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PMUT PACKAGE DESIGN OPTIMIZATION VIA MACHINE LEARNING

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ABSTRACT

This work uses supervised learning to optimize the package design with validated experimental results for piezoelectric micromachined ultrasonic transducers (PMUTs) to increase and alter the sound pressure level (SPL). Advancements as compared to the state-of-art include: (1) a neural network model to achieve a mean squared error of less than 0.65 dB^2 post 100 epochs; (2) increased vibration amplitude by 17.9 dBV at the first-mode resonance frequency of 33.5 kHz; and (3) SPL enhancements below the 20 kHz frequency range such as the magnitude increases of more than 60 dBV at 5 kHz. As such, the package design shifts the emitting acoustic energy from the ultrasound to audio range in favor of various applications, including audio speakers.

KEYWORDS

MEMS, PMUT, packaging, supervised learning, optimization

INTRODUCTION

Ultrasonic technologies, particularly the development of Piezoelectric Micromachined Ultrasonic Transducers (PMUTs), have witnessed considerable advancements in recent years. PMUTs, owing to their compact size and efficient energy conversion, have become increasingly crucial in diverse applications ranging from medical diagnostics [4], [5], communications [6], imaging [7], and consumer electronics. Despite the growing adoptions, PMUTs face inherent limitations due to their reduced size, which typically leads to a low Sound Pressure Level (SPL) [8]. This is significant as SPL is a critical factor in determining the effectiveness and range of applications.

The challenge of enhancing the SPL in PMUTs has been a focal point of research, with efforts primarily directed towards structural [9] and material optimizations [10], [11]. There is also research on the optimization of vibration modes [12]. While these approaches have yielded improvements, the optimization of PMUT packages hasn't been explored in the literature for further advancements. Intuitively, the acoustic outputs of PMUTs will change based on the package and this presents both a challenge and an opportunity for innovation in the field.

Understanding and addressing this gap is crucial for several reasons. First, optimizing packaging design could offer a pathway to enhance SPL without the need for extensive redesigns or material changes in the PMUTs. Second, improvements in SPL through packaging design optimizations could significantly broaden the scope of applications for PMUTs, especially in areas where high acoustic pressure output is essential [13], [14]. Exploring the impact of packaging on PMUT performance aligns with the broader trend in technology development, where holistic design approaches that consider all aspects of a device, including its packaging, are becoming increasingly important. In this context, research that focuses on optimizing PMUT packaging design not only addresses a specific technical challenge but also contributes to the understanding of how integrated design approaches can enhance device performances.

An intriguing aspect of PMUT packaging design is its ability to alter the SPL in the low-frequency range without the need for major structural changes to the PMUT itself. This capability is particularly significant for applications like audio speakers, where a specific frequency response is desirable [15], [16]. The potential to modify the frequency spectrum through packaging alone allows for greater flexibility and efficiency in tailoring PMUTs for specific applications, further enhancing their utility in a wide range of fields. This approach not only addresses the challenge of enhancing SPL but also adds a layer of versatility to PMUT design, enabling the fine-tuning of acoustic properties to meet diverse application needs. The integration of machine learning in the optimization of PMUT packaging design has opened new possibilities [17]. By employing machine learning, researchers can effectively navigate the complex relationship between packaging designs and acoustic performances, leading to PMUTs that are better suited for a wider range of applications.

As such, the study of PMUT packaging design optimization holds significant potential for advancing the field of ultrasonic technology. By exploring this relatively uncharted area, such research can provide valuable insights into how packaging modifications can lead to substantial improvements in device performance, thereby contributing to the broader goal of enhancing the efficiency and applicability of ultrasonic transducers.

