

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**DEVELOPMENT OF FLEXTENSIONAL TRANSDUCER FOR
UNDERWATER ACOUSTIC APPLICATIONS**



ATA CAN ÇORAKÇI

A THESIS OF DOCTORATE
DEPARTMENT OF ELECTRONICS ENGINEERING

ADVISOR: PROF. DR. SERKAN AKSOY

JANUARY 2025

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LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**SUALTI AKUSTİK UYGULAMALARI İÇİN ESNEK
GERİLMELİ TRANSDÜSER GELİŞTİRİLMESİ**

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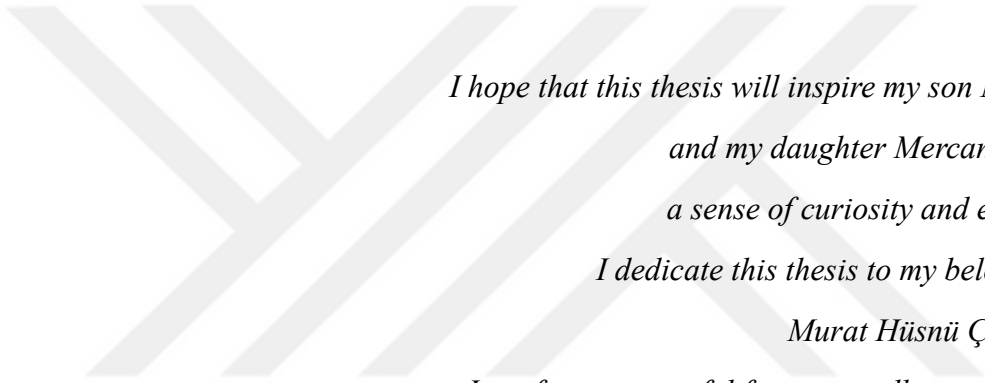
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*I hope that this thesis will inspire my son Murat Mete
and my daughter Mercan to develop
a sense of curiosity and exploration.*

*I dedicate this thesis to my beloved father,
Murat Hüsnü ÇORAKÇI...*

I am forever grateful for your endless support, Dad.

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ABSTRACT

This thesis presents a novel design for a low frequency underwater electro-acoustic projector element based on the Class V Flextensional transducer. Although Class V Flextensional transducers are typically used in medium and high frequency ultrasonic and medical applications, they have not been adapted for low frequency underwater acoustic applications ($f < 10$ kHz) due to manufacturing and assembly challenges. To address this need, smaller piezoelectric components compared to traditional Class V Flextensional transducers are utilized, and a segmented octagonal stack assembly structure along with a complementary cap design is developed.

The design, modeling, simulations, prototyping, and characterization activities for the segmented Class V Flextensional transducer element are carried out. Simulations are conducted using Finite Element Analysis (FEA) method in OnScale software, and the produced prototype is characterized in the open test tank of TÜBİTAK MAM Underwater Acoustic Laboratory. A strong agreement is observed between the simulation data and measurement results in the frequency range of 1 kHz to 11 kHz. For frequencies below 1 kHz, a new technique for free-field calibration of underwater acoustic transducer elements is introduced into the literature by applying the Two Equations - Two Unknowns (2E-2U) method.

This lightweight and dimensionally compact transducer design, relative to its operating frequency, can be used to meet the low-frequency projector needs of stationary and mobile underwater platforms. For beam steering and higher sound pressure levels, planar array structures with $N \times N$ or $M \times N$ elements can be created using this design. This thesis comprehensively examines the process from concept design to the characterization of the final product and details of its unique features.

Keywords: Class V Flextensional Transducer, Underwater Acoustic Transducers, Underwater Acoustic Measurement and Calibration, 2E-2U Method

ÖZET

Bu tez, Sınıf V Esnek Gerilmeli (Flextensional) transdüser uygulamalarına yönelik düşük frekanslı bir sualtı elektro-akustik projektör elemanı için yenilikçi bir tasarım sunmaktadır. Sınıf V Esnek Gerilmeli transdüserler genellikle orta ve yüksek frekanslı ultrasonik ve tıbbi uygulamalar için kullanılsa da üretim ve montaj zorlukları nedeniyle düşük frekanslı sualtı akustik uygulamalarına ($f < 10$ kHz) uyarlanamamıştır. Bu ihtiyacı karşılamak için, geleneksel Sınıf V Esnek Gerilmeli transdüserlere kıyasla daha küçük piezoelektrik bileşenlerin kullanılması sağlanmış, segmentlere ayrılmış sekiz köşeli (octagonal) yığın montaj yapısı ve tamamlayıcı bir kapak tasarımı geliştirilmiştir.

Segmentlere ayrılmış Sınıf V Esnek Gerilmeli transdüser elemanının tasarımı, modellenmesi, simülasyonları, prototiplenmesi ve karakterize edilmesi faaliyetleri gerçekleştirilmiştir. Simülasyonlar Sonlu Elemanlar Analizi (FEA) metodu kullanılarak OnScale yazılımında gerçekleştirilmiş, üretilen prototip TÜBİTAK MAM Sualtı Akustik Laboratuvarı'nın açık test tankında karakterize edilmiştir. 1 kHz ile 11 kHz arasındaki ölçüm sonuçları ile simülasyon verileri arasında güçlü bir uyum görülmüştür. 1 kHz altı frekans bölgesi için İki Denklem - İki Bilinmeyen (2E-2U) yöntemi uygulanarak sualtı akustik transdüser elemanlarının serbest alan kalibrasyonlarına yönelik yeni bir teknik literatüre kazandırılmıştır.

Bu hafif ve çalışma frekansına göre boyutsal olarak küçük transdüser tasarımı, sabit ve mobil sualtı platformlarındaki düşük frekans projektör ihtiyacına yönelik kullanılabilir. Işın yönlendirilmesi ve daha yüksek ses basınç seviyesi için bu tasarım kullanılarak $N \times N$ veya $M \times N$ elemanlı düzlemsel dizin yapısı oluşturulabilir. Bu tez, konsept tasarımdan nihai ürünün karakterizasyonuna kadar olan süreci kapsamlı bir şekilde incelemekte ve özgün özelliklerini detaylı bir şekilde açıklamaktadır.

Anahtar Kelimeler: Sınıf V Esnek Gerilmeli Transdüser, Sualtı Akustik Transdüserler, Sualtı Akustik Ölçüm ve Kalibrasyon, 2E-2U Metodu

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LIST OF SYMBOLS AND ABBREVIATIONS

AC	: Alternating Current
API	: Application Programming Interface
ASW	: Anti-Submarine Warfare
AWS	: Amazon Web Services
CAD	: Computer Aided Design
CAE	: Computer Aided Engineering
CWMA	: Complex Weighted Moving Average
DREA	: Defence Research Establishment Atlantic
FEA	: Finite Element Analysis
GCP	: Google Cloud Platform
GRP	: Glassfiber reinforced plastics
GUI	: Graphical User Interface
HBK	: Hottinger Brüel & Kjær
HPC	: High Performance Computing
IT	: Information Technology
Hz	: Hertz
kHz	: Kilohertz
MAM	: Marmara Araştırma Merkezi (Marmara Research Center)
PDE	: Partial Differential Equation
SAL	: Sualtı Akustik Laboratuvarı
SONAR	: Sound Navigation and Ranging
SPL	: Sound Pressure Level
TE-TU (2E-2U)	: Two Equations - Two Unknowns
TÜBİTAK	: Türkiye Bilimsel ve Teknolojik Araştırma Kurumu (Scientific Technological Research Council of Türkiye)
TVR	: Transmitting Voltage Response
UUT	: Unit Under Test
c	: Acoustic wave propagation speed in water
C	: Capacitance
d	: Distance
dB	: Decibel

d_{33}	: Piezoelectric charge constant
dd	: Direct distance
ds	: Shortest two-way distance between the transducers and the nearest tank surface
f	: Frequency
f_s	: Piezoelectric frequency constant
ID	: Inner diameter
L	: Length
ms	: Millisecond
mm	: Millimeter
M_H	: Free field receive sensitivity of hydrophone
$S_{V,P}$	: Transmitting response to voltage of a projector
T	: Thickness
Tan_{δ}	: Dielectric dissipation factor
T_{it}	: Initial transient duration
T_{TG}	: Time gated signal duration
U	: Measurement Uncertainty
V_P	: Transmitting electrical drive voltage at projector
V_{PH}	: Open circuit voltage at hydrophone, from a projector as sound source
V_{pp}	: Voltage peak to peak
V_{rms}	: Voltage root mean square
τ_{da}	: Direct arrival time
τ_{ef}	: Test tank echo free time
W	: Width

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1. INTRODUCTION

The development of underwater electroacoustic transducers has advanced significantly throughout the twentieth century and continues to evolve. These advancements integrate applications from acoustics, physics, electronics, mechanics, and material science. A transducer, in general, is a sophisticated device that converts energy from one form to another. Specifically, an underwater electroacoustic transducer converts electrical energy into acoustic energy or vice versa, making it essential for various underwater acoustic applications, such as SONAR systems [1].

SONAR is a technique used to detect and locate objects either by receiving the sounds they emit or by identifying objects through the echoes reflected from them when insonified. SONAR systems consist of two main subsystems: the Wet-End and the Dry-End. The Wet-End includes transducers, cables, and mechanical components that form the array structure. The Dry-End comprises electronics such as power supplies, transmitter channels, receiver channels, and software, including signal processing algorithms and user interfaces.

The use of sound in water requires transducers for both generating and receiving sound, most of which are electroacoustic. SONAR systems rely on projectors to emit sound, which hydrophones then detect, either directly or via reflections from a target. Naval applications are the primary drivers of innovations in underwater sound transducers.

Surface ships use hull-mounted arrays with hundreds of transducers for low and medium frequency applications, such as ASW SONAR, and high-frequency applications, such as mine-hunting SONAR. Submarine transducers must operate across a wide range of hydrostatic pressures. Developing long-range active SONAR systems is particularly challenging due to the need for high source level at low frequencies ($f < 10$ kHz).

Depending on the source level, bandwidth, and system requirements, projectors can take various geometric and mechanical forms, including spheres, cylinders, rings, piston radiators, benders, and amplified motion devices such as flextensional transducers. The operating frequency band for a specific application significantly

impacts the type of transducer required. For low-frequency operations, designs with low resonant frequencies and manageable sizes, such as benders or flextensional transducers, can be an option.

This thesis proposes a novel design approach to address the acoustical and mechanical challenges associated with applying low frequency to Class V Flextensional transducers. Literature indicates that research has primarily focused on developing Class V Flextensional transducers for moderate to high-frequency applications, especially in biomedical field and ultrasonic applications.

The primary objective of this thesis is to develop a novel type of Class V Flextensional transducers as underwater acoustic projectors for low-frequency ranges. The proposed approach involves creating a Computer Aided Design (CAD) model of the transducer, which will be analyzed using Finite Element Analysis (FEA) software. Based on the obtained CAD model, a prototype transducer will be manufactured, experimentally characterized in a test tank using both conventional calibration method and Two Equations - Two Unknowns (2E-2U) method and compared with the FEA model output.

2. LITERATURE SUMMARY

An electroacoustic transducer is a device that transforms electrical energy into mechanical (sound) energy, or the other way around. When such a transducer is used to produce sound waves in a medium, it is known as a sound projector or transmitter. On the other hand, when it is employed to detect sound, it is termed as hydrophone. Over the past fifty years, piezoelectric materials have been predominantly used as the active component in these transducers.

Underwater projectors achieve optimal efficiency and sound transmission when operated at their resonance frequencies. Literature classifies these projectors into three primary frequency ranges: low-frequency, mid-frequency, and high-frequency. Typically, the low-frequency range extends up to 10 kHz, the mid-frequency range covers 10 kHz to 100 kHz, and the high-frequency range is defined as frequencies above 100 kHz [2].

Among the different types of transducers used for underwater applications, Flextensional transducers are particularly notable. They gain special interest because their unique end-cap design amplifies the displacement of the piezoelectric actuator. Unlike other transducers, such as Tonpilz transducers, whose resonance frequencies are closely linked to their physical size, Flextensional transducers do not have this direct size-frequency correlation. As a result, Flextensional transducers designed for low-frequency operation are typically smaller than other transducers working in the same frequency range.

The term Flextensional describes a special type of electroacoustic transducer that works well for low to medium-frequency applications. These transducers operate at their first mechanical resonance, which matches the first symmetrical flexing mode of their shell (end-cap). At this resonance, they are usually much smaller than the sound wavelength in water. This makes them act like a non-directional sound source.

2.1. Flextensional Transducers

Flextensional transducers are utilized across a variety of frequency ranges and power levels for different applications, including underwater, biomedical, and ultrasound.

They emit sound through the flexing of a metal or Glassfiber Reinforced Plastic (GRP) shell, which is activated by a drive stack functioning in an extensional mode. The name "Flextensional" transducer initially used by Toulis in 1960s. The mode of this transducer is the constitution of flexural and extensional mode [1].

Basically, the piezoelectric stack inside the Flextensional transducer drives the mechanical shell [3]. The shell, the stack and the surrounding medium are the three sub-systems that form the Flextensional transducer. Flextensional transducers show important performance distinction due to their different design approach and material properties even though they mostly comprise from the basic components mentioned earlier. According to the literature, Flextensional transducers are classified into seven types, as given in Figure 2.1 [1]. These types have emerged since the 20th century to meet different kinds of needs according to their application areas.

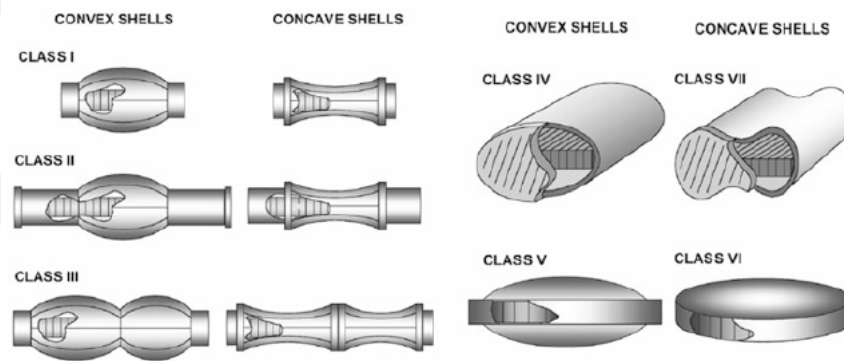


Figure 2.1: Sketch of various classes of Flextensional transducers.

In 1929, Hayes's research actually pioneered the generation of the first Flextensional transducer [4], even though it is generally known that Toulis was the inventor of the Flextensional transducer due to his patent in 1966 [4], [5]. Flextensional transducers can range in length from a few centimeters to several meters and can weigh up to hundreds of kilograms [5].

The design approach of the miniaturized Flextensional transducer is vital for low-frequency usage, which contributed to the advancement of Class V Flextensional transducers. The important features of the different types of Flextensional transducers are given in Table 2.1 [1], [3], [6].

Table 2.1: Features of Flextensional transducers.

Class	Features
I	Shorter cylindrical terminal sections with rotational symmetry Omnidirectional source, higher output, low frequency
II	Longer cylindrical terminal sections Higher working frequency than Class I, higher output
III	Broadband Frequency Response, each shell has a distinct resonance
IV	Oval-shaped shell design using a bar-shaped piezoelectric
V	End caps at each side Has piezoceramic disc
VI	Concave end caps at each side Functions at greater depth than Class V
VII	Dog bone shape, omni-source functions at greater depth Has a lower effective coupling coefficient than Class IV

Hayes's invention was based on an analogy demonstrating how the relatively high mechanical impedance of the drive rod matched the relatively low mechanical impedance on the surface of the shell [4]. This analogy provides a straightforward explanation of the mechanism of Flextensional transducers across all types, as shown in Figure 2.1.

The design by Hayes was recognized as too complicated, as the SONAR technology at that time was not capable of meeting the needs of transducer technology. Toulis's Flextensional transducer design had some similarity to Hayes's; however, it was driven by a piezoceramic driver and qualified for underwater use. The Flextensional transducer was also studied by Abbott and Merchant around this period. In the 1960s, Brigham and Royster established a classification system based on shell geometry, known as the Flextensional classes [4]. Abbott's design of the Class V Flextensional transducer led to the development of today's Cymbal transducer. Various Flextensional transducer designs and their performance modeling have been studied intensively.

2.2. History of Cymbal Transducer

The cymbal transducer was designed for use as a shallow underwater sound projector and is a miniaturized version of the Class V Flextensional transducer [7]. It is a variation of the ring shell projector geometry studied by the DREA [8]. In 1998, Newnham et al. patented the Cymbal type Flextensional transducer design, which was not the first generation of the Class V. In the 1980s, the Materials Research Laboratory developed the Moonie transducer. The main advantage of this design was its ability to reduce production costs and improve the assembly and manufacturing process of the Class V design [7]. Later, the Cymbal transducer design was further developed to achieve higher displacement and generative force than the conventional Class V design. To eliminate the risk of permanent deformation, the generative force must be carefully considered [7], [9].

This change in the design had a significant effect in reducing the stress at the end-cap, resulting in higher displacement values and overall enhancement [10]. The main difference between the Moonie and Cymbal transducers lies in their metal shell structures. The Cymbal transducer has a thinner metal shell and is lighter in weight.

Figure 2.2 shows the basic structures of the Moonie and Cymbal-type Class V Flextensional transducers [11].

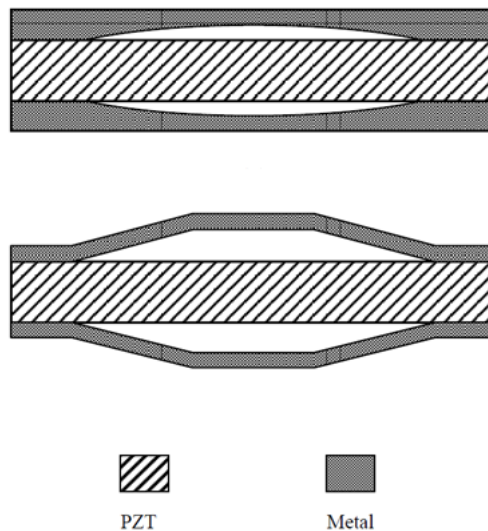


Figure 2.2: Moonie (top) and Cymbal (bottom) transducers.

The Cymbal transducers are omni radiators with high reactance and low resistance. Besides being used as single transducers, array configurations have also been studied for underwater usage [8]. Figure 2.3 shows the schematic view of a single Cymbal transducer and an array.

