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Simulation and Optimization of Ultrasonic Transducer

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ABSTRACT- The ultrasonic transducers have numerous applications in industries, including medical probes for performing ultrasound scans. One of the significant drawbacks of the ultrasonic transducer is the wastage of a large portion of energy, due to high acoustic impedance, while transmitting ultrasonic waves to the target object. The present study is aimed to investigate the material design of the piezo-composite transducer and improve its performance. Different piezo-composite transducers were simulated in the COMSOL environment by varying input parameters, and three key performance indicators (KPI) were calculated. Many constraint-based multivariable optimization algorithms have been used to maximize the KPIs. A set of parameters, such as Sensitivity and Fractional Bandwidth, have been found to increase the performance of piezo-composite transducer model and its overall efficiency. This study is intended to impinge unidirectional property to the transducer which is found to be beneficial in more accurate medical as well as structural reports and cost savings.

General Terms: Optimisation

Keywords: Ultrasonic transducer; Piezo-composite; Regression; Optimisation Algorithm.

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1. INTRODUCTION

An ultrasonic transducer is a device used for the production of ultrasonic vibration. Ultrasonic transducers are classified into many categories, based on energy source and the mode through which these ultrasonic waves are propagated. Electromechanical transducers are far more adaptable than mechanical or liquid driven transducers and include piezoelectric and magneto strictive devices. An ultrasonic transducer works when an electrical signal is applied to the piezoelectric crystal, and the crystal starts to vibrate, and this vibration leads to the formation of acoustic waves, also called Ultrasound waves with a frequency range in 2-8 MHz. The reverse process receives the echo generated back to the crystal and converts it to the electrical signal. This ultrasonic transducer has a variety of applications in many domains, and one of the significant usages is in the medical industry for ultrasound imaging. Medical Ultrasonic probes consist of piezoelectric material, backing material, matching layer and an acoustic lens. One of the essential characteristics of piezoelectric material is the smooth conversion of electrical to mechanical energy. When the element is excited by the external electrical source, it shows a high acoustic impedance. A large portion of acoustic energy gets wasted while transmitting the ultrasonic waves onto the target object. Initially, Piezoelectric ceramics like Lead Zirconate titanate (PZT), Lead-based relaxor family and piezoelectric single crystals: LN, PMN-PT, PIN-PMN-PT were commonly employed as they have high electromechanical coupling and low dielectric losses. With advancement in technology over the time, the piezo-polymers such as polyvinylidene difluoride and its copolymer with trifluoro ethylene were used.

But, nowadays, with advancements in material design, piezocomposites give far better performance than piezo-ceramics and piezo-polymers. The matching layer is attached, which helps in acoustic matching with the target object, provides good electromechanical coupling and reduces the electrical and mechanical losses. Alumina and silver loaded epoxy are commonly used for designing the matching layer. The backing layer is used to damp out the vibrations from the piezoelectric crystal, and it also acts as a supporting material for the transducer component. The transducer's performance (also called KPI) depends on three different parameters i.e sensitivity, fractional bandwidth, and the center frequency. The KPIs are calculated from the impedance curve of the transducer.

The main objective of this study is to optimize these KPIs and improve the performance of ultrasonic transducers. We studied various materials among conventional piezoelectric ceramics, piezoelectric polymers and piezoelectric composite. The behaviour of piezocomposites was the best suitable to carry out our research on ultrasonic transducers. Different piezo-composite transducers were simulated in the COMSOL environment by varying input parameters. The associated KPIs

(Key Performance Indicators) were calculated from the Impedance vs Frequency graph obtained from the simulation. Constraint-based multivariable optimization algorithms were used to optimize the KPIs of transducers. Our work is unique in the sense that we determined and optimized the KPIs using optimization algorithms that impinges unidirectional property to the transducer. No such work has been done earlier within this particular domain. The overall paper consists of 5 different components. The first part comprised of introduction; the second part presents the past studies in this field. The third part details the methodology and implementation respectively. The fourth part states the experimental results and summarises the conclusion.