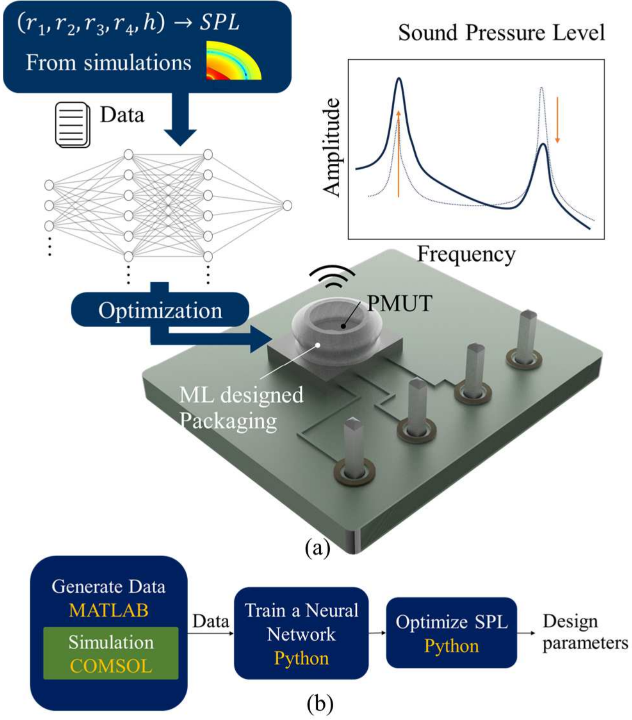


Figure 1: (a) Schematic of machine learning based PMUT package design optimization. Data generated by a

COMSOL model is used to train a neural network. The package shapes/parameters that maximize the desired acoustic pressure profile are obtained. (b) The design pipeline for generating the optimal design.

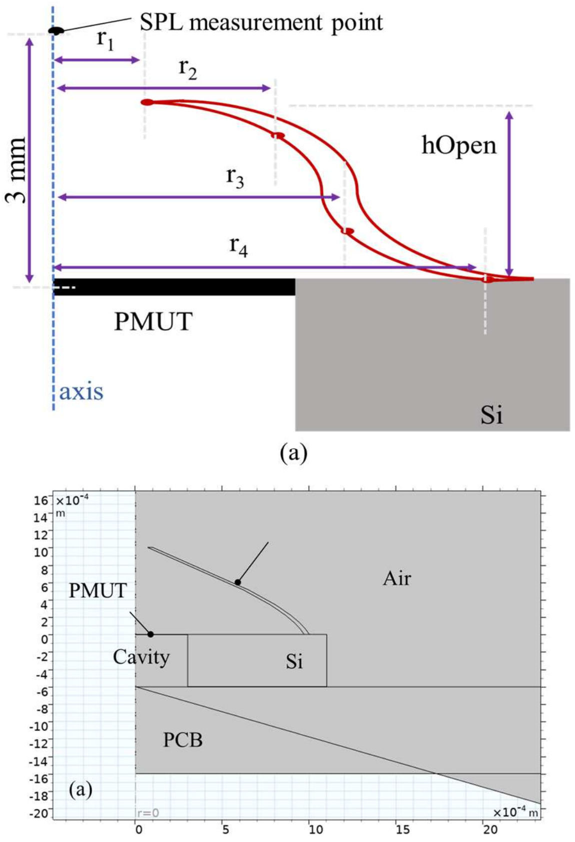
METHODOLOGY

Employing a combination of neural network and optimization algorithm, a cone-shape package with a Bezier curve shell has been developed to augment SPL at targeted frequencies as shown in **Fig. 1a**. The cornerstone of the design pipeline is the neural network trained on simulation data and the optimization algorithm that provides the best set of parameters, as shown in **Fig. 1b**. The goal is to generate an optimal packaging design that maximizes the output SPL at the resonance frequency.

The first step towards the optimal packaging design starts with a simulation model in commercial Finite Element Analysis software COMSOL. The 2D-axissymmetric model includes the PMUT unit and a package on top in **Figure 2**, which is defined by a Bezier curve. A Bezier curve is a mathematical curve defined by a set of control points widely used in computer graphics. It can produce both straight lines and complex, smoothly flowing curves, making them versatile tools for creating various shapes in design and modeling. In the simulation model, the cone-shaped package is represented by a Bezier curve defined by 5 parameters: (r_1, r_2, r_3, r_4, h). As shown in **Figure 3**, the height of the package is denoted as h. There are 4 points equally spaced in the vertical direction along the path that defines the package geometry. For each point, the location is determined by a radius measured from the rotational axis of the model and the combinations of all points metamorphose into a conical shape in the space. An SPL measurement point is strategically positioned 3 mm above the PMUT.

The generation of training data is primarily done on MATLAB. This includes randomly generating sets of parameters and passing them to the COMSOL model to get the corresponding SPL levels. Parameter boundaries are meticulously established, factoring in the limitations of the model and available fabrication method. The unique characteristics of the PMUT's wedge wire bonding and substrate define an upper limit of 3.5 mm to the horizontal coordinates. To avoid a completely closed package with no opening and to make sure the package encloses the PMUT diaphragm completely, there is also a set of lower bounds to the radii (2 mm for r_4 and 0.5 mm for r_1, r_2, and r_3). Considering the form factor and constraints, the dimension of the package is limited to a 3×3 mm^2 square.

