo- electric regions, using Matlab, and simulation using PZflx for FEM analysis, comparing the results of electrical impedance and then verification of the result. The Linbo3 transducer disc was used to simulate different thickness ratios. And checking the proposed model also for a specific thickness with FEM simulation, that is more complete and shows identical result at 14MHZ, which means HF, and that gives a clear picture for the surface areas.

Through examining reference studies in detail, reviewing the negatives and positives of these models and comparing them according to previous order, the proposed research was conducted as shown in Table (1).

**Table (1) Comparison of the reference studies and the pros and cons of each one.**

| References studies | Cases of comparing the results of each study | | | | Software used for simulation | Difficulty | The cost | Simulation results and frequencies |
|---|---|---|---|---|---|---|---|---|
| | 2D | 3D | ECM | Exp | | | | |
| [1] 2021 | ☺ | ☺ | - | ☺ | COMSOL | High | High | 1.4MHZ (LF) |
| [2] 2020 | - | ☺ | ☺ | - | - | Low | Low | (2,4,12) MHZ (LF & HF) |
| [3] 2020 | ☺ | - | - | ☺ | PZflex | High | High | 4MHZ(LF) |
| [4] 2004 | ☺ | - | ☺ | - | PZflex | Low | High | 14MHZ(HF) |

And based on mathematical equations that were deduced in this research (Estanbouli *et al*,2004) in the reference study [4], and as a continuation of this research was developed to obtain an ultrasound transducer modeling, where we modeled using mathematical equations that describe the actual physical behavior in the presence of a piezoelectric layer with good impedance and GUI interface to show that clearly, In order to monitor and improve the working performance of the transducer at both high and low frequencies.

## 4. Research Methodology.

In this paper, we create a GUI interface that shows the physical behavior of (UT) in a simple and easy way using Matlab. Mathematical equations were used in the research that describe the behavior of the transducer, changing the parameters of the piezoelectric material related to the mathematical equation, and observing the electrical impedance curve of (UT).

We designed a 2D and 3D piezoelectric material disc model, according to specific dimensions mentioned by (Allison,2020), material disc radius r=10mm, thickness L=2mm, to simulate the transducer using OnScale environment. In order to get the impedance of piezoelectric materials by FEM method, observing the impedance curve. The accuracy of the results were by comparing the impedance curves resulting from the mathematical equations in GUI with the impedance curve using FEM. The simulation results were compared in order to obtain an accurate medical image based on the output frequency.

### 4.1 GUI design using Matlab:

A GUI was designed using Matlab, as shown in Figure (2), and two drop- down lists are demonstrated, **1:** To choose the type of piezoelectric material from six other materials mentioned previously, **2:** To choose the type of curve to be shown for comparison, such as: Impedance, normal voltage and normal pressure. **3:** Parameters entry list, parameters are entered for the transducer and for each piezoelectric material. **4:** Operation keys appear in the interface to show the comparison between the results or show each result separately, and a key to play a 3D video of the piezoelectric material. **5:** To show the required curve.