2. LITERATURE REVIEW

B. Hailu et al. [1] Presents the comparison of different piezoelectric Materials for the design of transducers. Majorly three piezoelectric materials were proposed which were, lead zirconate titanate, modified lead titanate, and polyvinylidene difluoride, in combination with various 1-3 piezoelectric composite configurations. Then the finite element analysis was carried out to compare each embedded transducer configuration as a function of various different parameters to examine the potential behaviour and capabilities of the device in many different circumstances. With the use of the Pzflex modelling environment they were able to monitor the phenomenon. This method is not very efficient and time consuming. In our case we implemented optimization algorithms from Scipy library package which efficiently found the right parameters. [2] highlighted the need for artificial neural network models to describe the mapping relation between piezocomposite design parameters and performance parameters. Due to high time consumption of FEM simulations, artificial neural network models were established. In our case, we have used Comsol software to carry out FEM simulations. Also, we've carried out simulations for a larger set of data points for more accurate results and tried out different optimization algorithms to obtain the most suitable result. Bareiro et al. [3] focuses on optimising a group of parameters in ultrasound transducers using a genetic algorithm (GA) which are assessed by simulating B-mode scans for every single transducer configuration. The paper also emphasises on the significance of optimisation in the medical industry. The paper proposes a software-based and fully automatic optimization of transducer arrays so as to enhance ultrasound image quality by the help of ultrasound simulator and a genetic algorithm. [4] presents an electrical equivalent circuit model for piezoelectric transducers to analyse the performance of ultrasonic transducers by providing a close agreement between simulated and experimentally observed dynamic responses of the piezoelectric transducers which were designed and fabricated with composite sensor materials and epoxy-tungsten composite as a backing material. It introduces important characteristics of the transducers, like, electrical and acoustic impedance matching along with frequency response were simulated. Qifa et al. [5] underlines the excellent properties of piezoelectric single crystals that have extensively been employed for various sensors and actuators applications. Recent development of both the single-element and array transducers fabricated using the single crystals were presented. In our paper, we've targeted majorly 3 important key factors and summarised how we can optimise the performance of ultrasonic transducers to achieve better results. [11] demonstrated the design of ultrasound imaging probe and emphasises upon the importance of pulse-echo measurement for the precise measurement of electroacoustic properties of the probe. The significance of the Finite Element Method to deeply comprehend the model design, electro-acoustical performance parameters and their optimisation has also been explained. The transducer used was of a single array element type and the design consisted of a hard rubber backing substrate, four acoustic matching layers, standard piezoelectric ceramic and silicon rubber lens. In our case, we've used a similar approach, but instead of a single array element, we've carried out the simulations on a piezocomposite for several advantages like significant reduction in lateral resonances, improved electromechanical coupling coefficient and improved Tx/Rx Sensitivity. Grimaldi [12] discusses about the downsides of ultrasonic sensor performance and optimization of its parameters to improve the performance. This optimization technique is based on signal processing format. The only disadvantage is that it is only applicable to those which can be represented by transfer function whereas in our case we have used optimization algorithms which are computationally efficient and determines optimised parameters easily.

3. METHODOLOGY

A technique for estimating BP using 1D-CNN is proposed. CNN is effective technique when the input signal is highly correlated between neighboring samples. As shown in *Figure 2*, neighboring samples of PPG are correlated. Unlike the other deep natural networks, CNN maintains temporal information of input data so that CNN is suitable for the locally correlated input data such as PPG signals. 3 CNN model are proposed and compared.

3.1 Material Selection

After going through the literature review survey, we studied majorly three different categories of materials which are piezoceramics, piezopolymers and piezocomposites. Out of these piezocomposites were found to have the most outstanding performance. For designing the matching layer material Alumina loaded epoxy was considered. It has excellent acoustic matching properties with the target object, providing good electromechanical coupling and reducing the electrical and mechanical losses. For designing the backing layer Tungsten loaded epoxy is considered. They damp out the vibrations from the piezoelectric crystal, and also acts as a supporting material for the transducer component. In piezocomposites a single transducer block having multiple materials layered polymer matrix is placed next to each other and the pillars are mainly made up of PZT material and are part of the transducer. The choice of the polymer matrix depends also on the type of design we require. For example, when designing phased array devices, we avoid crosstalk (energy coupling laterally across the device)

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which is unwanted. Crosstalk adds noise to receive signals and can disrupt the directivity. Soft materials have better characteristics for reducing crosstalk as their attenuative properties are generally higher than stiffer materials.