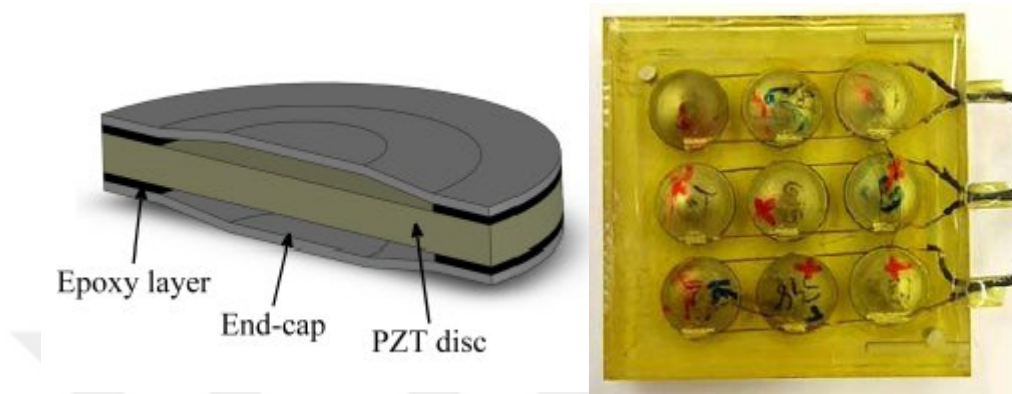


Figure 2.3: Cross section schematic view of classical Cymbal transducer (left), 3x3 array structure for drug delivery biomedical application (right).

For a Cymbal transducer with a diameter of about 12,7 mm (1/2 inch), the first resonance frequency can be around 15 to 20 kHz. It behaves as an omnidirectional source since the size of a Cymbal transducer is considerably smaller compared to the acoustic wavelength in underwater [8], [12]. Due to this small size relative to the wavelength, the Cymbal transducer has low radiation efficiency as a sound projector around resonance. Therefore, it is necessary to assemble them into arrays to achieve the desired source level and directivity at low frequencies. Numerous studies, both numerical and experimental, have been conducted on array arrangements [12]-[18].

To improve amplitude displacement, which was one of the main research areas, several Cymbal transducers were stacked vertically [19]. It was shown that this structure, subjected to symmetric and unidirectional loading, demonstrated high stability and achieved a displacement of 175 μm when five Cymbal transducers were stacked together.

A study was conducted in 1997 focusing on the design and characterization of a Cymbal transducer with two resonance frequency points. A Cymbal transducer was manufactured using two different end-cap materials, steel and brass, while maintaining the same dimensions. The aim of the study was to examine the resonance behavior of

the Cymbal transducer, which had end caps made of different materials. This difference in material properties resulted in two fundamental resonance frequencies. Additionally, the effect of varying the dimensions of the end caps while using the same material was also investigated in terms of their resonance behavior [20]. The same research group further investigated the effects of transducer material properties and end-cap geometry on the actuator performance of the Cymbal transducers through both analytical and numerical modeling [21].

In the 2000s, FEA tools began to be intensively used in the development of Cymbal transducers. The optimization of Cymbal transducer design and its performance evaluation started to be studied using these modeling tools. These tools allow designers to fine-tune key parameters of their designs by defining the transducer geometry and selecting materials. The consequences of these design changes can be simulated using FEA software suites [8], [22], [23].

The standard Cymbal transducer was designed for shallow water use due to its convex structure and thin caps. If the hydrostatic pressure exceeds a certain threshold, the metal caps can become permanently deformed, causing the cavity to collapse and thus destroying the amplification effect [24]. To withstand high hydrostatic loadings, a different design was introduced. In this design the convex end-cap was replaced with a concave type resulting in improved pressure tolerance.

From this stage onward, FEA modeling became more common. Additionally, an analytical model was developed to demonstrate the behavior of the Cymbal transducer [25]. This change underscores the increasing focus on the characterization of transducers by linking modeling with experiments.

In 2000, a significant innovation in the Cymbal transducer design was introduced. Shape memory alloys were used as caps for the Cymbal transducer. These active caps provided a tunable resonance frequency and a damage recovery mechanism due to the material transformation properties of the alloy. Research revealed a 25% change in resonance frequency with Ni-Ti alloy caps. Furthermore, it was demonstrated that the caps could fully regain their shape after being deformed by hydrostatic pressure [26].

In 2001, a directional Class V Flexensional transducer known as a double driver was introduced [27]. Its basic structure consisted of a bilaminar piezoelectric disc with metal caps, developed to address the issue of omnidirectionality. A directional design

was studied in 2003 and patented, utilizing two drivers to combine the bending and flexural mode to enhance sound pressure in one direction while preventing radiation in the other [28]. The use of a dual PZT actuator, which induces bending mode in the PZT and flexural mode in the end cap, enhances the directivity of acoustic radiation.

In 2002, the impact of material and dimensional changes on the Cymbal transducer, both in air and water, was examined experimentally and through finite element analysis (FEA) [29]. The study concluded that the fundamental resonance frequency of the Cymbal transducer can be easily customized for specific applications by adjusting the available dimensional parameters.

Piezoelectric materials with different compositions were used in the design of transducers. The material specifications play a crucial role in determining the displacement characteristics of the transducer [30], [31]. The acoustic performance of a prototype underwater sound projector, constructed from single crystal materials and driven at high levels across the frequency range of 500 Hz to 25 kHz, was reported. Additionally, no significant degradation in acoustic performance was observed when either the PZT-based or single crystal-based projectors were driven for 1-2 hours under high voltages [18].

In 2002, an intensive study was conducted on the design and production optimization of the Cymbal-type transducer, focusing on performance drops caused by non-symmetrical artifacts and their root causes [32]. It was found that asymmetry in cavity depth or the epoxy layer can lead to unwanted resonances, reducing in-water performance. The dimensions of the end cap are one of the key parameters contributing to the resonance response of the transducer. A slight change could significantly shift the frequency response. Despite these challenges, the ease of fabrication and ability to tailor performance to specific applications are appealing features of the Cymbal design. Research showed that increment on the PZT driver thickness may positively affect the undesired modes.

Further research aimed at maximizing displacement and energy transmission was conducted in 2004. The end caps of the Cymbal transducer were radially slotted to reduce stress in the tangential direction [33]. More studies were conducted in 2008 to reduce stress on the end cap, and a wagon-wheel-shaped end-cap design was introduced to the literature by removing portions of the material from the end cap. This modification significantly enhanced the response of displacement [34].

The adjustment of the frequency response of a Flextensional transducer was studied in 2005. Two different approaches were explored: first, adding mass to the end cap's apex, and second, introducing a fluid material into the cavity. The additional mass reduced the resonance peaks of the modes, and it was shown that introducing the necessary mass to the end caps could result in a unique resonance appearing in the response. It was also confirmed that introducing a fluid material into the cavity of the end cap is not as feasible as adding mass directly to the end cap [35].

In 2006, the optimization of the mechanical quality factor of the Cymbal transducers was investigated to characterize the sharpness of the electromechanical resonance spectrum and the bandwidth of the transducer. It was proposed to partially fill the cavities beneath the end caps of the Cymbal transducer with polymeric media [36]. In the same year, motivated by the need to improve the resonance frequency and power capacity of the Moonie and Cymbal transducers, designs featuring a piezoelectric ceramic thin ring with an inner metal disc and a piezoelectric ceramic disc with a circular metal ring were proposed [37], [38]. As a result, an electro-mechanical equivalent circuit was derived, and resonance frequencies were calculated and compared with measurements in an air regime. The underwater acoustic performance was not studied at all.

Research was conducted in 2007 to improve the performance of the Cymbal transducer by using Nitinol material for the end cap, leveraging its Shape Memory Effect. In this study, the design parameters and fabrication processes were examined to understand the behavior of the newly introduced end-cap material [39], [40]. Additionally, in the same year, modifications to the Cymbal-type transducer were studied by introducing a shape of rectangle and using a single-crystal material for the actuator to increase the displacement amplitude of the transducer [41].

A novel type of Cymbal, named spherical, was introduced in 2009 to improve the performance of the conventional Cymbal transducer in terms of frequency. The spherical Cymbal transducer consists of a piezoelectric ceramic disc sandwiched between two spherical metal end caps, each containing a shallow spherical inner cavity. The most important gain of this study was that this new type of Cymbal transducer promoted a decrease in the resonance frequency compared to a conventional Cymbal transducer with the same dimensional characteristics [42].

Excessive stress on the adhesive material used for bonding the end cap to the PZT material limits the performance of the Cymbal transducer when operating at its resonance frequency [43], [44]. Recent research has focused on adapting these transducers for high-power ultrasonic applications [45]-[47]. The design of the end cap plays a crucial role in the coupling mechanically of the Cymbal transducer when driven at high power levels, which can result in a debonding phenomenon of the adhesive material [10]. Since the bonding agent's strength is limited, the integrity of the piezoelectric ceramic disc and the metal caps can be compromised when the input power and vibrational displacement increase, sometimes resulting in debonding.

The mechanical coupling of the transducer needs improvement by modifying the coupling mechanism to eliminate the limitations of the bonding agent's finite strength. Some researchers have investigated this approach [10], [45]. With this design, the end caps were attached to a ring of metal with screws to enhance mechanical coupling and reduce stress on the epoxy layer. This improvement allows the transducer to achieve larger displacement amplitudes and enables the application of higher voltage levels. This concept was demonstrated, and a biomedical cutter was subsequently prototyped and tested [46].

Although many studies have been conducted individually and in array formats to enhance the properties of Cymbal transducers, they have mostly been used for high-frequency applications. Numerous investigations aimed at increasing displacement have been successful in many cases. Continued research aims to overcome limitations of bonding agent strength and expand applications for high-power ultrasonic devices. However, research and technology have largely overlooked SONAR applications, particularly in low-frequency usage.

2.3. Unique Aspect

The mentioned articles discuss the fundamental design approach and structural improvements of Class V Flexensional transducers used for various applications, as summarized in the Section 2.2.

A traditional Class V Flexensional transducer consists of a PZT disc, polarized in the direction of thickness, placed between two symmetrical end-caps. In this design, the piezoelectric disc is excited to produce radial displacement. The Class V Flexensional

transducer boasts high efficiency in converting electrical energy to acoustic energy, significant vibrational displacement, and high acceleration sensitivity due to the amplification of the resulting axial displacement of the end caps.

However, the conventional Class V Flextensional transducer design has some drawbacks, particularly when driven with high voltage as a sound projector. In this design, the piezoelectric ceramic disc and specially designed metal end-caps are bonded together using epoxy as a bonding agent. To address the issues of bonding strength and potential asymmetry, an improved design has been proposed, replacing the piezoelectric disc with a piezoelectric ring and an external metal ring [10].

To date, most studies have focused on disc-shaped piezoelectric materials, with end-caps attached to flat surfaces, thoroughly investigating the coupling problem to address bonding failures. Recently, a few studies have explored replacing the piezoelectric disc [10], [24], [38] with ring-shaped piezoceramics. However, these studies did not focus on the low-frequency regime, indicating a need for more detailed investigation to characterize the behavior of these materials for underwater low-frequency projector applications.

The ring, short thin-walled tube, or disc shape are among the most common forms of piezoelectric actuators used in underwater transducers for both projectors (e.g., piston type) and hydrophones (e.g., cylindrical type). These piezoelectric actuators can be stacked and integrated into array formats, end-capped and air-backed, or free-flooded and mostly operated in either the piezoelectric d31 or d33 mode.

The d31-mode piezoelectric ring, Figure 2.4, is the most commonly used ring-shaped piezoelectric material in the research cited in the literature chapter. In this mode, the 1 direction is along the circumference (T), 2 is along the height (H), and 3 is radial (R). The d31-mode excites cylindrical vibration with primary stress and strain in the circumferential direction (1), induced by an electric field orthogonal to that direction (3). This mode is favored for its simple construction, though it is not the optimal method for exciting circumferential motion.

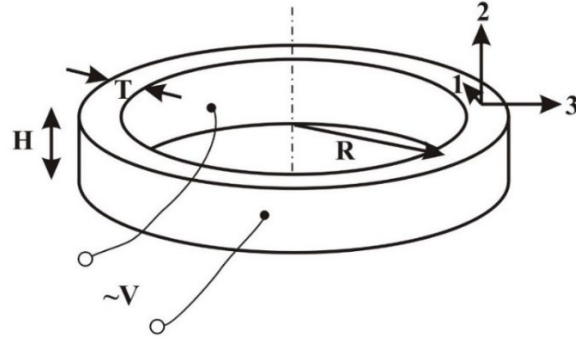


Figure 2.4: d31-mode piezoelectric ring with a mean radius R , thickness T and height H .

Although the d31-mode ring design is simple and effective, greater coupling power output and electrical efficiency can be obtained by operating in the d33-mode, Figure 2.5, where the electric field is directed along the circumference direction (3). To have electrical connections between each partition, the ring needs to be constructed from sub-sections called segments.

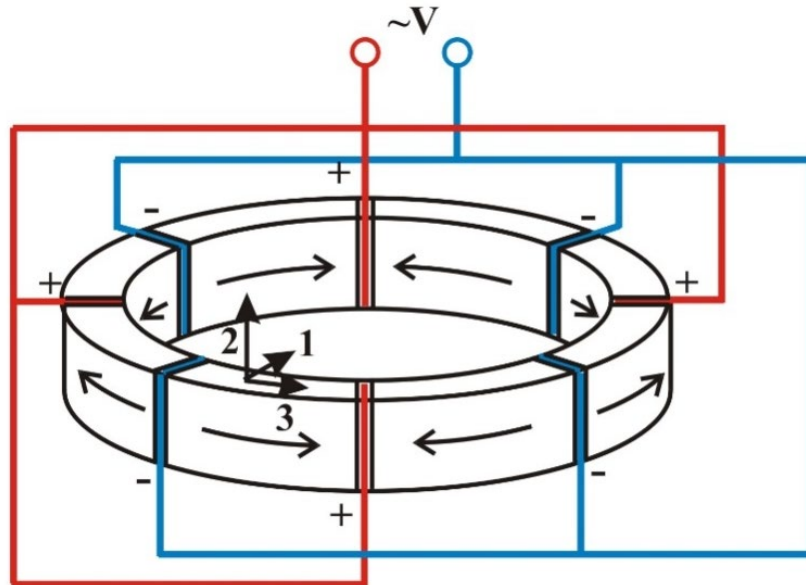


Figure 2.5: d33-mode piezoelectric ring (segmented-curved) with a mean radius R , thickness T and height H .

The main objective of this thesis is to investigate the segmented piezoelectric ring in the d33-mode, and to fully characterize and understand the underwater behavior of a

new Class V Flextensional type projector referred to as segmented Class V Flextensional transducer element.

To reduce the resonance frequency of the Class V Flextensional transducer, the diameter of the piezoelectric ring material needs to be increased, which can be challenging from a manufacturing perspective. However, it is preferable to manufacture a segmented ring rather than a monolithic one. In this case, the electrodes are placed on the adjacent surfaces of the piezoelectric segments and poled through the wedge thickness, as indicated by the arrows in Figure 2.6. Due to the simplicity of the manufacturing process, cornered piezoelectric material is proposed instead of curved material, as shown in Figure 2.6.

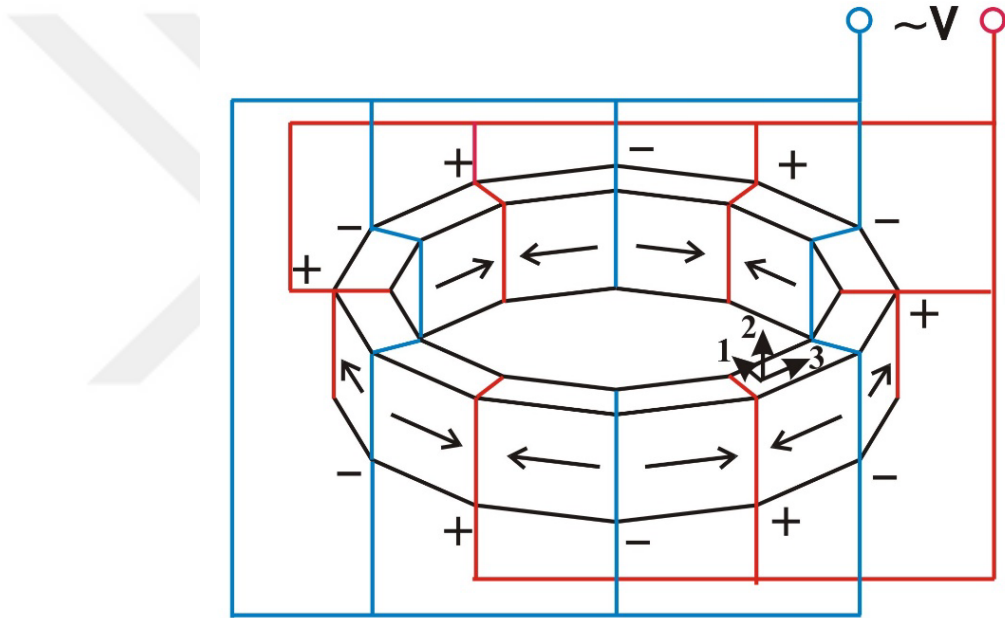


Figure 2.6: d33-mode piezoelectric ring (segmented - cornered) with a mean radius R , thickness T and height H .

The improved performance characteristics of the Class V Flextensional transducer compared to a simple piezoelectric disc or ring are due to the amplification behavior of the end-caps. Although these end-caps enhance the small lateral displacement associated with the d33/d31 to a large axial displacement, this mechanism generates very high tangential stress in the caps, which leads to a reduction in efficiency. Various types of end-cap designs have been suggested in the literature for different application areas [24], [33], [34], [48].

The studied end-cap designs are shown in Figure 2.7. The reason for the change in end-cap design is illustrated in Figure 2.8, which shows the stress of the end-caps. The stress distribution varies significantly between the designs of cymbals and wagon wheels. In the cymbal end cap structure, the stresses are concentrated near the inner edges of the flange and gradually decrease towards the apex, decreasing by an order of magnitude. Conversely, in the wagon wheel end cap, the stresses decrease by two orders of magnitude from the inner edge of the flange to just above the base of the six spokes [34].

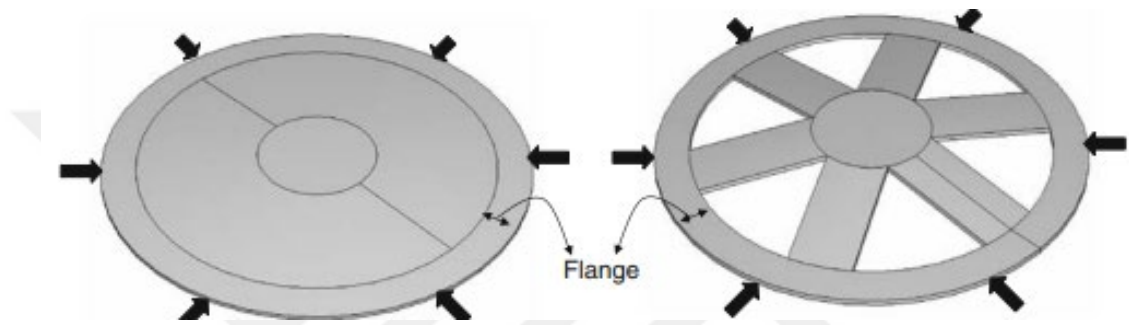


Figure 2.7: Generic Cymbal end-cap (left) and wagon wheel design (right).