With the training data, a neural network model is constructed in Python using PyTorch to predict SPL based on the normalized design parameters. The neural network for regression has one input layer, two ReLU-activated hidden layers with 64 neurons, and an output layer. After the training process, the optimal designs are determined using stochastic gradient descent (SGD) to find designs that maximize the output SPL profile.



(a)

(b)

Figure 2: (a) The design parameters of the 4 control points that define the Bezier curve of the package. Horizontal coordinates are measured from the rotational axis and the height is measured from the surface of the PMUT. (b) The 2D-axissymmetric model in COMSOL, including the PMUT, the PCB, and air as the medium.

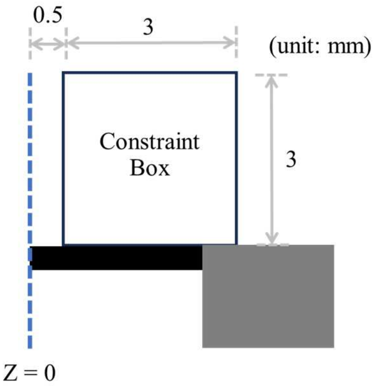


Figure 3: The constraint box.

EXPERIMENTAL RESULTS

A total of 3562 data sets have been generated based on the PMUT visualized in the COMSOL model, which has a resonant frequency at 107 kHz. The data set is generated in MATLAB, which is then used to run individual simulation in COMSOL to obtain the corresponding SPL output at the resonance frequency. Of all 3562 data, 80% were earmarked for training, and the remaining 20% was reserved for validation.

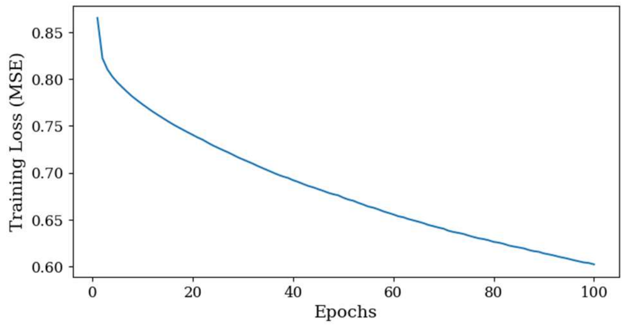


Figure 4: The training loss versus epochs. With 100 epochs, the mean squared error falls below 0.65 dB^2.

With a batch size of 32, the neural network model exhibits a precision with a mean squared error (MSE) of 0.65 dB^2 post 100 epochs as shown in **Figure 4**. Stochastic gradient descent is used to find the optima after the neural network is trained. Given the non-convexity of a neural network model, the optimization was repeated 5 times with different initial guesses, and only the one yielding the largest SPL was selected.

The design parameters are used to generate and print a 3D model package for testing, as illustrated in **Figure 5**. The prototype packages were printed with a Form 3 SLA printer from FormLabs with standard grey and clear resin. This package is then mounted on a potassium sodium niobate (KNN) bimorph PMUT [4], which boasts an 800 μm radius and twin mode shapes. A Brüel & Kjær 1/8" pressure-field microphone unit was used to measure the acoustic outputs with and without using the package at the measurement point of 3 mm above the KNN PMUT surface, same as in the simulation.

Results shown in **Figure 6** affirm a substantial alteration in the frequency spectrum due to the package. Particularly notable is that the vibration amplitude at first-mode resonant frequency of 33.5 kHz increases by 17.9 dBV, and the frequency band from 20 to 40 kHz gets a significant boost. Additionally, SPL enhancements are observed below the 20 kHz frequency, as the volume enclosed by the package acts as a resonance chamber. At 5 kHz, the magnitude increases by more than 60 dBV. Such an improvement in the low frequency performance is a demonstration of how the packaging design shifts the energy from the ultrasound to audio range, making it especially suitable for speaker development.

Comparative analysis with other randomly curated designs (**Figure 7** and **Table 1**) in simulation confirms that the optimized package induces the most pronounced amplification, with one of the randomly generated packages even reduced the SPL. The design's compatibility with a large-radius KNN PMUT and its resultant performance gains underscore the expansive applicability of this design methodology.

CONCLUSIONS

This study represents a significant advancement in PMUTs through the application of machine learning for packaging design. This approach led to a notable enhancement in SPL, crucial for the effectiveness of PMUTs in various applications.