3.2 Parameter Selection

We have studied many parameters to understand the transducer working. The results that allow us to analyse the performance of a transducer in general are called Key Performance Indicators (KPIs). The Sensitivity and Fractional Bandwidth are two important figures of merit, two KPIs of ultrasonic transducers are determined by matching layer thickness (MLT), composite volume fraction (CVF) and central frequency of Ultrasonic Transducers. Sensitivity is defined as the ratio of transmitter signal to receive signal after the 1st reflection of the ultrasonic waves. Fractional bandwidth is a fraction of a wide range of returning echo frequencies that are captured from a receive pulse. Matching layer is basically the layer located between piezoelectric element and the acoustic lens to help transfer the ultrasound energy from the elements to the medium. It is essential for steady penetration of the acoustic energy from the transducer to the body tissue and for easily tracing the reflected acoustic waves (the returning echo) back without much interruption to the transducer for detection. It also prevents the loss of transmission.

3.3 Model Design and Simulation

We started by designing a simple model of piezoelectric transducer in Onscale Solve. It comprised majorly of 5 components. The outer layer which was assigned with structural steel as the material. The insulation layer of Silicone Rubber. The Backing layer of Tungsten-loaded epoxy and the Matching Layer of unidirectional piezocomposite. Then, we configured the coordinate system to the Global coordinate system and defined all the key points as well as contact regions. We further created a mesh for the complete model and optimised it by analysing the element quality. Then, we inserted a time dependent forcing function to define the voltage loads across the piezoelectric material and other boundary conditions so that we can simulate the output parameters. Further it was replicated to form a linear patterned composite and the respective materials were assigned to the blocks. We exported the model to COMSOL in which we carried out the simulation. *Figure 1* shows the model design of piezoelectric transducer.

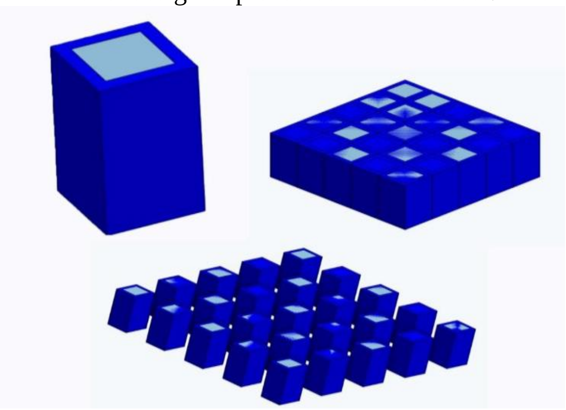

Figure 1: Piezoelectric Transducer Model Design

3.4 Dataset Formation

After performing the simulation, we created the dataset which involved the input parameters (matching layer thickness and composite volume fraction) and obtained the output parameters (sensitivity and fractional bandwidth). Results obtained from simulation were used to create each row of the dataset. Initially 25 simulations were performed with constrained input parameters (matching layer thickness: (0.4,0.8), composite volume fraction: (40,60), central frequency close to 1 MHz).

3.5 Optimization

Our main objective was to maximise the KPI's and with increase in volume fraction the sensitivity increases but the fractional bandwidth decreases. There should be an optimum value of inputs at which these KPIs are maximised. For this purpose, we took a single feature by multiplying both sensitivity & fractional bandwidth. Now for optimising this product term we formed an equation which satisfies both inputs values and the product term. This was done with the help of regression analysis in MS Excel. Fig. 2 shows the variation of sensitivity and fractional bandwidth with matching layer thickness.