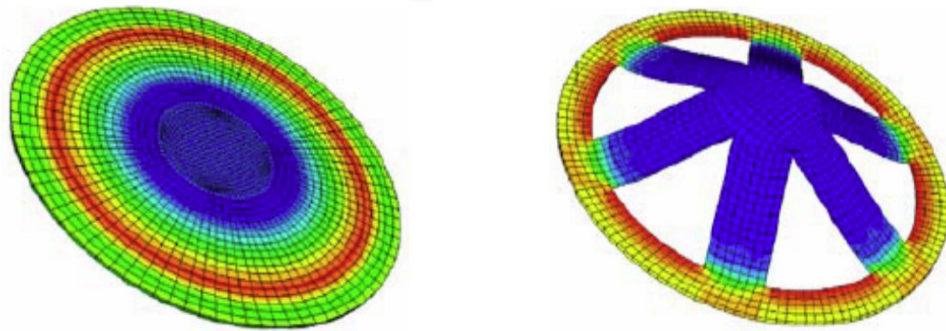


Figure 2.8: Stress distribution on the end-cap. Regular end-cap FEA model (left) and wagon wheel end-cap FEA model (right).

Another end-cap design with reduced stress and deformation, the slotted end-cap design, is given in Figure 2.9. It was demonstrated that incorporating slots in end caps could enhance the performance of the original cymbal transducer, particularly by increasing displacement and energy transmission efficiency, and effectively lowering the fundamental resonance frequency [33].

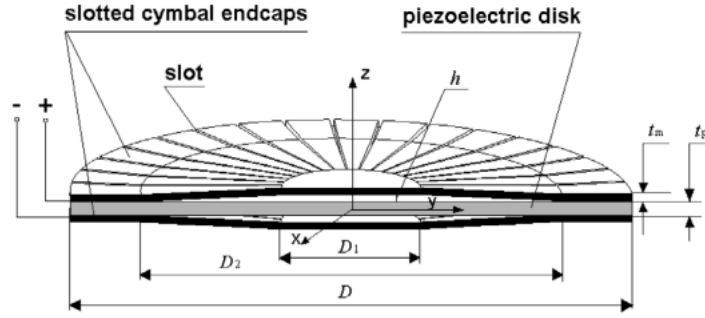


Figure 2.9: Cross sectional view of the slotted end-cap design.

Past studies clearly showed that the end-cap design and the mounting approach had a significant performance effect on cymbal transducers, which were mainly focused on air applications, i.e., medical usage. Another objective of this thesis is to implement a new type of end-cap design and installation method to reduce the risk of debonding of the end-cap when the underwater projector is driven with high voltage ($\approx 100 V_{pp}$) at low frequencies. Additionally, isolating the projector by encapsulating it presents a unique challenge when designing a transducer element for underwater applications, which will be detailed in Chapter 4.

The acoustic characterization of the transducer, which will be developed in this thesis along with application-specific end-cap designs and encapsulation, will be studied using finite element analysis and electroacoustic measurements. For these applications, where displacement is the principal objective (with low forces), copper-based materials will be used for the end-cap.

The adhesion of the end-cap to the ceramic actuator is highly important when the ceramic is driven with high voltages, especially in the low-frequency regime for underwater projector applications. Figure 2.10 illustrates the newly proposed design approach with non-polarized parts of a ring-type actuator, which can be used for integrating the end-cap and the actuator itself. Due to the rectangular shape of the piezoceramics, better homogeneity of the internal electric field will be achieved. Possible fixtures of the end-caps are indicated by dashed lines in Figure 2.10.

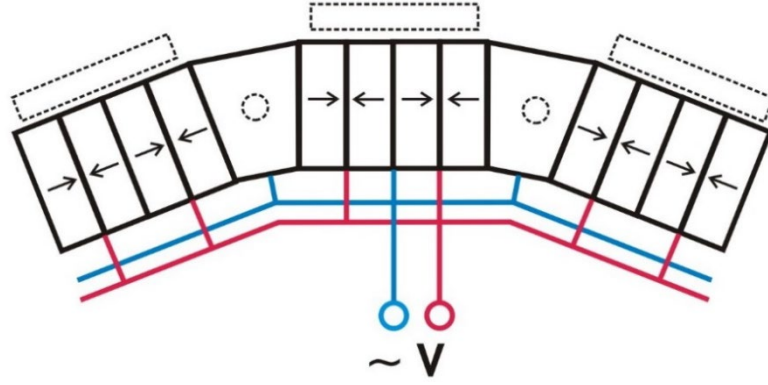


Figure 2.10: New design – segmented Class V transducer design with integration method of the end-cap (top view).

In this study, the free field calibration by the comparison method is used for the calibration of segmented Class V Flextensional transducer element in the open test tank facility of TÜBİTAK MAM SAL. However, due to the limited size of the open test tank for amplitude measurements in the frequency range below 1 kHz, additional methods are required to construct the steady state signal from the time gated received signals. This extends the calibration capability of the open test tank facility at low frequencies. To this aim, the main methods are:

- A time-delayed spectrometry method
- A method of using noise or pseudo-random noise signals
- A sound power measurement method
- A complex weighted moving average (CWMA) method
- A signal modeling method

The primary goal of these methods is to minimize the impact of reflections in the received signal to extend the echo-free time of the test tank. By sweeping the source signal, the time-delayed spectrometry method uses a tracking filter to isolate the direct signal between the transmitter and receiver. This is possible because the reflected signal, arriving at the receiver later, contains frequency components outside the passband of the tracking filter. As a result, this approach is essentially an application of a signal processing technique [49].

The method utilizing noise or pseudo-random noise signals involves measurements in a diffuse field within a reverberant tank [50], [51] with an extension of the sound power measurement method based on relationship between the acoustic field in the tank and

the source field in a free-field environment. This is performed by spatial averaging of a normal-mode representation for the acoustic power in the tank [52]. The complex weighted moving average (CWMA) method is structured on the complex averaging of the transducer transfer function of the reverberating field. Thus, it is possible to derive a free field transfer impedance of the laboratory test tank [53].

In the signal modeling method, the received signal waveform is matched to a specified signal model, enabling the estimation of the steady-state amplitude and phase values of the received signal. To determine the unknown parameters of the model, either a linear or non-linear fitting algorithm is employed, depending on the complexity of the signal model. A linear algorithm suffices for a simple model (without transients), while a non-linear algorithm is necessary for an extended model (with transients). For the extended model, accurate initial estimates of parameters, such as resonance frequencies and damping factors, are essential for successful application [54].

Another unique aspect of this thesis is the application of an alternative measurement method for free-field underwater calibration of transducers in a reverberant laboratory test tank at low frequencies. At low frequencies, amplitude and phase measurements for transducer calibration in the test tank are challenging because the echo-free time of the laboratory test tank is insufficient due to initial transients from the transducer and reflections from the tank walls. To address these challenges, the 2E-2U method [55] is applied to received (windowed) signals obtained during calibration measurements. The proposed 2E-2U method eliminates the need for any fitting algorithms, which is its primary advantage. This simplicity results in minimal memory usage and computational requirements, making its application highly efficient. This method enables calibration measurements at frequencies as low as 250 Hz. Within this scope, the calibration results of the prototype segmented Class V Flextensional underwater acoustic transducer, obtained using the 2E-2U method, are compared with the calibration measurements from the test tank.

In summary, the unique aspect of this thesis is the design, development, and prototyping of a novel Class V Flextensional transducer with a segmented actuator and applicable end cap design. Detailed modeling of the transducer using Finite Element Analysis and laboratory test tank calibration measurements are conducted to fully characterize the behavior of the segmented Class V Flextensional transducer.

3. DESIGN

In this Chapter, the main design parameters of a conventional Cymbal transducer element are studied to provide a baseline for the geometrical design of the segmented Class V Flextensional transducer element. Within this scope, based on the conducted literature review, the fundamental resonance frequency of a conventional Cymbal transducer is analyzed using analytical methods. The primary design goal is to develop a novel Class V Flextensional transducer with a fundamental frequency of 4-5 kHz, which is a challenging objective for today's underwater acoustic projectors.

Based on the baseline results of analytical methods, a 3D CAD model is created for use in modeling and manufacturing the parts for prototyping.

3.1. Determination of Class V Flextensional Transducers Design Parameter by Analytical Method

The fundamental resonance frequency of a Class V Flextensional transducer is tunable by carefully selecting the material of the end cap and adjusting its dimensions. The operating frequency of the Class V Flextensional transducer corresponds to the first mechanical resonance of the device, which is the first symmetrical flexure mode of the shell, or the end-cap, in a Class V Flextensional transducer.

During the analytical evaluation of these parameters, a generic Class V Flextensional transducer design is used to assess the first resonance frequency, primarily determined by the end-cap material and design. The proposed design within the scope of this thesis will have a similar end-cap, allowing the analytical evaluation of the conventional Class V Flextensional transducer to be applicable for assessing the first resonance frequency of the considered transducer design.

The cross-sectional view of the conventional Class V Flextensional transducer along with the dimension parameters and their respective symbols are given in Figure 3.1.

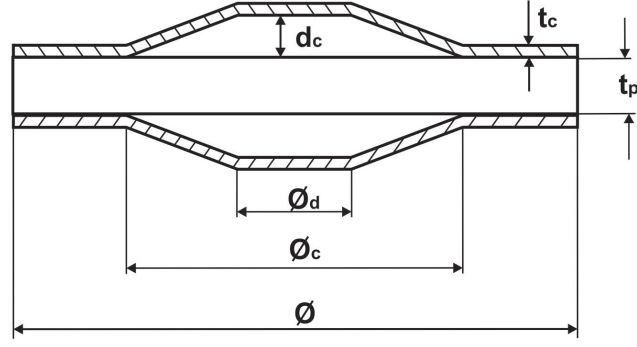


Figure 3.1: Cross sectional view of the conventional Cymbal type Class V Flextensional transducer.

Dimension parameters of the cross-sectional view of the Cymbal type Class V Flextensional transducer is given at Table 3.1. The same naming conventions will continue throughout the rest of the thesis.

Table 3.1: Dimension parameters of cross-sectional view of the Cymbal Class V Flextensional transducer.

Parameter	Symbol
End-Cap Diameter	$\emptyset$
Cavity Diameter at Base	$\emptyset_c$
End-Cap Thickness	t_c
Apex Diameter	$\emptyset_d$
Cavity Depth at Apex	d_c
Piezoelectric Material Thickness	t_p

The resonance frequency of a Class V Flextensional transducer primarily depends on the physical and material characteristics of the end caps, with the cavity base diameter and the thickness of the end cap particularly influencing the vibration response [56]. The first resonance frequency of the transducer is minimally affected by the thickness of the piezoelectric material, as the high vibrational displacement and acceleration sensitivity result from the amplification of the end-cap's axial displacement [57].

The main resonance frequency (3.1) of a Class V Flextensional transducer is primarily governed by the end-cap dimensions and material properties (elastic constants) when operating in air $f_{r,a}$. Analytical methods based on shell theory were used to calculate the resonance frequency [5], [58] as below

$$f_{r,a} \propto \sqrt{\frac{E}{\rho_c} \left(\frac{1}{\emptyset_c^2 (1 - \sigma^2)} + \frac{1}{R^2} \right)} \quad (3.1)$$

where E is young's modulus, ρ_c is material density, σ is poisson's ratio, R is end-cap radius, $\emptyset_c$ is cavity diameter at base, $f_{r,a}$ is first fundamental resonance frequency in air.

In another study, the fundamental resonance frequency (3.2) of a spherical-cymbal transducer is investigated, and an analytical method is developed to calculate the first resonance frequency in an air environment [42] as

$$f_{r,a} = \sqrt{\frac{E}{\rho_c} \left(\frac{\lambda_{r,a}^4}{\emptyset_c^4} \frac{t_c^2}{12(1 - \nu^2)} + \frac{1}{R^2} \right)} \quad (3.2)$$

where E is Young's modulus, ρ_c is material density, $\lambda_{r,a}$ is frequency coefficient (Wavelength calculation for 1 kHz), $\emptyset_c$ is cavity diameter at base, t_c is end-cap thickness, ν is poisson's ratio, R is end-cap radius.

Based on equations (3.1) and (3.2), the first resonance frequency of the end cap designed for the segmented Class V Flextensional transducer element is calculated during the initial design phase of the thesis. Since neither equation (3.1) nor equation (3.2) totally correlates with the working mechanism of the novel design segmented Class V Flextensional transducer element, this effort is made to establish a baseline relationship between the general dimensions of the segmented Class V Flextensional transducer element and its first resonance frequency.

Additionally, the relationship between the resonance frequencies in air and when water-loaded for the Class V Flextensional transducer is given in equation (3.3) which correlated to the first resonance frequency of it in air as

$$f_{r,w} = \frac{f_{r,a}}{\sqrt{1 + \left(\frac{4\emptyset_c}{3\pi} \right) \left(\frac{\rho_w}{\rho_c} \right) \left(\frac{0,7885}{t_c} \right)}} \quad (3.3)$$

where ρ_w is water density, ρ_c is end-cap density, t_c is end-cap thickness, $\emptyset_c$ is cavity diameter at base, $f_{r,a}$ is first fundamental resonance frequency in air, $f_{r,w}$ is first fundamental resonance frequency in water.

The four different key parameters are considered during the design stage of the segmented Class V Flextensional transducer element, as these parameters mainly determine the first resonance frequency in both air and water environments. It should be noted that these equations are based on curve deflection theory for a thin plate clamped around its rim [59], which is used in determining the size of the segmented Class V Flextensional transducer element for prototyping.

- Effects of End-Cap Material

The transducers made with different end-cap materials have their first resonance frequency proportional to the term $[E/\rho(1 - \sigma^2)]^{1/2}$ which is related to the sonic velocity of the end-cap material [29].

The resonance frequencies for equal dimension end-caps with different material properties are given in Table 3.2. Analytical calculations for different end-cap materials are done using the following transducer parameters: $\emptyset = 100$ mm, $\emptyset_c = 68$ mm and $t_c = 1$ mm. The resonance frequency in air is calculated using the two equations (3.1) and (3.2) given above.

Table 3.2: Effects of end-cap material on fundamental resonance frequency.

End-Cap Material	Brass	Aluminum	Titanium	Steel	Tungsten	Polyamide
E GPa	125	70,6	120,2	207	411	101
ρ_c kg/m ³	8400	2700	4500	7860	19300	1400
σ	0,34	0,34	0,36	0,30	0,28	0,40
End-Cap Material	Brass	Aluminum	Titanium	Steel	Tungsten	Polyamide
$f_{r,a}$ kHz (3.1)	3,1	4,1	4,2	4,1	3,7	6,9
$f_{r,w}$ kHz (3.3)	1,6	1,3	1,7	2,1	2,5	1,7

Table 3.2: Continuation.

End-Cap Material	Brass	Aluminum	Titanium	Steel	Tungsten	Polyamide
$f_{r,a}$ kHz (3.2)	2,5	3,3	3,3	3,3	2,9	5,4
$f_{r,w}$ kHz (3.3)	1,3	1,1	1,3	1,7	2,0	1,3

The results show that the first resonance frequency can be adjusted simply by changing the end-cap material while keeping the transducer size fixed. The calculated data indicate that an end-cap material with a density closer to that of water will exhibit a much more significant shift in its first resonance frequency when immersed in water than a higher-density end-cap material.

- Effect of End-Cap Thickness

The resonance frequencies for end-caps of equal dimensions made from brass, with varying thicknesses, are presented in Table 3.3. Analytical calculations for different end-cap thicknesses are done using the following transducer parameters: $\varnothing = 100$ mm, $\varnothing_c = 68$ mm and End Cap Material = Brass.

The results indicate that as the end-cap thickness decreases, the first resonance frequency decreases linearly in water. However, the analytical method shows that the end-cap thickness does not affect the resonance frequency when the transducer is in air. Additionally, the results show that when the transducer is immersed in water, the difference between the in-air and in-water resonance frequencies decreases as the end-cap thickness increases.

Table 3.3: Effects of end-cap thickness on fundamental resonance frequency.

End-Cap Thickness t_c	0,25 mm	0,5 mm	1,0 mm	1,5 mm	2,0 mm	2,5 mm
$f_{r,a}$ kHz (3.1)	3,1					
$f_{r,w}$ kHz (3.3)	0,9	1,2	1,6	1,9	2,0	2,2
$f_{r,a}$ kHz (3.2)	2,4	2,4	2,5	2,5	2,5	2,5
$f_{r,w}$ kHz (3.3)	0,7	1,0	1,3	1,5	1,6	1,7

- Effect of Cavity Diameter

The resonance frequencies for devices with equal diameter and end-cap thickness, using brass material properties, are provided in Table 3.4 for various cavity diameters. Analytical calculations for different cavity diameters are done using the following transducer parameters: $\emptyset = 100$ mm, $t_c = 1$ mm and End Cap Material = Brass.

Table 3.4: Effects of cavity diameter on fundamental resonance frequency.

Cavity Diameter $\emptyset_c$	40 mm	50 mm	60 mm	68 mm	80 mm	90 mm
$f_{r,a}$ kHz (3.1)	4,1	3,6	3,3	3,1	2,9	2,8
$f_{r,w}$ kHz (3.3)	2,5	2,1	1,8	1,6	1,4	1,3
$f_{r,a}$ kHz (3.2)	2,5	2,5	2,5	2,5	2,4	2,4
$f_{r,w}$ kHz (3.3)	1,6	1,4	1,3	1,3	1,2	1,1

The increase in cavity diameter causes a decrease in the first resonance frequency in both in-air and in-water conditions, which is more significant in calculations based on equation (3.1).

- Effect of Device Diameter

The resonance frequencies for equal cavity diameter and thickness of end caps with brass material properties for different device diameters are given in Table 3.5. Analytical calculations for different device diameters are done using the following transducer parameters: $\emptyset_c = 68$ mm, $t_c = 1.0$ mm and End Cap Material = Brass.

Table 3.5: Effects of device diameter on fundamental resonance frequency.

Device Diameter $\emptyset$	80 mm	90 mm	100 mm	110 mm	120 mm	130 mm
$f_{r,a}$ kHz (3.1)	3,6	3,3	3,1	2,9	2,8	2,7
$f_{r,w}$ kHz (3.3)	1,9	1,7	1,6	1,5	1,5	1,4

Table 3.5: Continuation.

$f_{r,a}$ kHz (3.2)	3,1	2,7	2,5	2,2	2,0	1,9
$f_{r,w}$ kHz (3.3)	1,6	1,4	1,3	1,2	1,1	1,0

The results show that an increase in device diameter causes a decrease in the first resonance frequency both in-air and in-water.

The analytical calculations show that the Class V Flextensional transducer's end cap material and mechanical properties have significant effects on the first resonance frequency. The calculations are performed when the Class V Flextensional transducer is loaded with air or water medium. Since the given equations (3.1) and (3.2) are derived for the original Cymbal and Spherical Cymbal transducers based on shell theory, the results presented in the tables Table 3.2, Table 3.3, Table 3.4 and Table 3.5 are used to understand the frequency relationship with the material and mechanical properties for the initial design of the segmented Class V Flextensional transducer element. The first resonance of the segmented Class V Flextensional transducer element will be determined by FEA study and underwater acoustic measurements and studied in detail in Chapter 5 and Chapter 6.