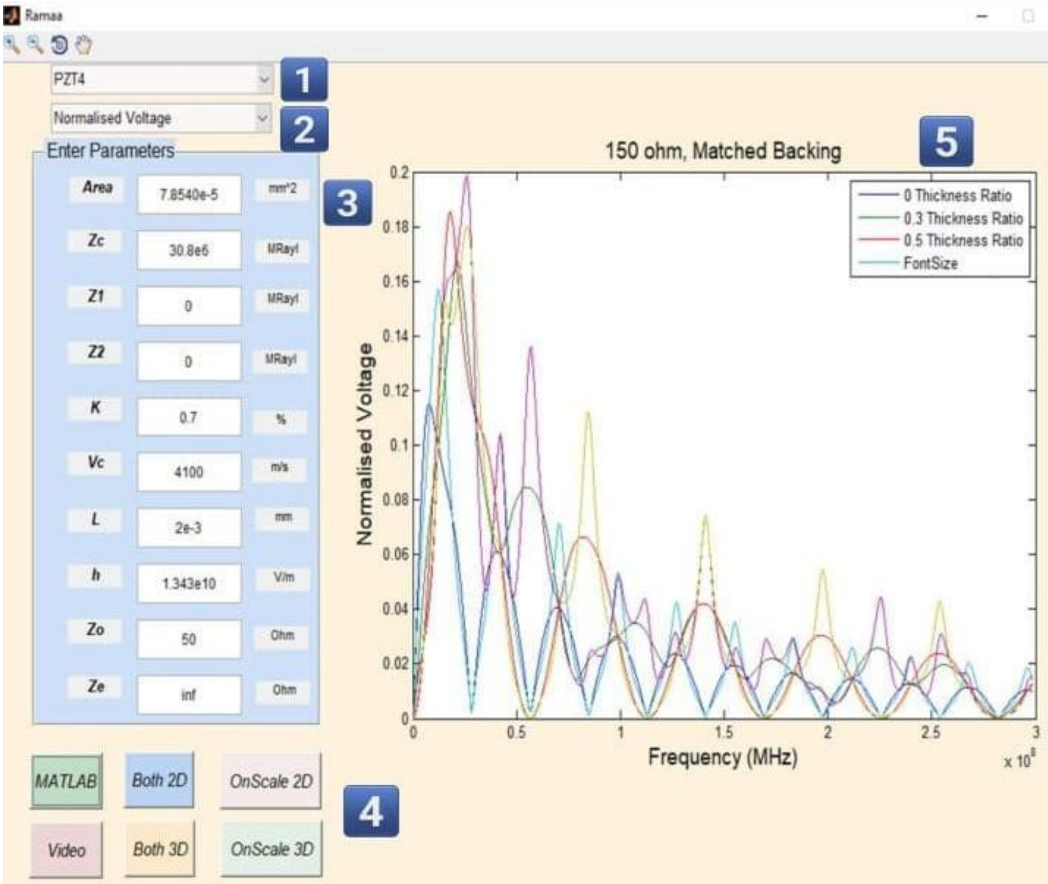


**Figure (2) GUI interface using Matlab.**

Several mathematical equations were used to construct the GUI interface, expressing the electrical impedance, the normal pressure and the normal voltage, but considering that this research only based on impedance of the PZT4, it was the mathematical expression, which gives the impedance of the transducer that was deduced by (Estanbouli *et al*, 2004) as in equation (1):

$$Z_T(s) = \frac{1}{sC_0}\left\{1 - \frac{K^2}{sT}\left[K_{F0}(s).X_0 + K_{B0}(s) + e^{st`} - e^{-st`}\right]\right\} \quad (1)$$

Where:

$$X_0 = -1 + e^{st`} + e^{-st`},$$

$$K_{F0}(s) = \frac{-2e^{-sT}+2e^{-st`}-1+2e^{-2sT}e^{st`}-2e^{-2sT}}{1-e^{-2sT}},$$

$$K_{B0}(s) = \frac{2e^{-sT}-2e^{-sT}e^{st`}+1-2e^{-sT}e^{st`}+e^{-2sT}}{1-e^{-2sT}}$$

Where (Estanbouli,2004) mentioned $T = \frac{L}{V_C}$, the time required for a sound wave to pass through the transducer. $t` = l`/V_C$, the time required for the sound wave to pass through the inverted layer. $K_{F0}$ was defined by Hayward as the front face vibration factor of a transducer which represents the difference in displacement between the front and back faces when a pulse is applied to the front face. In the same way, $K_{B0}$ is defined as the vibration factor for the back face, which represents the difference in displacement between the front and back faces when a pulse is applied to the back face.

$C_o$: Static capacitance of the transducer, which is the capacitance in the absence of a piezoelectric effect.