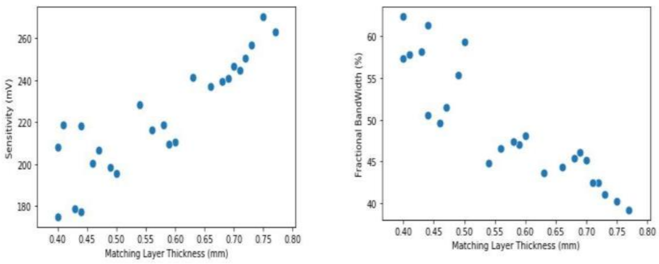

Figure 2: Variation of MLT with Fractional bandwidth and sensitivity

3.5.1 Linear Regression

In Linear regression [6], features of degree 1 are used to fit the data points with a straight line. Within Excel, Analysis ToolPak is used to perform the regression. The required features and output variable are selected and this ToolPak automatically performs the regression analysis. The problem with the linear regression model is that it is prone to overfitting and not robust with outliers. We used the R2 metric and residual plot to evaluate its performance. The coefficient values represent the coefficient of features.

3.5.2 Polynomial Regression

In polynomial regression [7], higher degree of features used to fit the data points. 2- and 3-degree terms are generated from matching layer thickness & volume fraction. Different combinations of terms are used to form the equation for optimization.

The results of the regression analysis is mentioned within the results and discussion section. From regression analysis we obtained the equation to be optimised for maximising the KPI's. This is a multivariate constrained optimization problem. Defined the bound constraints for matching layer thickness and volume fraction. The open-source Python library for scientific computing called SciPy provides a suite of global & local

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optimization algorithms. Three local optimization algorithms are used in our study. They are Trust Region constrained Algorithm [8], Sequential quadratic programming (SQP) [9] and BFGS algorithm [10]

4. RESULTS AND DISCUSSION

4.1 Simulation Results

This section discusses the graphs obtained by simulating the piezoelectric transducer on COMSOL environment. *Figure 3* shows the receive signal on the device. It is the excitation pulse from which we get two return/receive signals. From this we are going to look at the first one in detail. *Figure 4* shows the impedance curve. We post-processed this first reflection by plotting Voltage inputs as a function of Time and applying Fast Fourier Transform on the receive pulse to obtain Piezo Impedance plot as a function of Frequency so as to look at the frequency content and the amplitude of the signal. Then, the two plots were superimposed to calculate the sensitivity. *Figure 5* shows the frequency spectrum of the received pulse which is superimposed on receive voltage pulse. Impedance spectrum of the piezocomposite device was again plotted separately as shown in *Figure 6* to determine the improved performance of the device in terms of lateral resonances, electromechanical coupling coefficient and sensitivity. *Figure 6* shows impedance spectrum of piezo-composite device.