This understanding provides a starting point for the design stage of the segmented Class V Flextensional transducer element considered for the frequency range of interest in this thesis, which is primarily focused on low-frequency applications. During the FEA of the segmented Class V Flextensional transducer element with the proposed design, the acoustic and electrical performance of the transducer will be examined both numerically. The preliminary design stage will then be finalized for the prototyping stage.

In the next stage, the electro-acoustic performance of the manufactured segmented Class V Flextensional transducer element will be measured both acoustically and electrically. It will be calibrated using standard calibration procedures and a newly proposed calibration procedure by the 2E-2U method. The validation of the numerical analysis will be conducted through these measurements.

3.2. Overall Design of Segmented Class V Flextensional Transducer Element

The general view of the segmented Class V Flextensional transducer element 3D model is shown in Figure 3.2. Based on the general design of the transducer, the detailed design of the subparts is developed for the manufacturing process and the FEA study.

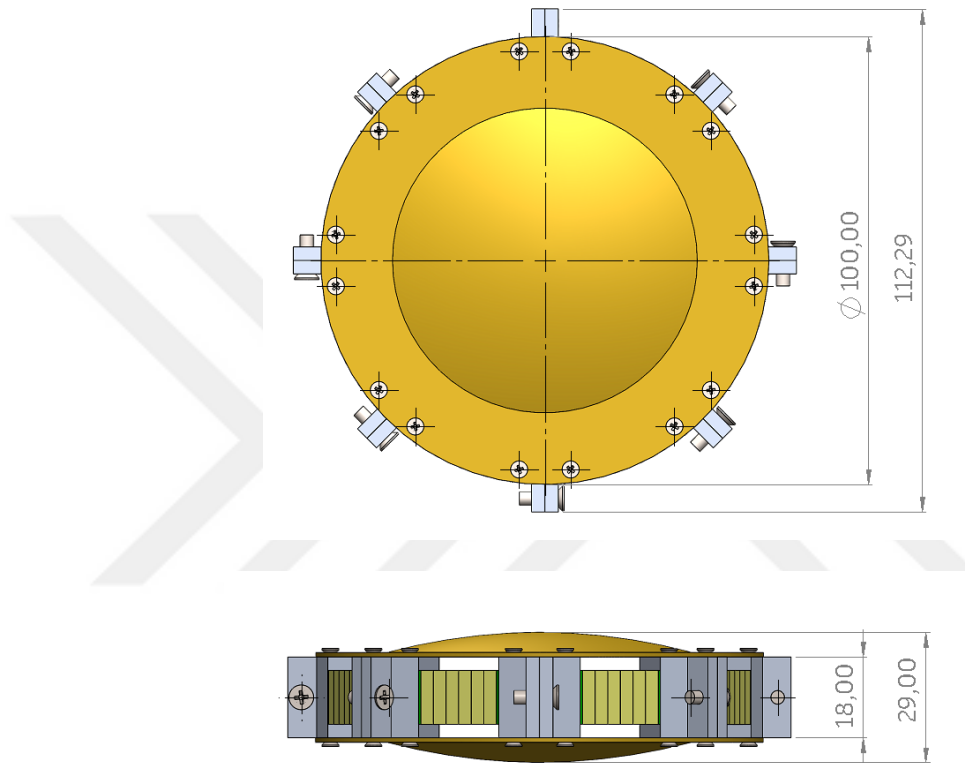


Figure 3.2: Top (top) and side (bottom) view of general design of the segmented Class V Flextensional transducer element design without encapsulation.

3.3. Design Details of Segmented Class V Flextensional Transducer Element

The design stage of the subparts of the segmented Class V Flextensional transducer element is studied for the sub-categories listed below:

- a) End-Cap Design
- b) Piezoelectric Material Design
- c) Non-PZT Materials Design

3.3.1. End-Cap Design

The end-cap dimensions for the segmented Class V Flextensional transducer element are provided in Table 3.6.

Table 3.6: End-cap dimensions of the segmented Class V Flextensional transducer element.

Parameter	Dimension (mm)
End-Cap Diameter	100
Cavity Diameter at Base	68
End-Cap Thickness	1
Cavity Depth at Apex	4,5

The 3D drawings for the manufacturing process and the FEA modeling work are shown in Figure 3.3.

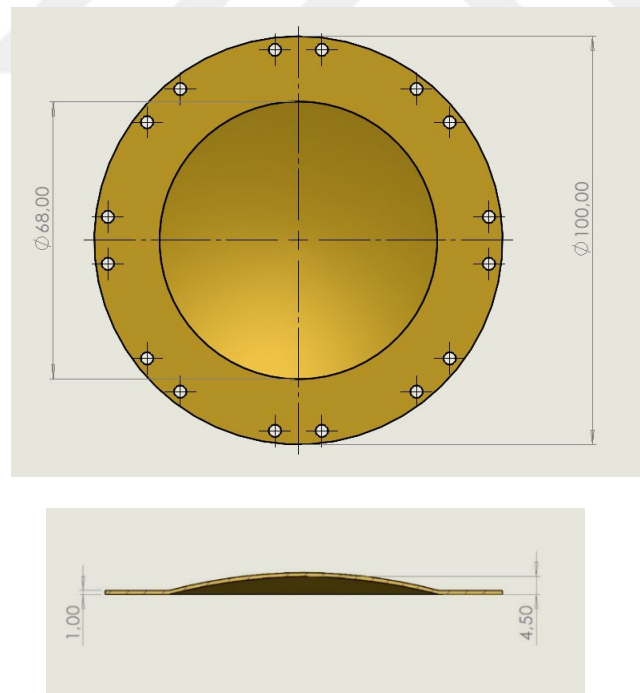


Figure 3.3: Top (top) and cross section (bottom) view of the segmented Class V Flextensional transducer element brass end-cap design.

3.3.2. Piezoelectric Material Design

PZT is one of the most widely used piezoelectric ceramic materials in the world in the field of transducer applications. In simple terms, when a piezoelectric material is deformed, it generates an electric charge, a phenomenon known as the piezoelectric effect. Conversely, if an electric field is applied to a piezoelectric material, it undergoes deformation, which is referred to as the inverse piezoelectric effect.

PZT is a piezoelectric ceramic material based on metallic oxides, developed by scientists at the Tokyo Institute of Technology around 1952. Compared to the earlier-discovered barium titanate, another metallic oxide-based piezoelectric material, PZT exhibits greater sensitivity and can operate at higher temperatures.

The manufacturing process of PZT involves multiple stages, starting from the powder phase and continuing to the ceramic element phase. PZT ceramic materials are used in a wide range of applications. Soft (sensor) PZT ceramic powders are typically chosen for applications requiring high coupling and/or charge sensitivity, such as hydrophones, flow or level sensors, ultrasonic nondestructive testing, or precise inspections of automotive, structural, or aerospace products. These materials are characterized by their high dielectric constant, high coupling, high charge sensitivity, fine-grained structure, high density, high Curie point, and clean, noise-free frequency response.

Hard (projector) PZT ceramic powders are used when high-power performance is needed, such as in generating ultrasonic or high-voltage energy in sonar devices and ultrasonic cleaners. Key characteristics of these powders include a high piezoelectric charge constant (d_{33}), a higher mechanical quality factor that reduces mechanical loss and allows for lower operating temperatures, a low dissipation factor for cooler and more economical operation, high dielectric stability, and low mechanical loss under demanding conditions.

3.3.2.1. Piezoelectric Constants

Due to the anisotropic nature of piezoelectric ceramics, their physical constants are influenced by both the direction of the applied mechanical or electrical force and the directions perpendicular to it. As a result, each constant typically has two subscripts

indicating the directions of the two related quantities, such as stress (force on the ceramic element/original length of the element) and strain (change in length of the element/original length of the element) in relation to elasticity. The positive polarization direction is usually aligned with the z-axis in a rectangular coordinate system consisting of the x, y, and z axes as shown in the Figure 3.4 [60].

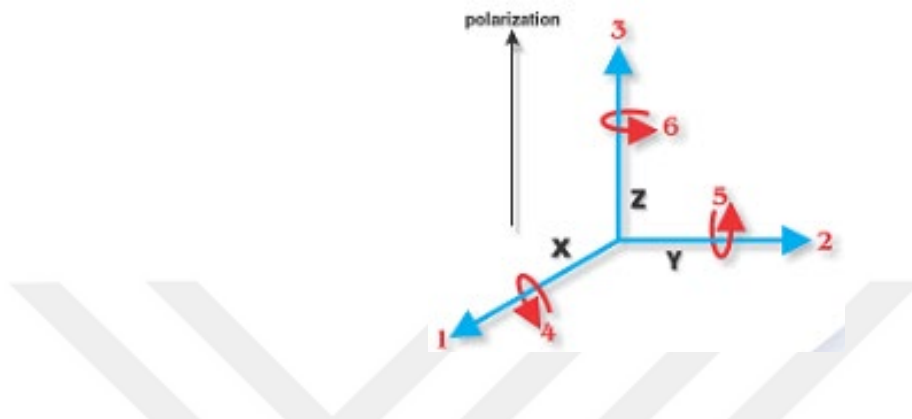


Figure 3.4: Direction of forces affecting a piezoelectric element.

The x, y, and z directions are represented by subscripts 1, 2 and 3, respectively, while shear around these axes is represented by the subscripts 4, 5 and 6. The definitions of the most commonly used constants for projectors, along with equations for determining and interrelating them, are summarized below.

- Piezoelectric Charge Constant - d_{33}

The piezoelectric charge constant d represents the polarization generated per unit of mechanical stress (T) applied to a piezoelectric material or, alternatively, the mechanical strain (S) experienced by the material per unit of applied electric field. The first subscript in d indicates the direction of polarization generated when the electric field (E) is zero, or alternatively, the direction of the applied electric field. The second subscript denotes the direction of the applied stress or the induced strain, respectively.

Since the strain induced in a piezoelectric material by an electric field is the product of the electric field value and the d constant, d is a critical indicator of a material's suitability for strain-dependent applications like projectors.

For example:

d_{33} : The induced polarization in direction 3, which is parallel to the polarization direction of the ceramic element, per unit of stress applied in direction 3,

d_{31} : The Induced polarization in direction 3, which is parallel to the polarization direction of the ceramic element, per unit stress applied in direction 1, perpendicular to the polarization direction of the ceramic element.

- Dielectric Dissipation Factor - $\tan \delta$

The parameter δ , or $\tan \delta$, for a ceramic material represents the tangent of the dielectric loss angle. $\tan \delta$ is calculated as the ratio of effective conductance to effective susceptance in a parallel circuit, typically measured using an impedance bridge. Values for $\tan \delta$ are commonly determined at a frequency of 1 kHz.

- Piezoelectric Frequency Constant - f_s

When an unrestrained piezoelectric ceramic element is exposed to a high frequency alternating electric field, the impedance reaches a minimum at the planar or radial resonance frequency, which aligns with the series resonance frequency f_s . The final resonance frequency of the transducer element is related to the piezoelectric frequency constant; however, the frequency response of the transducer itself is also influenced by the contributions of components such as the end-cap, non-piezoelectric materials, etc., for the segmented Class V Flexensional transducer element.

3.3.2.2. Details and Characterization of the PZT Material

Hard PZT (Lead Zirconate Titanate) material is used in the segmented Class V Flexensional transducer element. The dimensions and the general view of the PZT plates for the segmented Class V Flexensional transducer element are given in Table 3.7 and Figure 3.5 as requirement to the manufacturer.

Table 3.7: Dimensional requirement of PZT materials of the segmented Class V Flextensional transducer element.

Parameter	Dimension (mm)	Tolerances (+/-)
Plate Length	12	0,1
Plate Width	12	0,1
Plate Thickness	3	0,1
Diameter of Center Hole	3,5	0,1

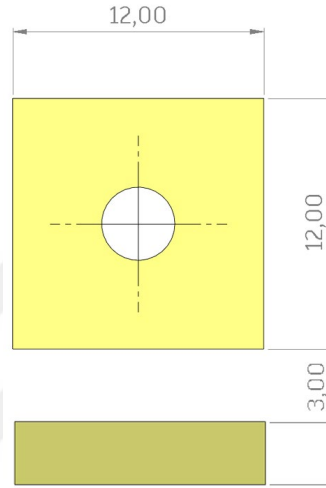


Figure 3.5: Top (top) and side (bottom) view of the PZT plate design.

In addition to the dimensional requirements, the electrical parameters of the PZT plate are also provided to the manufacturer, as specified in Table 3.8.

Table 3.8: Electrical parameters requirement of PZT materials of the segmented Class V Flextensional transducer element.

Parameter	Value	Tolerances (+/-)
Capacitance	620 pF	20 pF
Dielectric Dissipation Factor	0,5 %	0,02 %
Piezoelectric Frequency Constant	366 kHz	1 kHz
Piezoelectric Charge Constant	350 pc/n	10 pc/n

The characterization of the purchased PZT plates is performed using a piezometer and compass in the laboratory to verify that the materials received from the supplier met the desired requirements. For this purpose, as mentioned above, the dimensional and electrical parameters of the PZT plates are measured and are listed in Table 3.9. A

sampling of the overall production is conducted, and a total of 20 samples are inspected during this process.

Table 3.9: Characterization of the dimensional and electrical properties of the PZT plates.

Sample	L	W	T	ID	C	Tan δ	f_s	d_{33}
#	mm	mm	mm	mm	pF	%	kHz	pc/n
1	12,00	12,05	3,00	3,44	632	0,49	365,20	345
2	12,01	12,05	3,02	3,45	621	0,48	367,00	355
3	12,03	12,06	3,05	3,42	623	0,49	365,00	350
4	12,04	12,04	3,02	3,42	619	0,48	367,00	350
5	12,03	12,04	3,02	3,42	619	0,48	365,00	345
6	12,04	12,05	3,05	3,45	626	0,49	365,00	344
7	12,03	12,06	3,01	3,46	628	0,48	366,00	344
8	12,02	12,05	3,02	3,46	612	0,50	366,00	346
9	12,04	12,05	3,02	3,45	627	0,48	367,00	345
10	1203	12,06	3,03	3,44	628	0,49	367,00	345
11	12,00	12,05	3,00	3,44	632	0,49	365,20	345
12	12,01	12,05	3,02	3,45	621	0,48	367,00	346
13	12,03	12,06	3,05	3,42	623	0,49	365,00	355
14	12,04	12,04	3,02	3,42	619	0,48	367,00	355
15	12,03	12,04	3,02	3,42	619	0,48	365,00	345
16	12,04	12,05	3,05	3,45	626	0,49	365,00	346
17	12,03	12,06	3,01	3,46	628	0,48	366,00	355
18	12,02	12,05	3,02	3,46	612	0,50	366,00	346
19	12,04	12,05	3,02	3,45	627	0,48	367,00	352
20	12,03	12,06	3,03	3,44	628	0,49	367,00	355
Max	12,04	12,06	3,05	3,46	632	0,50	367,00	355
Min	12,00	12,04	3,00	3,42	612	0,48	365,00	344
AVG	12,027	12,051	3,024	3,441	623,36	0,486	366,02	348,54
STDV	0,0166	0,0075	0,0197	0,0151	5,0067	0,0055	1,0100	4,2622
Pass/Fail	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass

3.3.3. Non-PZT Materials Design

In addition to the end-cap and PZT ceramic materials, a set of non-PZT materials is introduced into the design of the segmented Class V Flextensional transducer element to establish the stacks of the transducer and integrate them with the end-cap for

assembly. The parts are made from aluminum to facilitate easier and more feasible production. Additionally, aluminum is preferred due to its low density, which minimizes the contribution of mass to the transducer.

In enhance the transducer element's antenna displacement, which in our case is the end-cap unit, thereby increasing the amplitude of the acoustic sound generated by the transducer, a stack unit is assembled by stacking the PZT ceramic plates on top of each other in the direction of their polarization direction and sandwiching them between non-PZT materials. This helps hold the assembly and harness the benefits of attaching it to the end-cap of the segmented Class V Flextensional transducer element. Additionally, the stack unit aids in terms of the voltage applied to the transducer. The PZT plates in each stack element are electrically connected in parallel. Each PZT plate in the stack structure requires a voltage reduced in proportion to the number of PZT plates that make up the stack, compared to the voltage required by a single PZT plate of the same height. Non-PZT Materials are as follows:

- Bottom Corner Part

This part is made of Aluminum and used as the bottom part of the stack assembly. The design of this part is shown at Figure 3.6.

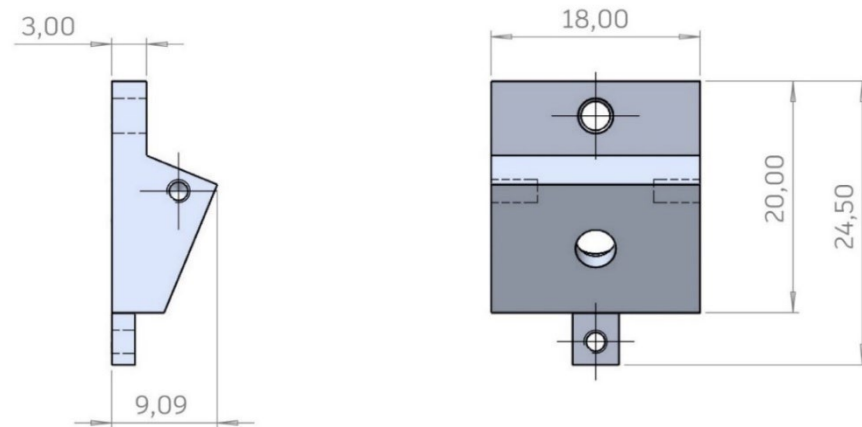


Figure 3.6: Side (left) and top (right) view of the Bottom Corner part design.

- Top Corner Part

This part is made of Aluminum and used as the top part of the stack assembly. The design of this part is shown at Figure 3.7.

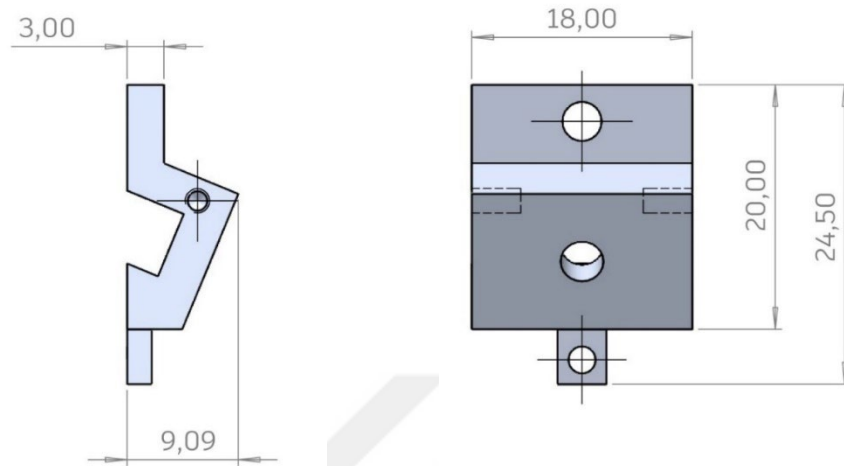


Figure 3.7: Side (left) and top (right) view of the Top Corner part design.