The parameters of the transducer which are used in the mathematical equations describing the behavior of a piezoelectric material, and that can be entered into the interface structure are:

$Area$: Cross section area of transducer, $Area = \pi r^2$.

$Z_c$: Acoustic impedance of the transducer. $Z_1$: Impedance of the matching layer (front layer).

$Z_2$: Impedance of the backing layer (back layer). $V_c$: Longitudinal Acoustic velocity in a transducer material.

$L$: The thickness of the piezoelectric material. $Z_e$: lumped impedance of arbitrary electrical load (Open circuit).

$Z_o$: External impedance. $h$: The piezoelectric constant that relates voltage and charge or electric field and mechanical stress, measured under open circuit conditions.

$\rho$: Density of the piezoelectric material. $\varepsilon_{33}^{S}$: Strain dielectric constant. $K$: Electromechanical coupling coefficient.

Considering that the transducer is operating in the transmitter state.

This situation is analogous to air surrounding the transducer, with backing material.

In this case $Z_1 = Z_2 = 0$، $Z_o = 50$،$Z_e = \infty$، $h = 1.343e^{10}\ \frac{v}{m}$.

The parameters related to PZT4 are shown in Table (2) reported by (Rathod, 2019).

**Table (2) Parameters of the piezoelectric material.**

| piezoelectric material | $V_c(\frac{m}{s})$ | $\rho(\frac{Kg}{m^3})$ | $L(mm)$ | $Z_c(MRayls)$ | $K$ % |
|---|---|---|---|---|---|
| PZT4 | 4100 | 7500 | 2 | 30.8 | **0.7** |

After entering the necessary parameters from Table (2), whose values are obtained from the materials datasheets according to its manufacturing, to ensure we enter values that are close to real values, and the thickness of the disc is selected according to the design preference, and we note the changes in the impedance of the PZT4, giving a mechanical resonant frequency pulse of approximately 1MHZ, as shown in Figure (3).