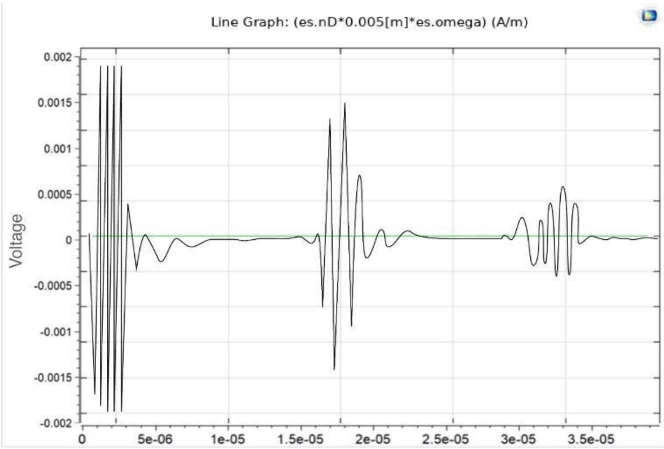

Figure 3: Receive Signal on Device

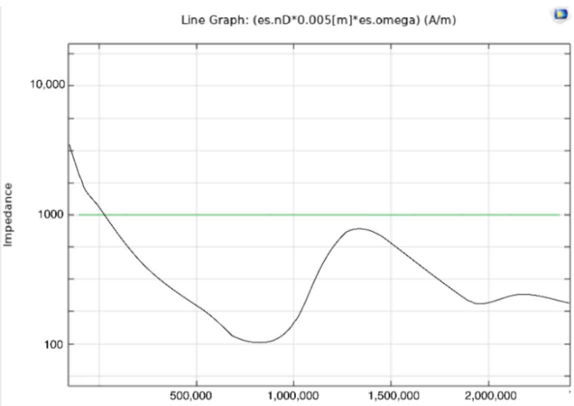

Figure 4: Impedance Curve

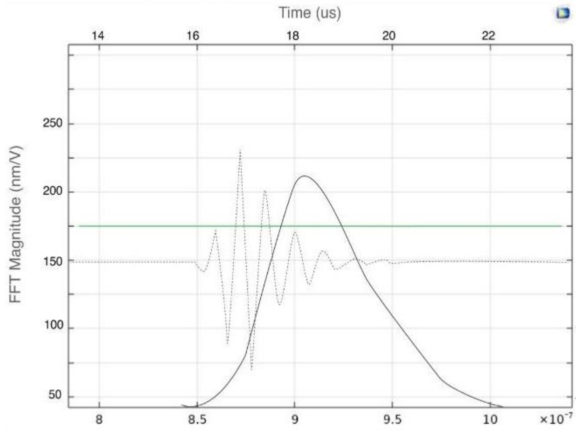

Figure 5: Frequency spectrum of receive pulse imposed on voltage pulse

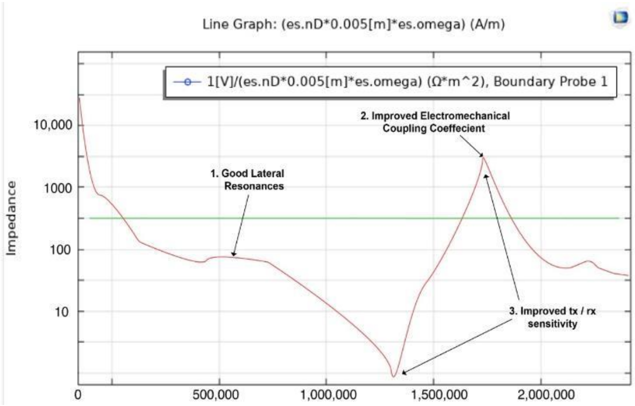

Figure 6: Impedance spectrum of piezocomposite device

4.2 Optimization Results

This section discusses the outputs after performing the optimization. After calculating the KPIs in order to understand the variation of inputs with outputs, we plotted several graphs which shows the relationship between inputs & outputs. *Figure 7, 8, 9* shows the variation of frequency, fractional bandwidth & sensitivity as function of input variables *i.e.* MLT and CVF *Figure 10* plots the variation of inputs with outputs along with sensitivity bandwidth product as pair-grid. Matching layer thickness shows certain correlation with KPIs.

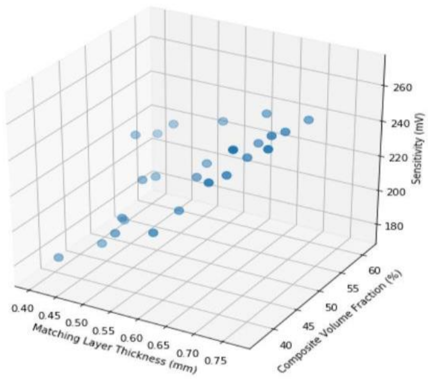

Figure 7: Variation of sensitivity with input parameters

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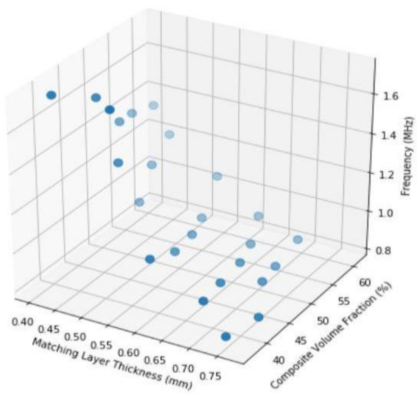

Figure 8: Variation of frequency with input parameters

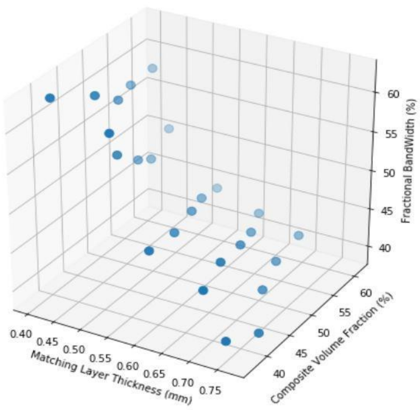

Figure 9: Variation of fractional bandwidth with input parameters

Linear & Polynomial Regression was used to create the equation for optimization function. The results of the regression analysis are mentioned below. R^2 value is calculated for each type in order to compare each model performance. *Table 1* shows the different combination of 1,2- and 3-degree features for linear and polynomial regression along with adjusted R^2 value.