- Isolation Plate

This part is made of a printed circuit board to provide electrical isolation between the PZT plates and both the top and bottom corner parts. The surface area of the isolation plate is the same as that of the PZT plate, with a hole of the same diameter in the middle to ensure a geometrical match with the PZT plate for better integration and neatness. The design of this part is shown at Figure 3.8.

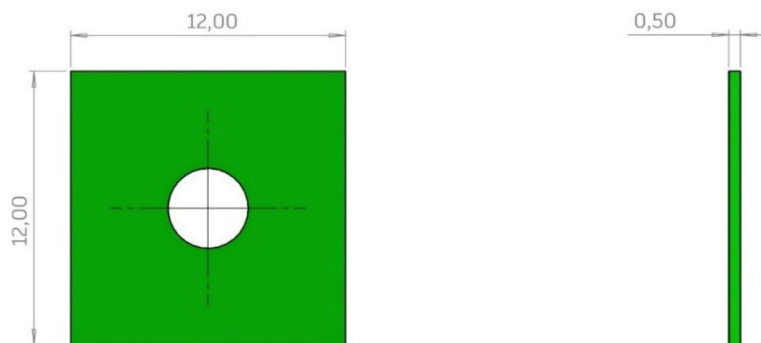


Figure 3.8: Side (left) and top (right) view of the isolation plate part.

- Contact Plate

This part is made of beryllium copper to provide conductive material on the surface of the PZT plates along the direction of polarization, allowing a sinusoidal signal to be applied as the driving signal. The applied signal causes displacement of the PZT plates, resulting in the vibration of the stacks and the end-cap. The general view of the contact plate is similar to the one as isolation plate where the thickness is only 0.05 mm and with an extra short flag area for soldering the positive and ground pole of the connector of the segmented Class V Flexensional transducer element.



4. MANUFACTURING AND PROTOTYPING

In this chapter, the manufacturing and assembly of the prototype segmented Class V Flextensional transducer element is carried out based on the design details. Using the 3D design and technical specifications of each subcomponent (end-cap, PZT ceramic materials, and non-PZT materials), manufacturing files and technical requirements are created and sent for production. A sufficient number of subcomponents are ordered to allow for the assembly of more than one segmented Class V Flextensional transducer element, if needed. Upon receiving the subcomponents from the manufacturing process, they are subjected to quality checks (both mechanical and electrical) in the laboratory to ensure they meet the required technical specifications.

Once the subcomponents pass the quality check, the assembly process of the prototype segmented Class V Flextensional transducer element is conducted. First, custom-built assembly equipment for stack production is designed, built, and manufactured to enable repeatable and accurate assembly of stack elements to eliminate the asymmetry problem. One segmented Class V Flextensional transducer element consists of eight stack elements. Therefore, ten stack elements are prepared, of which eight are selected for the assembly of the segmented Class V Flextensional transducer element.

Before proceeding to the next stage, which is the assembly of the Class V Flextensional transducer, the stack elements are electrically tested in air to analyze their resonance response at the frequency of interest. Additionally, the isolation resistance of each stack is individually checked to confirm that there are no short circuits between the leads or between the non-PZT and PZT materials.

Finally, the assembly and encapsulation processes are performed to build the prototype of the segmented Class V Flextensional transducer element. The details of the above summary are provided in the following section.

4.1. Manufacturing of Subcomponents

As detailed in Section 3.3, the manufacturing of the segmented Class V Flextensional transducer Element's end-cap, PZT and non-PZT materials is carried out. For this purpose, qualified manufacturers in the market are subcontracted. Taking into account the trials of the assembly process and the intended usage of the subcomponents, a

sufficient quantity of materials is manufactured to enable the construction of three segmented Class V Flextensional transducer elements, if needed. A view of the manufactured samples of the segmented Class V Flextensional transducer element is shown in Figure 4.1 and Figure 4.2. The dimensional qualification of all the parts used in production is performed using a digital compass. (The ruler shown in the pictures below was used solely to indicate the scale of the sizes for comparison with known measurements.)



Figure 4.1: Diameter (left) and thickness (right) of the brass end-cap part.

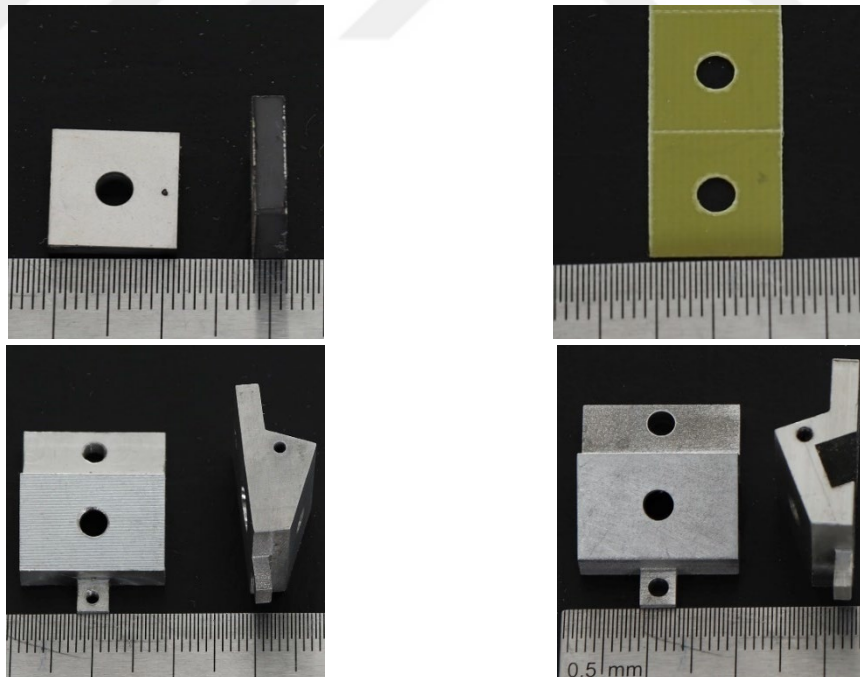


Figure 4.2: PZT ceramic plates (PZT-4 material) (top left), Isolation Plates (FR-4 material – 2 pieces) (top right), Bottom Corner part (aluminum) (bottom left – top and side view), Top Corner part (aluminum) (bottom right – top and side view).

4.2. Production of Stack Elements

The stack element is the core of a transducer element, where electrical energy is converted into displacement and vice versa. Accurate assembly of the stack element is crucial for ensuring the proper and efficient functioning of the transducer element. Achieving assembly accuracy requires a robust assembly infrastructure and a well-defined assembly procedure. All stack assemblies must be performed according to the established procedure, which was thoroughly tested during initial trials for practice purposes.

After the mechanical assembly of the stack elements, each stack undergoes a series of tests to ensure they meet the expected technical and dimensional specifications as well as quality standards. First, the assembly procedure for the stack elements will be provided, followed by the qualification tests for the assembled stack elements.

4.2.1. Assembly of Stack Elements

As mentioned earlier, assembly accuracy and repeatability are crucial for the proper functionality of the transducer element. This is because the individual resonance frequency of each stack element contributes to the fundamental resonance frequency of the transducer element itself. This principle applies to all types of sensing elements, particularly when the transducer consists of multiple stacks. If each stack element of the segmented Class V Flextensional transducer element exhibits slight variations in frequency response, it can lead to additional harmonics when all components are integrated into the final product. These harmonics result in power dissipation to undesired frequencies, causing an amplitude reduction in the fundamental resonance frequency and generating relatively high-amplitude unwanted harmonics.

Each subcomponent of the segmented Class V Flextensional transducer element is designed to have a manageable size for manual production. Additionally, the components are engineered to achieve a fundamental resonance frequency in the 4-5 kHz range, primarily determined by the diameter of the end-cap design. To minimize the effects of artifacts caused by inconsistent stack assembly, a stack assembly fixture has been designed to assemble one stack element at a time.

The 3D general view, along with an image of the stack assembly fixture and a full set of subcomponents comprising a single stack element, is shown in Figure 4.3.

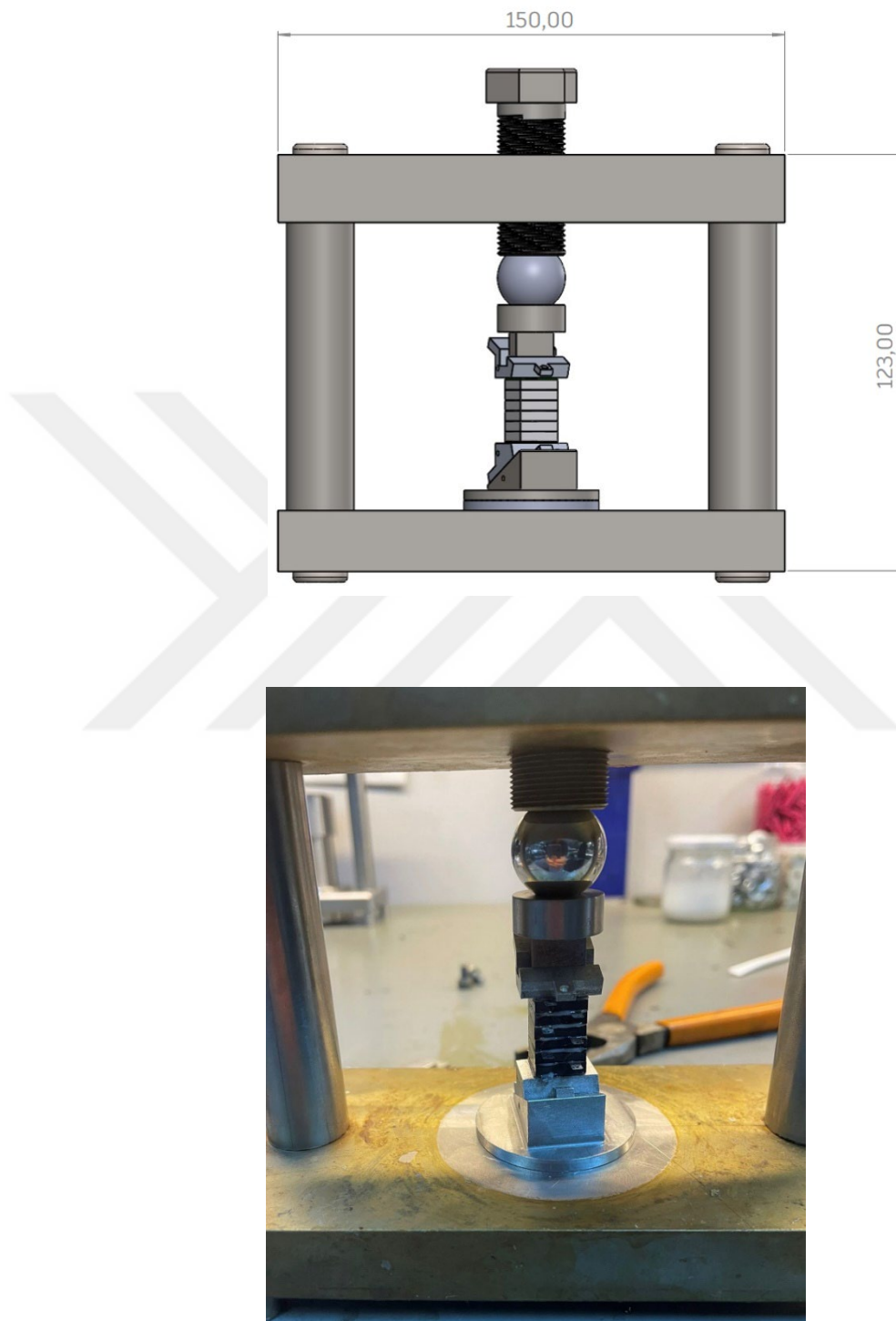


Figure 4.3: The 3D general view (top) along with an image (bottom) of the stack assembly fixture included a full set of subcomponents comprising a single stack element.

The fixture shown in Figure 4.3 is used during the assembly of each stack. The subcomponents of the stack element are assembled sequentially from bottom to top as follows: Bottom Corner Part, Isolation Plate, six PZT plates, seven Beryllium Copper contacts (with one contact and one PZT plate), another Isolation Plate, and finally the Top Corner Part. Adhesion of the parts is achieved using purpose-specific glue and silver-based contact paste to enhance electrical conductivity between the Beryllium Copper contacts and the PZT plates.

The required mechanical stress is applied vertically to the stack element from the top by tightening the hexagon head bolt of the fixture. After assembly, the stack is placed in a chemical drying oven for the curing process, with the curing time determined by the specifications of the adhesive chemicals used. The amount of adhesive, curing time, and temperature of the chemical drying oven are optimized based on the results of preliminary trials.

One of the assembled stack elements after the curing process is shown in the Figure 4.4. Following this step, the contacts, which are connected to the surfaces of the PZT plates perpendicular to the polarization direction, are grouped into positive (+) and negative (-) poles. These poles are then soldered separately to create one main positive pole and one main negative pole.

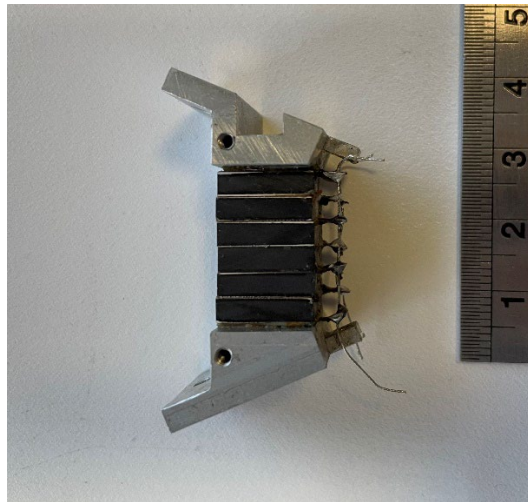


Figure 4.4: An assembled stack element comprising bottom and top aluminum corners, isolation plates, contacts and PZT plates.

4.2.2. Characterization of Stack Elements

To produce one segmented Class V Flextensional transducer element, eight stack elements are required. For this purpose, ten stack elements are assembled, and eight of them are selected based on the results of electrical tests. Each stack element undergoes an isolation test and impedance measurement. The isolation resistance and electrical impedance measurement results, conducted in air for the selected eight stack elements, are provided in the Table 4.1 and Figure 4.5, respectively.

The isolation resistance of each stack element is measured using a handheld isolation resistance tester (Fluke 1507), and the readings are recorded in the Table 4.1. As shown in the table, it can be concluded that the isolation resistance of each stack is sufficiently high, indicating that the stack was assembled properly to ensure good insulation between the poles and between the aluminum parts and the corresponding pole.

Table 4.1: The isolation resistance values of the eight stack elements.

Stack No	Between the Poles	Between the Bottom Corner and Positive (+) Pole	Between the Bottom Corner and Negative (-) Pole	Between the Top Corner and Positive (+) Pole	Between the Top Corner and Negative (-) Pole
Stack 1	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm
Stack 2	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm
Stack 3	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm
Stack 4	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm
Stack 5	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm
Stack 6	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm
Stack 7	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm
Stack 8	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm	> 550 M Ohm

The impedance value across the frequency range of each stack is measured using a computer-based Impedance-Amplitude Phase Analyzer (Cypher Instruments: C-60) from 10 kHz to 40 kHz.

Figure 4.5 shows the frequency response (modulus of impedance – top plot, and phase – bottom plot) of all eight stack assemblies, plotted together for comparison. It is clearly observed that the frequency response of all the stack assemblies exhibits similar behavior. The measurements indicate that all stacks have a resonance frequency around

35 kHz. It should be noted that the resonance frequency of the stack assembly results from the integration of six PZT plates, as well as other subcomponents, such as aluminum corner parts, contacts, isolation plates, and adhesion material, all of which contribute to determining the stack assembly's resonance frequency. The similar frequency response behavior of all the stack assemblies serves as evidence that the integration process has been carried out properly, ensuring repeatability.

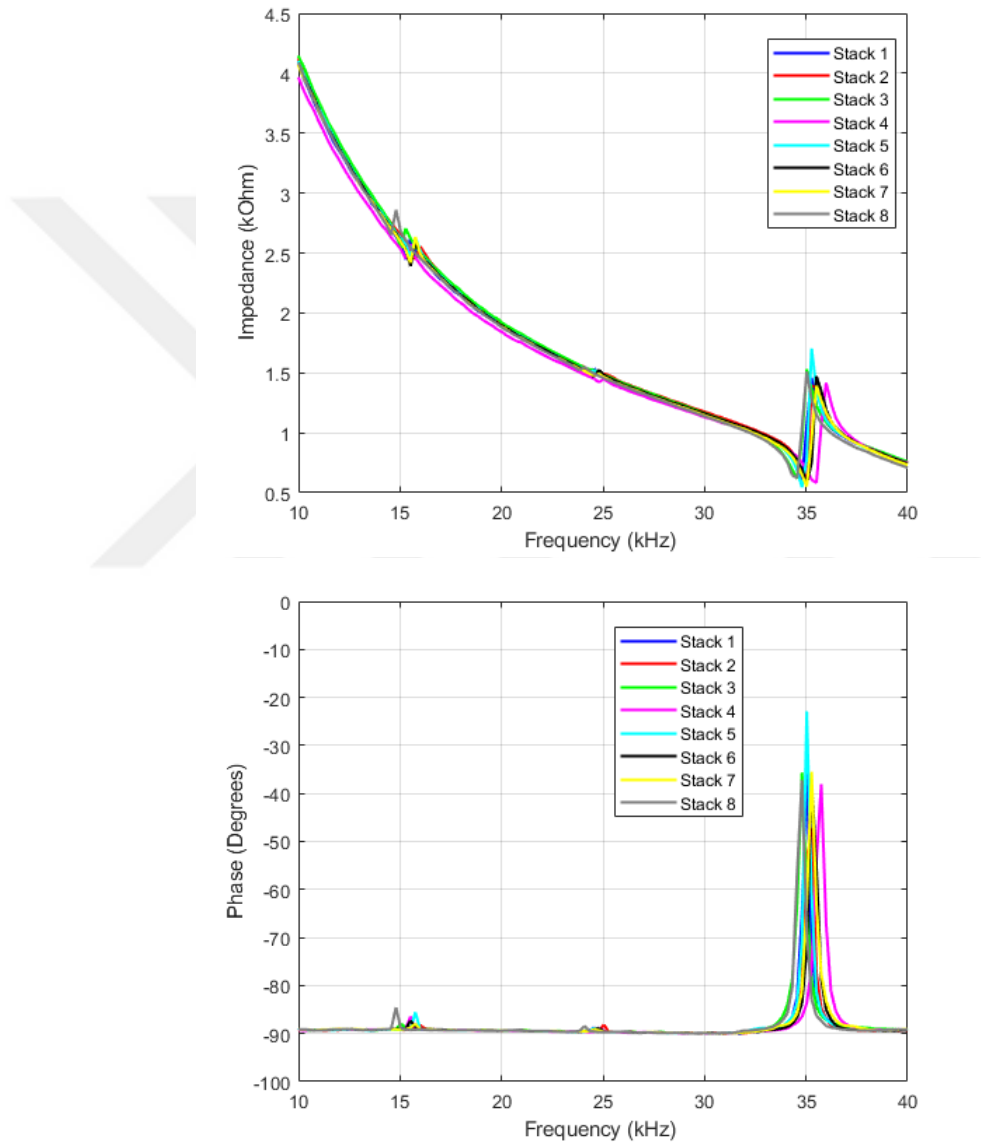


Figure 4.5: Impedance and phase measurement of the eight stack elements in the frequency range between 10 kHz up to 40 kHz (In the air).