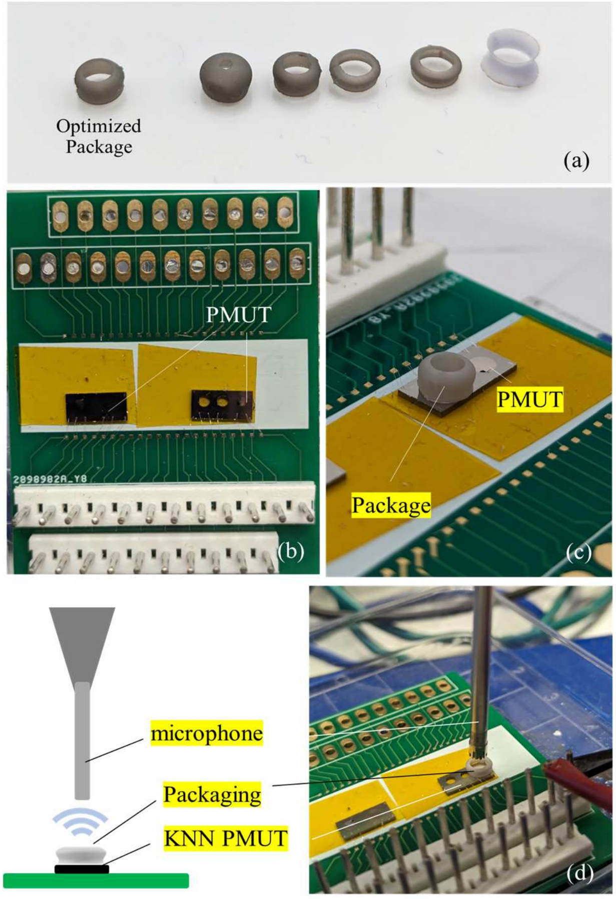


Figure 5: (a) The 3D-printed packages. The left most one is the optimal design, the others are possible shapes of the package. (b) The KNN PMUT used for the experimental validation, on which the simulation is based. (c) During testing, the package is placed directly on top of the PMUT element, and the bottom encloses the diaphragm. (d) The experimental setup using a microphone. The microphone is placed 3 mm above the KNN PMUT.

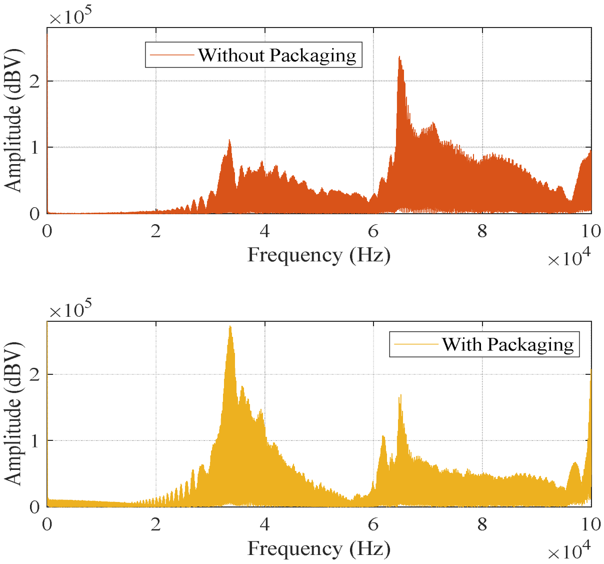


Figure 6: Comparison between PMUT outputs with and without the package. The performance at the first-mode resonance is significantly improved, while the high-frequency output is suppressed. Within the audible range (< 20 kHz), there is notable increase in amplitude.

Figure 7: Comparisons between bare PMUT, optimized and randomly generated designs.

Table 1: Comparisons between different package designs.

Setup	SPL (dB)	Sound Pressure (Pa)	Pressure Compared to Bare PMUT
Bare PMUT	102.35	2.62	-
Optimized	112.31	8.25	+214.77%
Random #1	109.55	6.01	+129.09%
Random #2	104.79	3.47	+32.43%
Random #3	75.062	0.113	-95.68%

Key experimental outcomes include a 17.9 dBV increase in vibration amplitude at the first-mode resonance frequency and a remarkable SPL enhancement in the low-frequency spectrum, such as over 60 dBV at 5 kHz. Such a boost in the audible range is particularly relevant for applications in audio technology. It also demonstrates the potential of optimized PMUT packaging in expanding the utility of these transducers in new domains, as the resonance output can be amplified by passive designs and the frequency response of the element can be fine-tuned without altering the material or the structure.

The integration of machine learning into PMUT packaging design has not only addressed the challenge of enhancing SPL but has also added versatility and efficiency in tailoring PMUTs for specific needs, paving the way for more advanced and diverse applications of PMUTs.

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