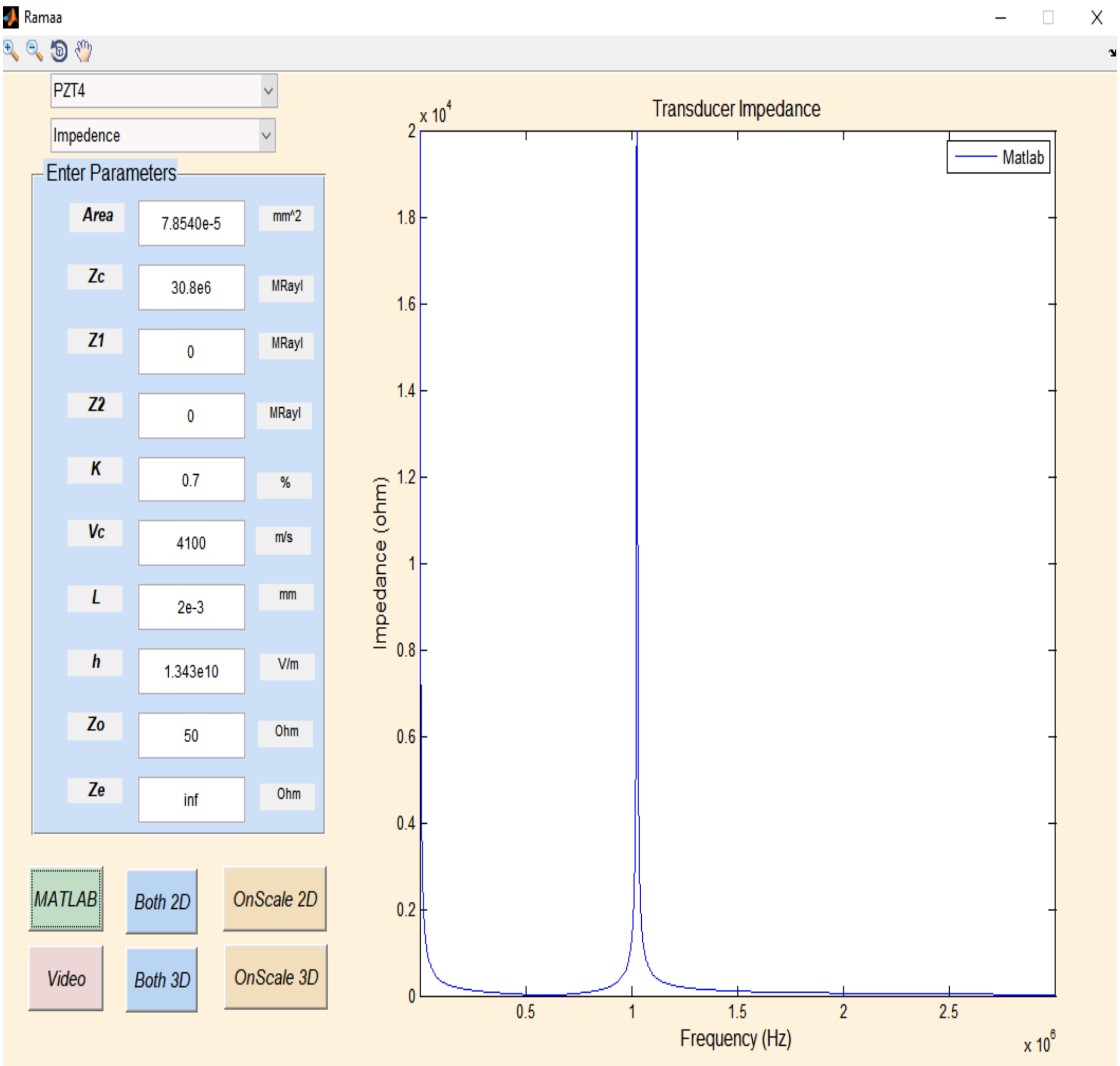


Figure (3) GUI showing the impedance of the PZT4.

### 4.2 2D and 3D piezoelectric material design using the OnScale:

We designed the piezoelectric material as a 2D and 3D disc by OnScale, in order to simulate the PZT4 material using the FEM method. Radius of piezoelectric material r=10mm, thickness L=2mm, these dimensions were used in Matlab also. where the piezoelectric material used in the design appears as a disc in 3D and half a disc in as 2D shown in Figure (4).