Table 1: Regression Analysis of Input Features

Regression Type	Adjusted R^2 value	Features Involved
Linear Regression	0.03	MLT, CVF
Polynomial Regression	0.20	MLT, MLT^2, CVF
Polynomial Regression	0.19	MLT, MLT^2, CVF, CVF^2
Polynomial Regression	0.29	MLT, MLT^2, CVF^2
Polynomial Regression	0.20	MLT, MLT^2, CVF^3

Polynomial regression model with MLT, MLT^2, CVF^2 fits the data points really well with high R^2 value. *Fig. 11, 12, 13* plots the residuals of the accepted features. Different optimization algorithms are used to maximise the sensitivity bandwidth product with the help of objective function obtained from regression analysis. *Table 2* shows the optimisation algorithm used then optimised values for MLT & CVF and its corresponding sensitivity bandwidth product.

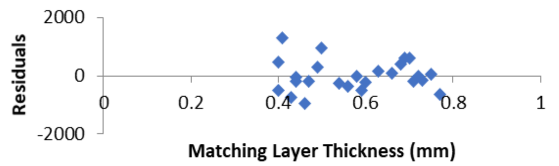

Figure 10: Residual plot for MLT

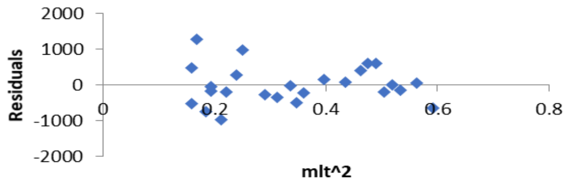

Figure 11: Residual plot for MLT2

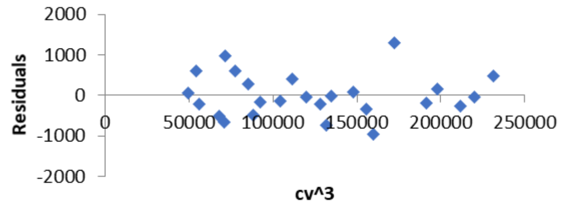

Figure 12: Residual plot for CV3

Table 2: Optimisation Algorithm Results

Algorithm	Optimised Values (mm, %)	Sensitivity-Bandwidth Product
Trust Region constrained algorithm	(0.40, 61.39)	11931.8
Sequential Least Squares Programming	(0.40, 40.78)	10909.5
BFGS algorithm	(0.44, 45.23)	10878.9

5. CONCLUSION AND FUTURE REMARKS

This paper has found the parameters (Matching Layer Thickness and Composite Volume Fraction) which optimise the KPIs (Sensitivity, Fractional Bandwidth and Central Frequency) by the help of various optimisation algorithms and thus result in increased performance and overall efficiency of the piezocomposite transducer model. There are certain drawbacks in our analysis, as we have performed limited number of simulations. This may hamper the accuracy of optimized figures resulting from optimization. Apart from that more computationally efficient, robust and effective optimisation techniques can be used. In our study, we used MLT and CVF as input parameters. More variables could result in better performance of transducer. We can conclude that with optimized values, ultrasonic transducer can be designed in laboratory which would have several different applications. In medical field, a high-performance transducer could result in good resolution in eye imaging, noninvasive imaging of skin morphology, multi-modality in photoacoustic imaging etc. In industries more advanced automated machinery, object navigation etc. It has more diverse future applications in agriculture, military, aerospace, chemical and construction. With use of optimization algorithms like genetic algorithm, particle swarm optimization better results can be derived.

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