4.3. Prototyping of the Segmented Class V Flextensional Transducer Element

Once the assembly and characterization of the eight stack elements are completed, the preparation of the prototype is conducted. The eight stack elements are arranged to construct the segmented Class V Flextensional transducer element. Care is taken to ensure that the connection surfaces of consecutive stack elements are aligned correctly so that the screw holes on the top and bottom aluminum parts align properly. At this stage, the integration of the two caps with the octagonal stack structure is also practiced.

The screw holes on the cap are prepared, and the alignment of these screw holes with the corresponding stack elements is checked to ensure that no additional bending stiffness occurs due to the improper placement of the cap on the octagonal stack structure. Figure 4.6 shows the pre-integration of the octagonal stack structure and the two brass end-caps.

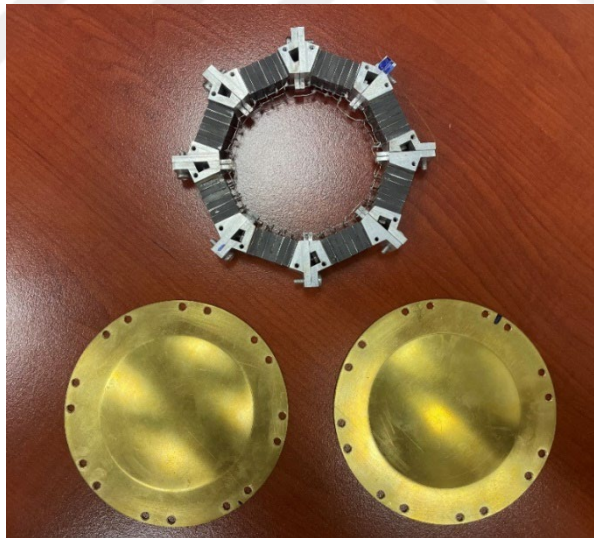


Figure 4.6: Octagonal stack structure and the two brass end-caps (one for each side of the stack structure).

4.4. Integration and Encapsulation of the Segmented Class V Flextensional Transducer Element

The integrated segmented Class V Flextensional transducer element is shown in Figure 4.7. All stacks are screwed to each other to establish the octagonal stack structure, and the two end-caps are screwed onto that structure. The symmetrical design of the transducer in both directions perpendicular to the end-caps creates a similar radiation pattern.

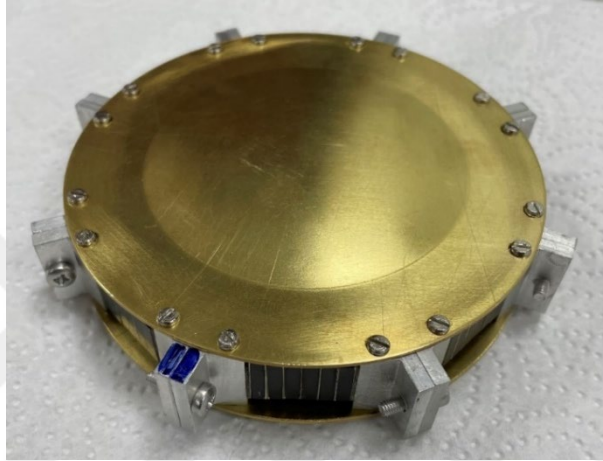


Figure 4.7: Integrated segmented Class V Flextensional transducer element without signal cable.

As the integrated transducer element is subjected to an underwater environment during the underwater acoustic characterization, isolating the transducer element is one of the challenging issues to be addressed. For this reason, the pouring technique is chosen for implementation. Isolation can be achieved by encapsulating the transducer with a material that is insulating and suitable for underwater environments. For the global encapsulation of the transducer element in a single step, a metal mold is designed and manufactured. The mold design includes two lids, which are used to enclose the segmented Class V Flextensional transducer element. The lids of the mold are then screwed together to sandwich the transducer between them. The view of the mold together with the segmented Class V Flextensional transducer element is shown in Figure 4.8.



Figure 4.8: The mold structure together with the segmented Class V Flextensional transducer element.

The segmented Class V Flextensional transducer element is encapsulated with an elastomeric casting resin used for mold-making. This resin consists of two components (Component A and Component B) and additional resin to enhance the flexibility of the encapsulation. The shore level, which is considered a measure of the material's stiffness, is an important factor influencing the impedance and the sound pressure level (SPL). For this reason, four different composition samples of the casting materials are prepared, varying the proportions of Components A and B, as well as the ratio of the additional resin, to achieve different levels of flexibility. The most suitable composition recipe is selected for encapsulating the segmented Class V Flextensional transducer element. The samples prepared are presented in Figure 4.9.

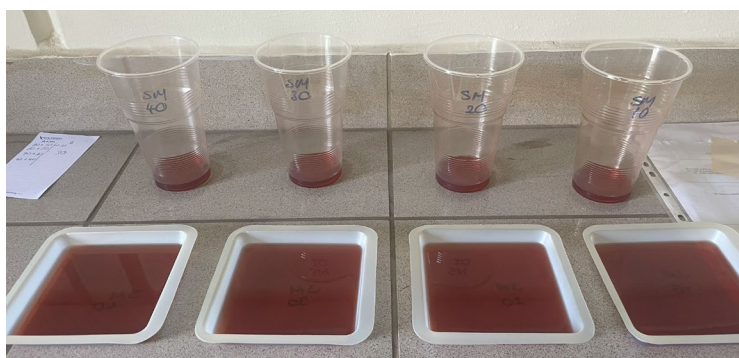


Figure 4.9 : Polyurethane samples for encapsulation of segmented Class V Flextensional transducer element.

Once enough encapsulation material is prepared, it is poured into the mold through the top opening and left to cure for 24 hours in a stable laboratory environment. The view of the finalized production of the segmented Class V Flextensional transducer element is shown in the Figure 4.10 ready to be characterized in an underwater acoustic environment.

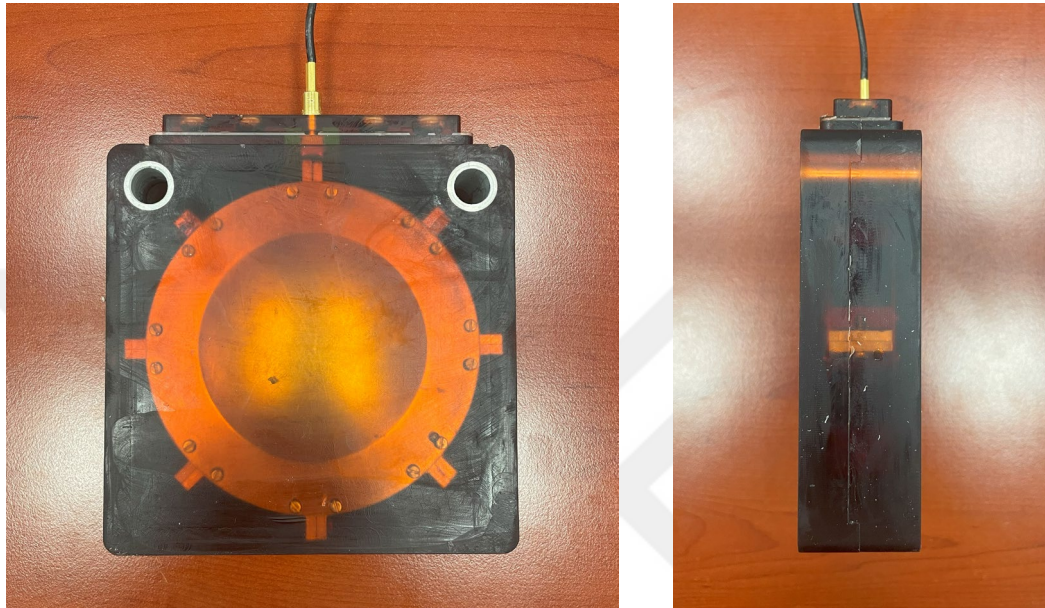


Figure 4.10: Front (left) and side (right) view of the segmented Class V Flextensional transducer element.

5. FEA MODELING AND SIMULATIONS

One of the commercially available finite element analysis software packages, OnScale, is used to perform the electro-acoustical analysis of the segmented Class V Flextensional transducer element during the thesis work. OnScale, a computer-aided engineering (CAE) tool, is based on proprietary Multiphysics solvers. These solvers were originally designed for highly parallel mainframe computers to tackle large-scale engineering simulation problems and have evolved into an efficient tool for modern, cloud-based high-performance computing (HPC).

Using OnScale, various analyses such as 3D implicit static mechanical analysis, thermal analysis, thermomechanical analysis, modal analysis, and fluid dynamics can be conducted. These capabilities enable the creation of true digital prototypes - digital representations of high-tech devices that capture their complete behavior across their operational envelope. By replacing expensive and time-consuming physical prototyping with digital prototyping, OnScale significantly reduces costs, risks, and time-to-market for research and development teams at the forefront of technological innovation.

OnScale integrates high-performance, natively parallel multiphysics solvers developed for the most demanding organizations worldwide. It leverages public or private cloud supercomputers and offers a functional graphical user interface (GUI), an application programming Interface (API) for seamless integration into design workflows, scripting capabilities for customizable simulations, and plugins to enhance engineering functionality. The software also includes tools for data importing, exporting, and postprocessing. Engineers can run simulations on HPC cloud systems, allowing the software to handle computationally intensive tasks. As a multi-tenant platform, OnScale eliminates the need for software licenses and IT license management. It also ensures world-class data security, utilizing best-in-class security components from cloud partners like AWS and GCP.

In essence, Computer-Aided Design (CAD) focuses on creating a digital geometric representation of a physical product or design, while Computer-Aided Engineering (CAE) models the physical and operational characteristics of a design through a set of partial differential equations (PDEs). These equations are solved numerically to

analyze the product's behavior under specified initial conditions and loads. While CAD defines the geometrical features of a product, CAE enables a comprehensive digital analysis of its behavior, bridging the gap between design and practical application.

OnScale offers 3 available work modes [61]

- **Designer Mode:** An accessible but powerful approach to building models. Use parametric primitives and CAD geometry as a starting point for simulations.
- **Analyst Mode:** An advanced method for building models using the robust symbol scripting language, which offers more flexibility than a graphical approach.
- **Post Process:** A suite of tools to visualize and analyze output data generated from OnScale simulations.

In this thesis work, the FEA work is conducted by first using the Designer Mode of OnScale to develop the main structure of the model by importing the CAD model of the segmented Class V Flextensional transducer element. Then it is switched to Analyst Mode to implement vital features by working on the script to finalize the model structure as the Designer Mode does not support such advanced implementations. The goal of this exercise is to create a model that accurately represents the structural and material properties of the prototyped transducer. Once the model is set up the FEA is run and the results are visualized using the Post Process tool or a custom scripted review program.

5.1. Establishment of the Model

OnScale 1.130.11.0 version is used during this thesis work. The import function of OnScale Designer Mode is utilized to import the 3D CAD design of the segmented Class V Flextensional transducer element.

Once the import process is completed properly, the model is set up according to the model tree shown in Figure 5.1. In summary, the proper model is established by defining the materials from the existing library or creating new material for use, assigning the materials to the subcomponents of the model, specifying the type of signal to drive the model, configuring the mesh sizes, boundary conditions, and loads, and finally setting up the analysis configuration and defining the outputs.

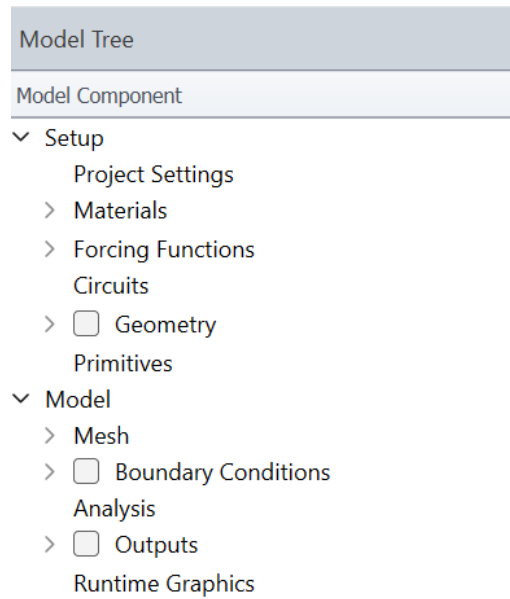


Figure 5.1: Model tree in Designer Mode of Onscale.

5.1.1. Model Tree - Setup

Due to the symmetrical structure of the segmented Class V Flextensional transducer element, the model is established as a quarter piece to reduce both the model size and computation time. The model is established using the Setup menu.

5.1.1.1. Project Settings

The project is identified under this menu. This includes setting the model's name, selecting the model type (2D or 3D), defining the units (distance, time and frequency), specifying the frequency of interest (to set the maximum frequency range for the analysis, which is set to 20 kHz for this work), and configuring the conversion factor for coordinates, if necessary. In this work, no conversion factor is required, as a one-to-one model is created during the preparation of the CAD model.

5.1.1.2. Material Settings and Geometry

The existing material library is preferred for use during this thesis work, as defining new materials from scratch is a comprehensive task that could be the subject of another study. Although predefined materials from OnScale's existing library are used, some adjustments needed to be made to meet the specific requirements of the segmented Class V Flextensional transducer element.

The materials added to the library for this work are shown in the Figure 5.2. Aluminum (“alum”) is assigned to the top and bottom corner components, Brass (“brass”) is assigned to the cap material, PZT-4 (“pzt4”) is assigned to the piezoelectric plates, Urethane (“uret”) is assigned to the encapsulation material, and Water (“watr”) is assigned to the medium surrounding the transducer with their respective assigned colors.

Materials	
Material Property	Value
> alum	
> brass	
> pzt4_left	
> pzt4_leftn	
> pzt4_right	
> pzt4_rightn	
> uret	
> watr	

Figure 5.2: Material library for FEA work.

As shown in Figure 5.2, four different types of PZT plate materials are assigned for this work to the library. This is because the polarization direction of the PZT plates must align with the orientation of each plate according to the model's coordinate system. Therefore, since the quarter model includes two stack assemblies, they are grouped under the names "left" and "right" based on their positions. Within each stack assembly, the PZT plates are further distinguished by their polarization directions, either positive or negative. The material name, position of the stack, and polarization direction are shown in Table 5.1.

Table 5.1: Description of the material configuration of the stack assemblies.

Material No	Material Name	Stack Assembly Position	Polarization Direction
1	pzt4_right	Right	Positive
2	pzt4_rightn	Right	Negative
3	pzt4_left	Left	Positive
4	pzt4_leftn	Left	Negative

As mentioned earlier in this chapter, the Designer Mode allows the user to model simple geometries and enables one to work within the capabilities of the mode. For instance, since the segmented Class V Flextensional transducer element's stack assemblies are oriented at corresponding angles to the origin point (0,0,0), the script needs to be manually modified to define the polarization direction of the PZT plates in the stack assemblies in terms of angles. For this reason, the script generated in the Designer Mode is updated in the Analyst Mode.

The syntax and the additional code are provided in Figure 5.3.

Syntax: defn axisname axistype x0 y0 z0 x1 y1 z1

```

220 axis
221 form angl
222 defn left      cart 0. 0. 0. 0. 157.5 -90.
223 defn leftn    cart 0. 0. 0. 0. 337.5 -90.
224 defn right   cart 0. 0. 0. 0. 112.5 -90.
225 defn rightn  cart 0. 0. 0. 0. 292.5 -90.
226 c

```

Figure 5.3: The syntax and additional code for Analyst Mode.

Once the materials library is created and the proper model geometry along with its custom settings are finalized, the assignment of materials to the corresponding parts is carried out accordingly. The Figure 5.4 shows a quarter portion of the segmented Class V Flextensional transducer element (top views), highlighting the material allocation to specific parts.

The top-left view illustrates the left stack assembly (parts in light blue and purple colors) and the right stack assembly (parts in yellow and dark blue colors), along with the bottom and top corner parts (parts in red). The top-right view includes the addition of the bottom-side brass cap (part in green). The bottom-left view shows the addition of the top-side brass cap (part in green). Finally, the bottom-right view demonstrates the inclusion of the polyurethane encapsulation (part in light orange).

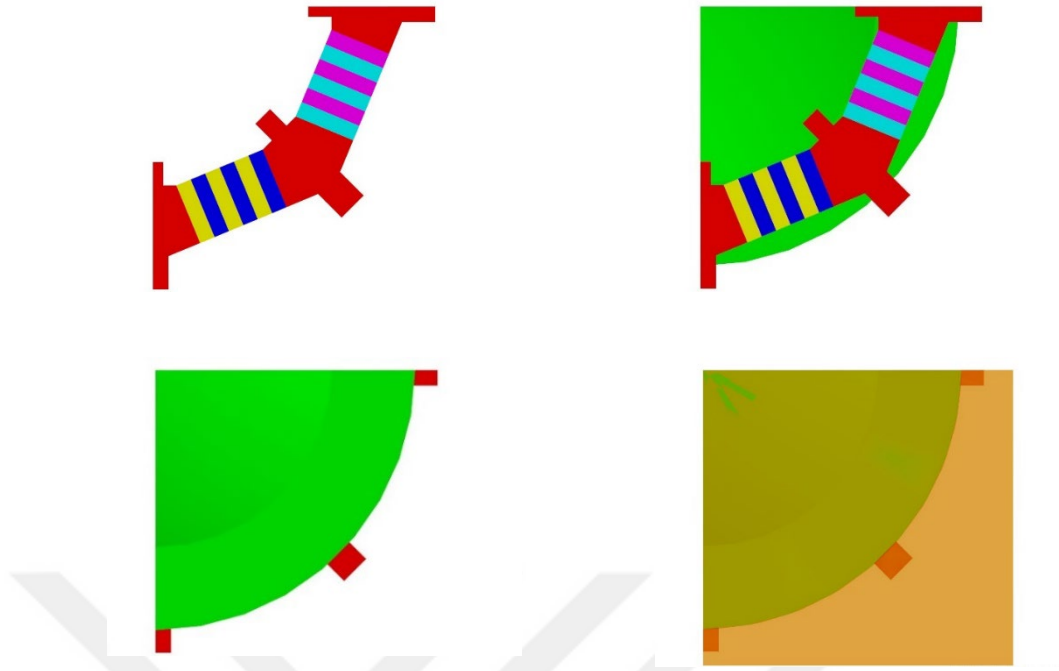


Figure 5.4: The four stages of material assignment for the segmented Class V Flextensional transducer element are as follows (top views) : two stack assemblies (top left), two stack assemblies with the bottom cap (top right), two stack assemblies with bottom and top caps (bottom left) and two stack assemblies with bottom and top caps together with encapsulation (bottom right). All views are presented as a quarter geometry model for computational simplicity.