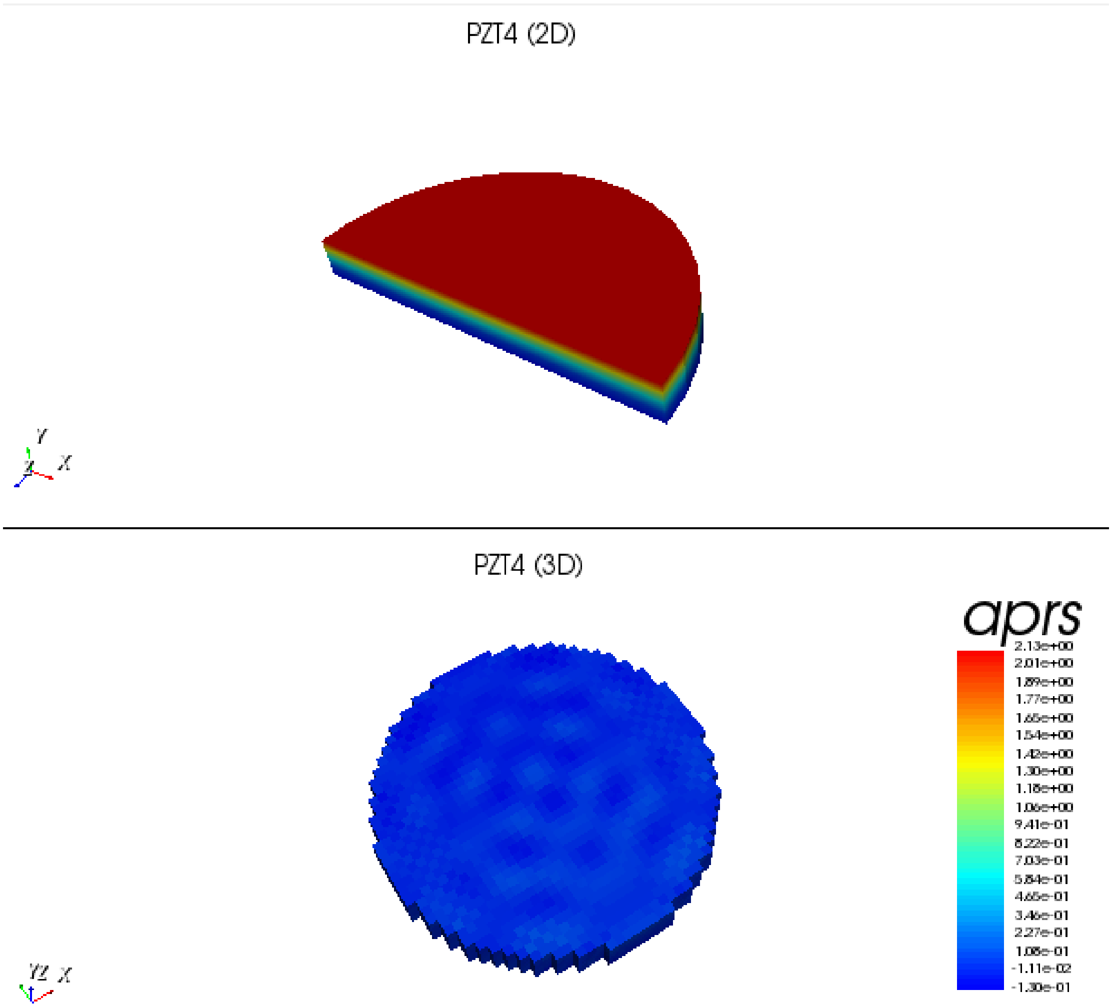


**Figure (4) The design of the PZT4 is shown as 3D,2D by OnScale.**

## 5. Improving the performance of the transducer:

### 5.1 Comparison of the impedance changing between Matlab and OnScale:

The output changes represented by the PZT4 were compared using mathematical equations in the GUI interface by Matlab, with 2D disc design using FEM method and obtaining the output changes of impedance in OnScale, and the matching between them was observed in the designed GUI interface. As shown in figure (5).