The cross-sectional view of a quarter portion of the segmented Class V Flextensional transducer element, without (left) and with (right) polyurethane, is shown in the Figure 5.5. As it can be seen from the uncoated version, the structure of the transducer is designed with openings between the end-cap and the stack assembly to allow the polyurethane to fill the inside and outside of the transducer homogeneously. This design concept enables the polyurethane to electrically isolate the transducer from the water medium and also provides a uniform medium that encapsulates the transducer evenly.

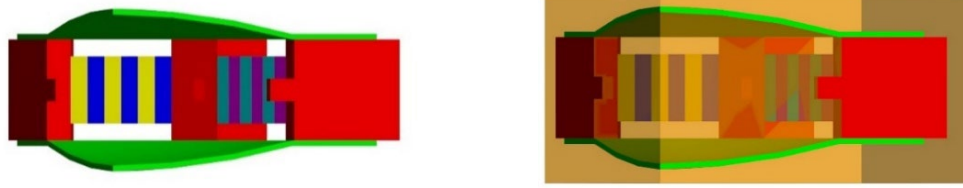


Figure 5.5: Cross-sectional view of a quarter portion of the Segmented Class Flextenisonal transducer element, without (left) and with (right) polyurethane coating.

The full model for the FEA is shown in the Figure 5.6. As previously represented, the full model is also displayed in a quarter portion. In the figure below, the transducer is shown with the surrounding water environment to make the simulation similar to the real-life measurements, which will be explained in the next chapter. The surrounding water environment is modeled as a 300 mm cubic structure and shaped symmetrically in alignment with the agreed-upon design for the transducer element. The specifications of the boundary conditions will be discussed later.

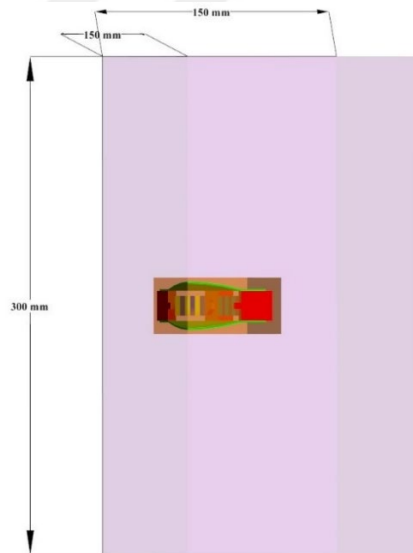


Figure 5.6: The complete structure of the model. The segmented Class V Flextensional transducer element within the water environment.

5.1.1.3. Forcing Functions

A Ricker wavelet is used as the forcing function, with a drive frequency of 10 kHz and an amplitude of 1 V peak-to-peak. This drive frequency is selected because it is the center frequency of the frequency of interest (20 kHz), as recommended by the software instructions. Four sub-wavelets are chosen to excite more frequency components in the spectrum. The simulation runs for 3 ms, which is reasonable to allow sufficient time for the transducer resonance to attenuate significantly.

The forcing function (functimefunc_1) to the transducer element and the acoustic pressure (aprs) that is received by the receiver at point (100,0,0) mm is shown respectively in Figure 5.7.

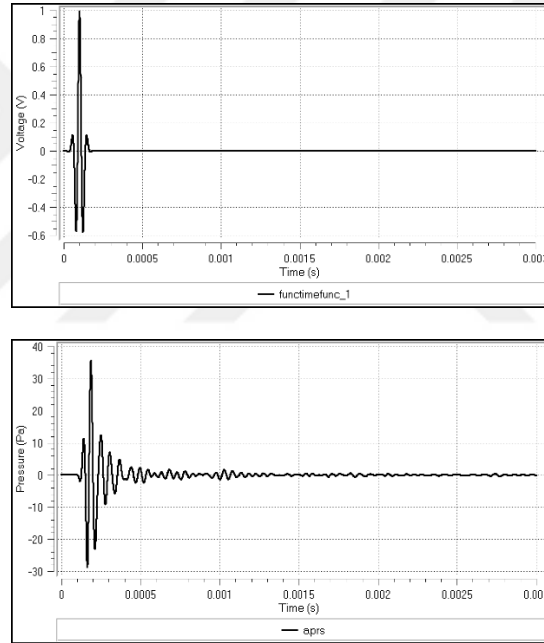


Figure 5.7: Forcing Function – 10 kHz Ricker Wavelet with four sub-wavelets (top), received acoustic pressure signal by the receiver at the point of (100,0,0) mm (bottom).

5.1.2. Model Tree - Model

The established setup is executed according to the model configuration defined here. The configuration of the mesh, boundary conditions, and outputs is specified within this menu.

5.1.2.1. Mesh

A mesh size of 1 mm is used during the modeling work. This value is determined by considering the minimum bulk material velocity present in the model and the software's recommended minimum number of elements per wavelength. Additionally, the computational duration and the model size that a standard computer can handle are taken into account when defining the mesh size. The meshed quarter size of the segmented Class V Flextensional transducer element is shown in Figure 5.8.

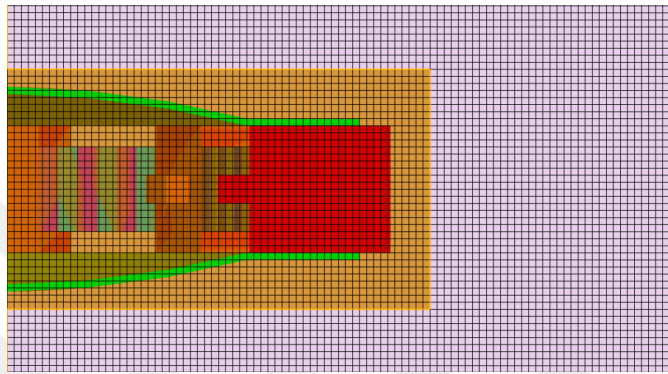


Figure 5.8: The meshed quarter size of the segmented Class V Flextensional transducer element (cross sectional view).

5.1.2.2. Boundary Conditions

Under the Boundary Conditions submenu, the allocation of the loads represents the contacts between the PZT plates and the boundary conditions of the model structure (which play an important role when running a half or quarter structure of the model).

a) Loads

The proper identification of the loads is critical, as it represents how electrical signal connections (Forcing Function or Ground) are applied to the corresponding sub-component (PZT Plates) of the transducer. If a symmetry property is involved in the modeling work, the corresponding Area Scaling parameter must be correctly set based on the symmetry considered.

In this model, the voltage is defined as the load type, and a previously defined Forcing Function or Ground is selected for each of the Load. The Area Scaling parameter is set

to 4, as the model is built as a quarter model. A sample of the loads settings is shown in Figure 5.9.

Properties	
Load Type	Voltage
Area Scaling	4.0
Circuit (Optional)	No Circuit
Termination	Ground

Figure 5.9: Overview of the load settings.

b) Domain Boundaries

To accurately simulate real-world conditions, we must configure the external boundaries of our model to reflect the behavior of the areas beyond it. By default, all domain boundaries are set to "Free," meaning that nodes can move without any external forces applied. This configuration is suitable for cases where the model's edge corresponds to an air boundary, allowing unrestricted movement of the boundary nodes.

In our model, the Y Minimum, Z Maximum domain boundaries are set to Symmetry, as the model is axisymmetric around the x and z-axes. The remaining four domain boundaries are set to Absorbing, allowing energy to pass through the boundaries without any reflections. The boundary names and the boundary types are shown in Table 5.2.

Table 5.2: Boundary names and boundary types of the Segmented Class V Flextensional transducer model (quarter size).

Boundary Name	Boundary Type
X Minimum	Absorbing
X Maximum	Absorbing
Y Minimum	Symmetry
Y Maximum	Absorbing
Z Minimum	Absorbing
Z Maximum	Symmetry

5.1.2.3. Outputs

This menu allows users to save records of time-varying fields at multiple nodes during their simulations. Data such as pressure, displacement, voltage, and other variables

over time are stored in history files for post-processing and future access after the simulation run. It is also where the expected outputs of the simulation are specified. In this study, the acoustic pressure at a specific point is determined and utilized for further analysis, such as evaluating impedance across a frequency band.

Software operates most efficiently when models are sized at tens of wavelengths along each axis. However, medical and sonar devices often require pressure amplitude predictions at distances hundreds of wavelengths away from the source, making full modeling either impractical or inefficient. In such cases, extrapolation is the most effective solution.

The Kirchhoff Extrapolation technique, integrated into OnScale, provides a powerful solution. By applying analytical methods, essentially combining Green's functions and Huygen's principle, it uses pressure/time data from the FEA to extrapolate a complete pressure/time response at any chosen location or multiple locations.

The technique is applicable in both near and far fields but is based on several assumptions:

- The propagating medium is homogeneous, meaning no intervening layers are present.
- The propagating medium is fluid, implying the absence of shear waves.
- The medium is either lossless or has very low loss.
- The response is linear.

These assumptions are appropriate for our case and are generally applicable to transducers in water.

5.2. Simulation of the Model

In Section 5.1, the establishment and simulation settings of the segmented Class V Flextensional transducer element is explained in detail. The model input file is run on a cloud server, and the output files are downloaded from the server for post-processing purposes.

Onscale Post Process interface can be used to investigate basic output files; however, customized scripts provide more flexibility for detailed and application-specific

outputs. To address this, a review script has been prepared for further processing of the model output files.

During this thesis work, two main parameters of a projector transducer element were considered for characterization purposes. Therefore, the electrical impedance and the transmitting voltage response (TVR) parameters of the segmented Class V Flextensional transducer element are modeled within a water environment to simulate real working conditions.

5.2.1. Electrical Impedance of the Segmented Class V Flextensional Transducer Element

The electrical impedance of the segmented Class V Flextensional transducer element is modeled from a couple of hundred hertz up to 11 kHz in a water environment, and the resulting electrical impedance is shown in the Figure 5.10.

When an electrical signal is applied to piezoelectric materials, the equivalent impedance of the piezoelectric element changes with the excitation frequency. The drop and peak that appear between 4 kHz and 5 kHz can be defined as the resonance frequency region of the segmented Class V Flextensional transducer element's model.

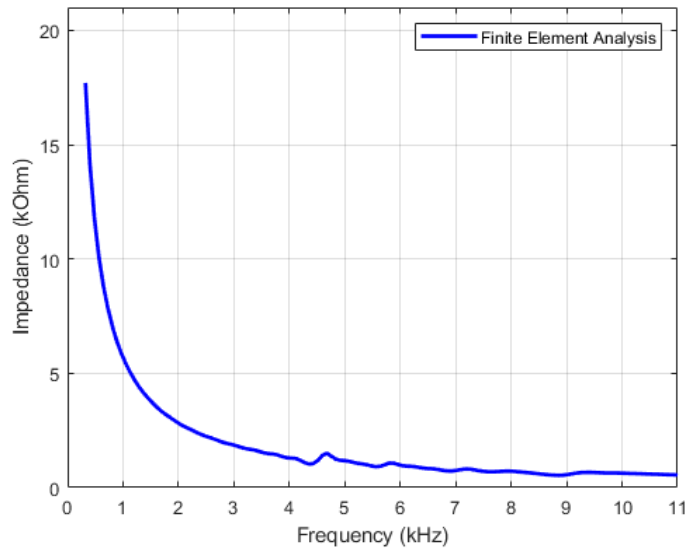


Figure 5.10: Electrical impedance plot of the Segmented Class V Flextensional transducer model finite element analysis.

5.2.2 Transmitting Voltage Response (TVR) of the Segmented Class V Flextensional Transducer Element

Secondly, the TVR parameter of the segmented Class V Flextensional transducer element model is analyzed from 1 kHz to 11 kHz in a water environment, and the resulting electrical impedance is shown in Figure 5.11. TVR is defined as the output sound pressure level generated at a 1 m distance by the projector per 1 V of input voltage as a function of frequency.

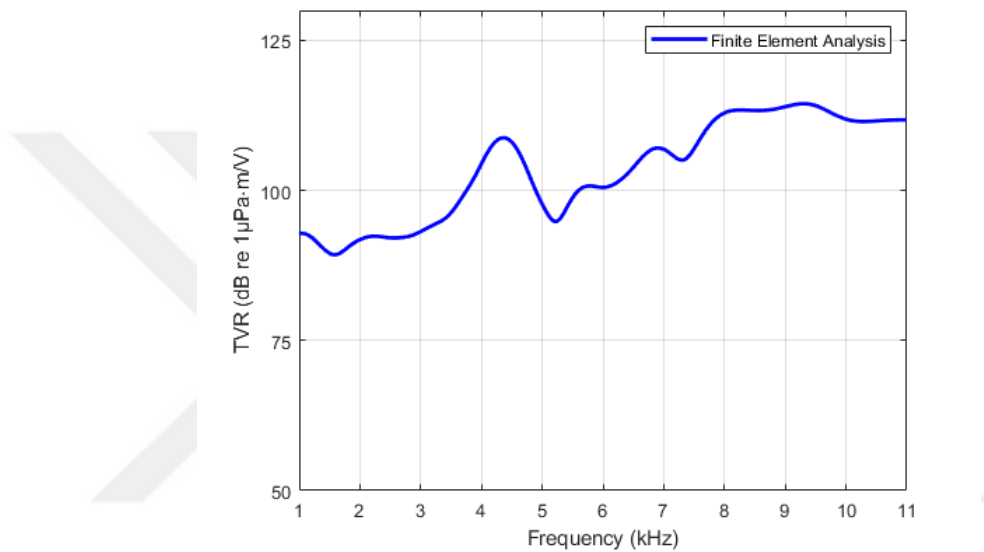


Figure 5.11: Transmitting voltage response plot of the segmented Class V Flextensional transducer model finite element analysis.

6. TEST TANK MEASUREMENTS AND COMPARISON WITH THE MODELING STUDY

In this chapter, the electro-acoustic characterization of the segmented Class V Flexensional transducer element is performed using the Open Test Tank infrastructure at the TÜBİTAK MAM SAL Laboratory. This infrastructure was established as a sub-work package within the scope of the MILGEM SONAR Project. Verification of the test laboratory was conducted as part of the project, and it was accredited for the frequency range of 2 kHz to 120 kHz for the calibration of projector and hydrophone elements used in underwater acoustic applications. The laboratory is periodically audited by both national and international technical experts. The general view of the TÜBİTAK MAM SAL is shown in Figure 6.1.



Figure 6.1: The general view of the TÜBİTAK MAM SAL open test tank facility and the Precise Positioning System.

The laboratory's open test tank has dimensions of 15 m in length, 10 m in width, and 7,5 m in depth, with the test tank walls providing reverberant surface boundary conditions. Calibration measurements are conducted in the test tank within the frequency range of interest, ensuring that free-field conditions are met. The Precise Positioning System is a key piece of infrastructure in the laboratory for deploying the Unit Under Test (UUT) and the other transducer (projector or hydrophone) used during

the test into the open test tank with high precision at the millimeter level. This precision is necessary because the distance between the elements and to the boundary conditions needs to be known accurately perform to perform primary calibration.

First, free-field comparison calibration measurements are performed in accordance with the relevant standard [62], which is discussed in detail. The results of these measurements are also presented. Using the comparison technique, the segmented Class V Flextensional transducer element is calibrated within the frequency range of 1 kHz to 11 kHz, where free-field conditions are valid for this specific application.

Subsequently, calibration with the 2E-2U method is discussed, and its results are presented for frequencies ranging from 250 Hz to 11 kHz. Additionally, sinusoidal waveform plots for frequencies ranging from 250 Hz to 1 kHz, obtained using both the Comparison Calibration Technique and the 2E-2U Method, are compared.

Finally, the Test Tank Measurements obtained using the Comparison Calibration Technique and the 2E-2U Method are compared with the outcomes of OnScale Model. These results are analyzed and discussed in detail.

6.1. Test Tank Measurements

6.1.1. Impedance Measurement

The standard [62] defines the electrical impedance of an electroacoustic transducer with a piezoelectric element as comprising two components:

- **Purely Electrical Impedance:** This represents the inherent electrical characteristics of the transducer and corresponds to the impedance when the radiating surface is stationary.
- **Motional Impedance:** This reflects the mechanical impedance caused by the vibrational motion of the radiating surface and includes the acoustic radiation impedance, which accounts for the influence of the surrounding medium on the transducer.

Electrical impedance measurements are conducted within the frequency range of interest and the acoustic load on the radiating surface affects the results. Therefore, the measurements must be performed under conditions similar to the working

environment (e.g., water or air) and working conditions. Additionally, the boundary conditions of the measurement setup, such as test tank walls, may influence the results if reflections from the walls create a significant acoustic load on the vibrating surface of the transducer element. Therefore, the impedance measurements need to be conducted significantly away for the boundary conditions, preferred in the middle of the open test tank.

6.1.1.1. Measurement Setup

The accredited measurement setup established at TÜBİTAK MAM SAL, as shown in the Figure 6.2, has been used for the electrical impedance measurement of the segmented Class V Flextensional transducer element, covering the frequency range from 250 Hz to 11 kHz.

The segmented Class V Flextensional transducer element (a) is positioned within the test tank measuring 7,5 m in length, 5 m in width, and 3,5 m in depth using the Precise Positioning System. The measurements are conducted using the HIOKI Impedance Analyzer (b), which steps through the frequency range of interest and measures the electrical impedance by applying a continuous wave AC voltage signal to the transducer. The measurement data are collected by a GETAC Laptop PC (c).

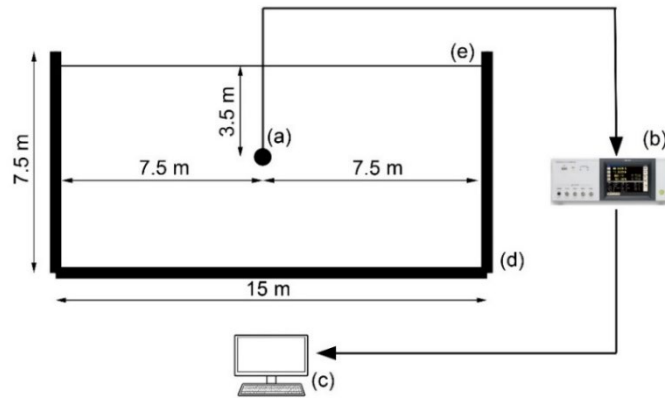


Figure 6.2: Electrical impedance measurement setup (a): Segmented Class V Flextensional transducer element, (b): HIOKI IM3570 Impedance Analyzer, (c): GETAC Laptop PC, (d): TÜBİTAK MAM SAL Open Test Tank, (e): water surface level. Note: The sketch is provided in two dimensions solely for illustration purposes.