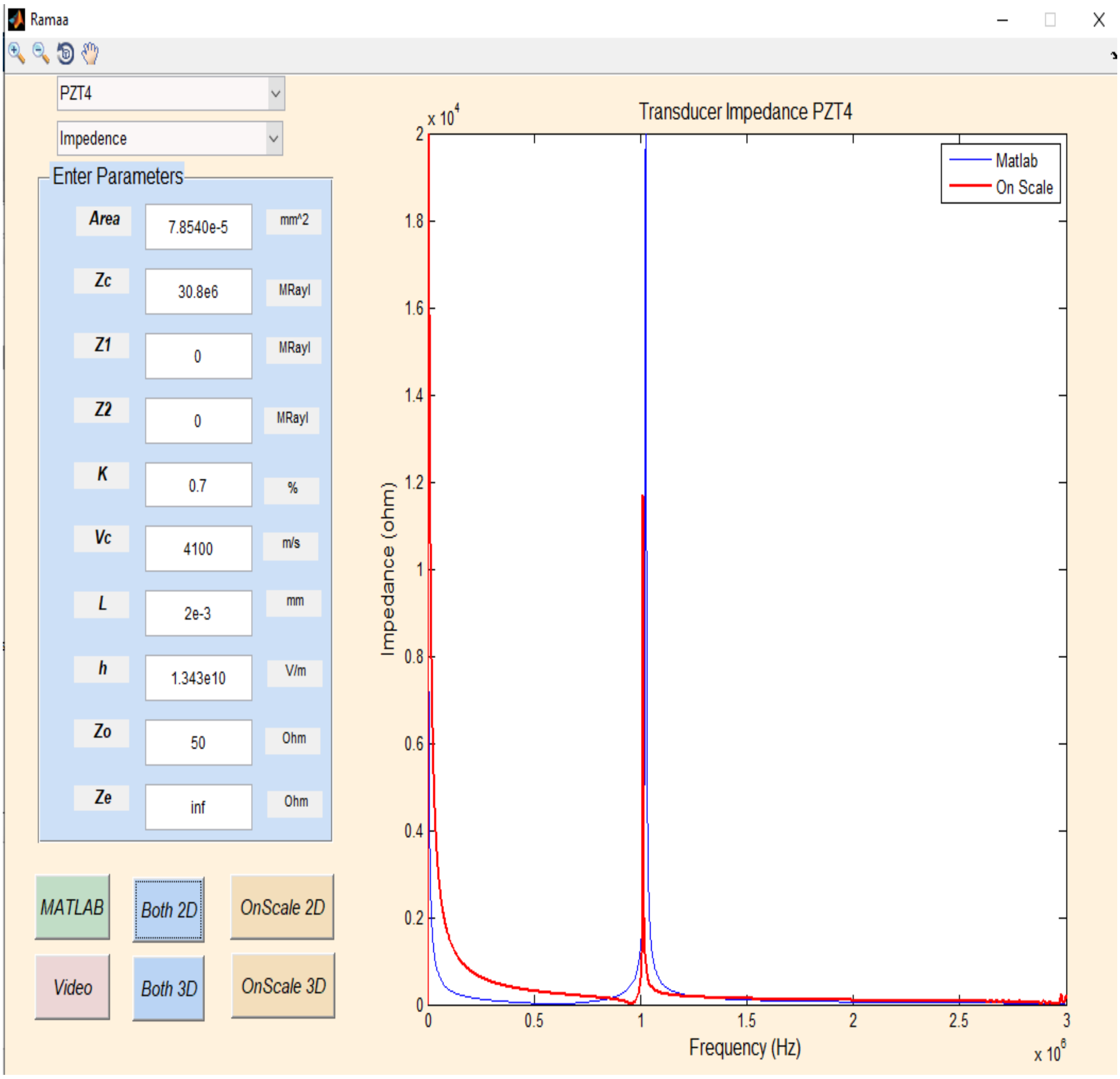


**Figure (5) Comparison of impedance between Matlab and 2D by OnScale.**

Figure (5) shows the impedance of the PZT4. The impedance curve is matched between Matlab and OnScale (**Blue line**: Matlab, **Red line**: OnScale), and the pulse is realized at a mechanical resonant frequency of 1MHZ.

We also compared the impedance of the PZT4 in the GUI in Matlab using mathematical equations with 3D disc design based on the FEM method using OnScale as in Figure (6).

And we noticed a slight shift in the impedance curve with respect to frequency in the 3D curve from the mathematical equations curve by 0.1MHZ, (**Blue line**: Matlab, **Red line**: OnScale).

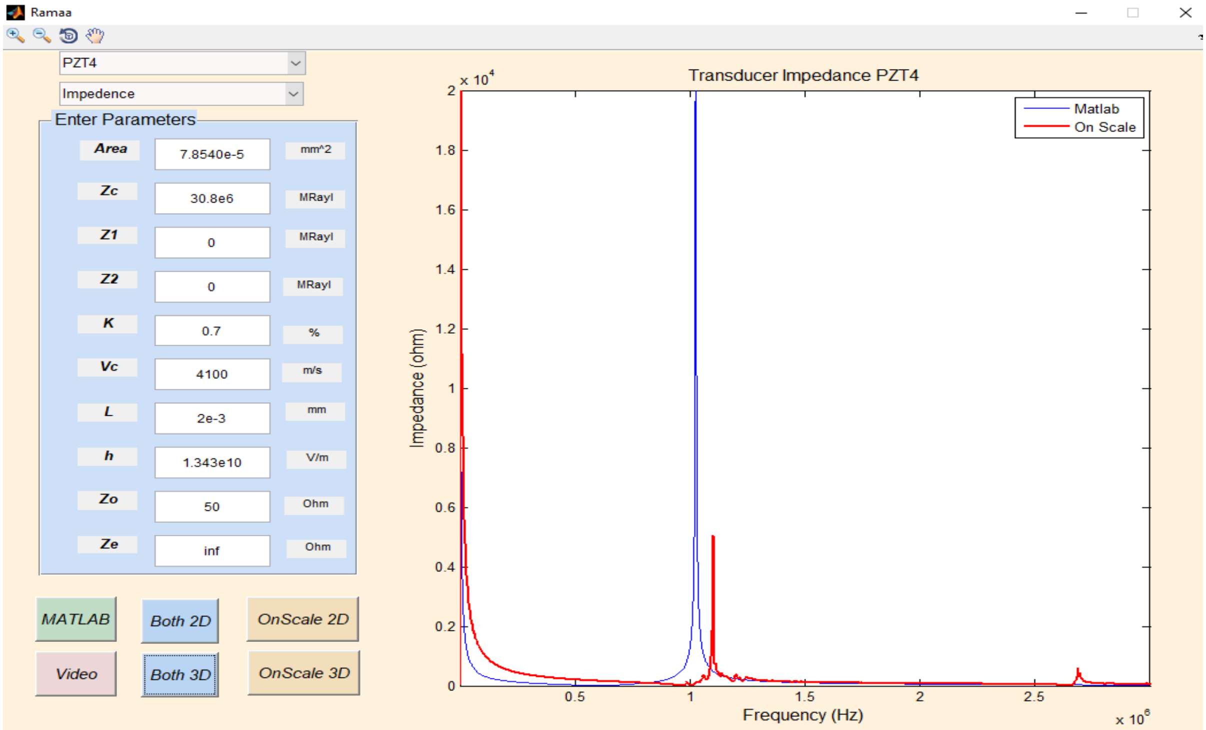


**Figure (6) Comparison of impedance between Matlab and 3D by OnScale.**

Figure (6) shows a 3D pulse at a resonant frequency of 1.1MHZ using FEM, and a Matlab pulse at a frequency of 1MHZ, and this shift is caused by the complex structure in designing a 3D model compared to a 2D model.

## 6. Conclusions.

In this paper, the output changes represented by the electrical impedance of the piezoelectric material PZT4 in the GUI interface using Matlab, by using mathematical equations to model the physical behavior of the piezoelectric material.

We compared this result from Matlab with a 2D designed model and also with a 3D model using the FEM method in OnScale, with the same dimensions of the piezoelectric material, where radius r=10mm, and thickness L=2mm. At 1MHZ there was a match between Matlab and a 3D model with a slight shift of 0.1MHZ, caused by the complex structure in the 3D model design.

And this results obtained from comparing the simulation results, and giving the LF frequency, enables us to obtain a clear image in the deep areas of the body, and thus obtain an accurate medical image.

## 7. Recommendations.

This research can be completed by modifying the structure of the ultrasound transducer, where transducer layers can be increased, by adding a backing layer and matching layer to the piezoelectric material, choosing a material for the backing layer with an impedance close to that of the piezoelectric material for better performance. We can add matching layer, in front of the piezoelectric material and also add more than one piezoelectric material. Where the addition of several layers help us to obtain a medical image for the surface and deep areas at the same time.

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