6.1.1.2. Measurement Result

The electrical impedance of the segmented Class V Flextensional transducer element is measured from 250 Hz to 11 kHz in a water environment, and the resulting electrical impedance is shown in the Figure 6.3. The expanded uncertainty ($k = 2$) [63] for the electrical impedance measurement is calculated to be 4 %. Expanded uncertainty is used to provide coverages with a high level of confidence. A value of $k = 2$ corresponds to a confidence level of approximately 95 %. The uncertainty of measurement refers to the range between the measured value (actual value) and the upper and lower limits of the expected deviation from this value. It is calculated by considering Type A uncertainty, based on the statistical analysis of a series of measurements, and Type B uncertainty, based on scientific judgment using all relevant information, such as manufacturer specifications, calibration data, reports, and uncertainties assigned to reference data taken from books.

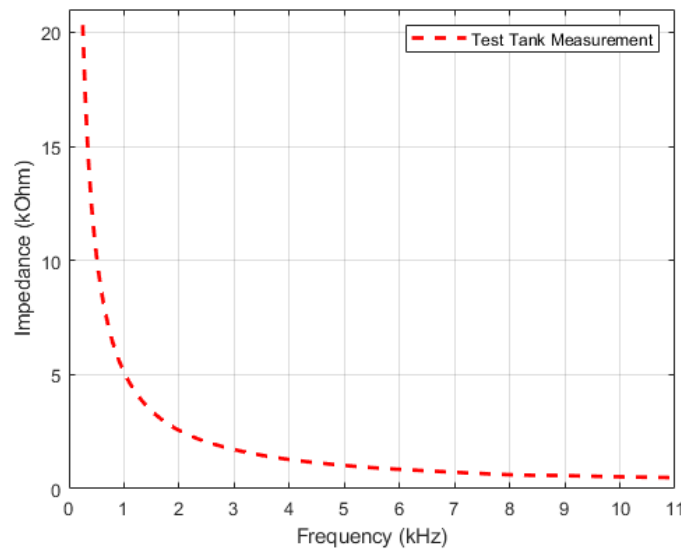


Figure 6.3: Electrical impedance plot of the Segmented Class V Flextensional transducer element measurement in the Test Tank.

6.1.2. Projector Calibration Using a Calibrated Hydrophone

The standard [62] defines the methods and procedures for free-field calibration of hydrophones, along with individual electro-acoustic transducers that can operate as hydrophones (receivers) and/or projectors (transmitters). It details two primary

calibration approaches: absolute calibration, utilizing the three-transducer spherical wave reciprocity method, and relative calibration, which compares the device with a reference transducer that has already been calibrated using an absolute method. Within the scope of this thesis, the comparison calibration method is chosen due to its relatively straightforward procedure and shorter duration, despite its higher uncertainty, which is acceptable for the objectives of this work.

The developed and prototyped segmented Class V Flexensional transducer element, functioning as a projector, is characterized using the “Projector calibration using a calibrated reference hydrophone” method.

In summary, the sound field generated in water by the projector under test is measured using a calibrated reference hydrophone placed in the acoustic far-field. The free-field transmit response of the projector is determined based on the hydrophone's open-circuit voltage readings, the distance between the projector and the hydrophone, the free-field receiving sensitivity of the calibrated hydrophone, and the electrical signal driving the projector.

To satisfy the acoustic far-field requirement, the distance d between the projector and the hydrophone must be sufficiently large. The separation should exceed the largest dimensions of the transducer, ensuring that the hydrophone is positioned at the acoustic far-field of the source.

The minimum separation distance d , between two transducers with maximum sensitive area dimensions D_1 and D_2 , is calculated using the following relationships given in (6.1) and (6.2)

$$d > K_f \left(\frac{D_1^2}{\lambda} + \frac{D_2^2}{\lambda} \right) \quad (6.1)$$

and simultaneously

$$d > 5D_1 \quad \text{and} \quad d > 5D_2 \quad (6.2)$$

where K_f represents the far-field correction factor, selected to ensure that the acoustic field closely approximates spherical spreading within a specified tolerance. The

standard requires K_f to be greater than 1,3. Additionally, λ denotes the wavelength of sound in water.

For the calibration measurements, an HBK brand 8104 model hydrophone (Serial Number: 2486868) is used as the hydrophone element, routinely calibrated by TÜBİTAK MAM SAL using the absolute calibration method. According to its specifications, the maximum dimension of the element is 41 mm, although the sensitive area of the element is not disclosed in the documentation. In comparison, the maximum sensitive area of the Segmented Class V Flextensional transducer element is 110 mm.

The equations (6.1) and (6.2) provide the minimum separation distances as listed in the Table 6.1. The wavelength required in equation (6.1) is calculated for 11 kHz, which represents the highest frequency of interest in this study. K_f is set to 1,5 to ensure a greater margin of safety.

Table 6.1: Acoustic far field requirements for the test tank measurement.

Equation Number	Separation Distance (d)
(6.1)	151 mm
(6.2)	For $D_1 = 550$ mm For $D_2 = 205$ mm

Table 6.1 indicates that the minimum separation distance must be 550 mm, as per the standard's requirements. The minimum separation distance achievable by the Precise Positioning System, a key component of the open test tank facility at TÜBİTAK MAM SAL, is 1600 mm.

The standard also requires maintaining steady-state conditions during measurements. When using tone burst signals for calibration, the time window for signal analysis must be set to begin after an appropriate delay, ensuring the projector has reached its steady-state regime following the arrival of the direct signal.

For the calibration of the projector, based on the measured electrical drive voltage v_P , the TVR is calculated using the following equation

$$S_{V,P} = \frac{d \times V_{PH}}{M_H \times V_P} \quad (6.3)$$

where $S_{V,P}$ represents the TVR of the projector, d is the distance between the projector and the calibrated hydrophone, V_{PH} is the open circuit voltage at the calibrated hydrophone due to the projector, M_H , is the free field receiving sensitivity of the calibrated hydrophone, and V_P is the electrical drive voltage applied to the projector.

6.1.2.1. Measurement Setup

The accredited measurement setup established at TÜBİTAK MAM SAL, as shown in the Figure 6.4, has been used for the Transmitting Voltage Response measurement of the segmented Class V Flextensional transducer element, covering the frequency range from 1 kHz to 11 kHz.

The segmented Class V Flextensional transducer element (a) is positioned within a test tank measuring 6,5 m in length, 5 m in width, and 3,5 m in depth, while the HBK 8104 Calibrated Hydrophone Element (b) is positioned within a test tank measuring 8,5 m in length, 5 m in width, and 3,5 m in depth, using the Precise Positioning System. With this positioning, the distance between the transducers is 2 m, and the closest reflecting boundary is the water surface, which is 3,5 m away from the transducers' depth, where the first reflection originates.

With the existing calibration procedure in house and due to the reflective boundary conditions of open test tank facilities, calibration measurements cannot be conducted in the continuous time regime. This is because the reflected signals from the boundaries (walls, water surface) overlap over time, causing constructive or destructive interference on the direct signal used for measurements. Therefore, all measurements must be performed within the echo-free time period, which is defined as the available time to observe only the direct, steady-state signal from the transmitter to the receiver. The echo-free time depends on the tank's size and the distance between the transmitter and receiver in the test tank.

Considering the separation distance between the segmented Class V Flextensional transducer element (projector) and the HBK 8104 Hydrophone (receiver) is 2 m, as shown in Figure 6.4, the direct signal arrives at the receiver 1,3 ms after t_0 , when the transmitter starts to transmit. The first reflected signal will occur due to the nearest

reflective surface - in this case, the water surface - and appears at the receiver 4,8 ms after t_0 . Based on the arrival times of the direct signal, the transient decay of the projector (0,7 ms in this case), and the first reflected signal, the echo-free time is determined to be approximately 2,8 ms, during which the measurement must be concluded for the specified frequency.

Therefore, the calibration is conducted frequency by frequency by transmitting a defined number of sinusoidal cycles (tone-burst signals) during the echo-free time and receiving the transmitted signal through the hydrophone.

The determined echo-free time also plays an important role in defining the minimum frequency limit for the measurement. A significant number of oscillations without overlapping from reflected signals must be recorded for each frequency. As the wavelength increases due to a decrease in frequency, fewer oscillations can fit within the echo-free time period. For instance, at 1 kHz, only 2,8 sinusoidal oscillations can fit into 2,8 ms echo-free time period, which is already very limited for accurate measurement. Accuracy at lower frequency measurements can be improved by increasing the number of averages.

The rest of the setup can be explained as follows: the transmitter (a) is driven at each frequency point through the Agilent Arbitrary Waveform Generator (f), and its output is amplified by the Crest Audio Power Amplifier (e). On the receiver side, the signal captured by the HBK Hydrophone element (b) is filtered and amplified by the Stanford Research System Low Noise Preamplifier. Both the output of the power amplifier (e) and the low-noise preamplifier (c) feed into the Pico Scope High-Resolution Oscilloscope (d) for amplitude readings, which will be used for calculations. The measured signals are averaged 50 times to minimize the effect of the broadband noise. Note that the necessary amplification to the input of the transmitter (a) and to the output of the receiver (b) is implemented using the Power Amplifier (e) and the Low Noise Preamplifier (c), respectively, to achieve better signal-to-noise ratios. These amplification levels are considered during the calculations of the TVR level of the segmented Class V Flexensional transducer element.

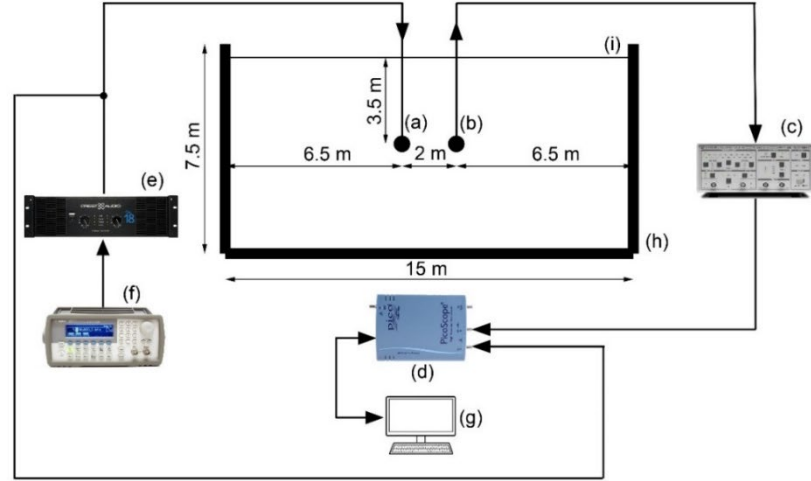


Figure 6.4: TVR measurement setup (a): Segmented Class V Flextensional transducer element, (b): HBK 8104 Calibrated Hydrophone Element, (c): Stanford Research Systems Model SR 560 Low Noise Preamplifier, (d): Pico Scope 4262 High Resolution Oscilloscope, (e): Crest Audio CA18 Power Amplifier, (f): Agilent 33220A Arbitrary Waveform Generator, (g): GETAC Laptop PC, (h): TÜBİTAK MAM SAL Open Test Tank, (i): water surface level. Note: The sketch is provided solely for illustration purposes.

The photograph taken during the calibration of the segmented Class V Flextensional transducer is shown in the Figure 6.5. The scene is captured through the visualization windows located at a depth of 3,5 m in the open test tank facility at TÜBİTAK MAM SAL. The distance between the projector and the hydrophone elements is 2 m.

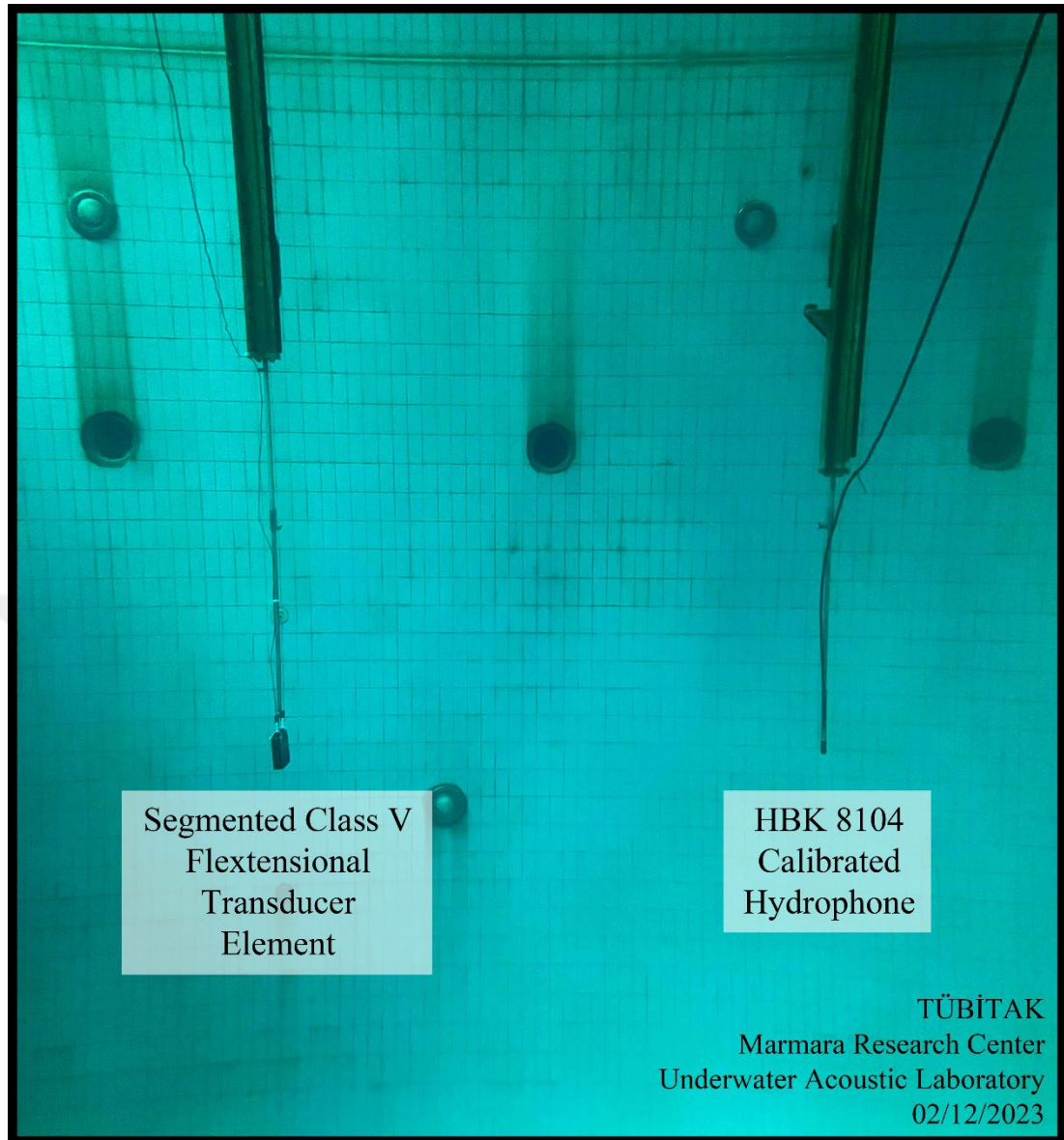


Figure 6.5: Photograph from the visualization window of TÜBİTAK MAM SAL's open test tank during the calibration measurements for the segmented Class V Flextensional transducer element.

6.1.2.2. Measurement Result

The TVR response is calculated using equation (6.3), and the values for the segmented Class V Flextensional transducer element are presented in the Table 6.2.

Table 6.2: TVR values of the segmented Class V Flextensional transducer element.

Frequency	d	V_{PH}	M_H	V_P	$S_{V,P}$
Hz	m	V_{rms}	dB $re V/\mu Pa$	V_{rms}	dB $re 1\mu Pa$ $* m/V$
1000	2	1,70E-5	-205,9	34,16	85,9
2000	2	4,65E-5	-205,5	33,70	94,3
3000	2	2,50E-5	-205,9	33,94	89,3
4000	2	3,57E-5	-206,0	33,92	92,5
5000	2	5,44E-5	-206,2	33,83	96,3
6000	2	1,23E-4	-206,0	33,95	103,2
7000	2	1,29E-4	-206,8	33,88	104,4
8000	2	4,88E-4	-206,5	33,86	115,7
9000	2	8,24E-4	-206,5	33,92	120,2
10000	2	8,00E-4	-206,6	33,86	120,1
11000	2	6,09E-4	-206,5	33,87	117,6

The Transmitting Voltage Response ($S_{V,P}$) of the segmented Class V Flextensional transducer element is measured from 1 kHz to 11 kHz in 1 kHz step, and the results are shown in the Figure 6.6 with an uncertainty of 1,5 dB. The error bars in the figure indicate uncertainties for a cover factor of $k = 2$ [63].

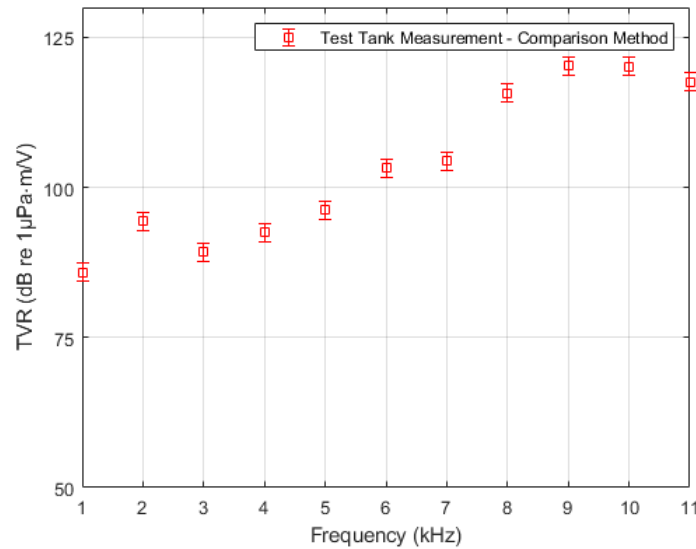


Figure 6.6: Transmitting voltage response of the segmented Class V Flextensional transducer element measurement in the test tank using the comparison method.

6.1.3. Two Equations - Two Unknowns (2E-2U) Method

The 2E-2U method allows for the calculation of amplitude and phase from a single-frequency signal by solving two equations with two unknowns. This method enables one to determine the amplitude and phase within a fraction of a cycle, provided the signal has reached its steady state after transients and before reflected signals from the boundaries. Under these circumstances, the Fourier method cannot work, as it requires at least a full cycle period after the transient regime to calculate amplitude and phase.

In the 2E-2U method, the field values u_1 and u_2 at two given time values of t_1 and t_2 are written as [55]

$$u_1 = A \sin(\omega t_1 + \theta) \quad (6.4)$$

$$u_2 = A \sin(\omega t_2 + \theta) \quad (6.5)$$

Here, A represents the amplitude, ω the angular frequency and θ the phase of the fields. A and θ are two unknowns in two-equations given in equation (6.4) and (6.5), the method is referred to as Two Equations - Two Unknowns (2E-2U) method. The solution of equation (6.4) and (6.5) for the two different time values t_1 and t_2 are

$$A = \frac{u_1}{\sin(\omega t_1 + \theta)} \quad (6.6)$$

$$\theta = \arctan \left(\frac{u_2 \sin(\omega t_1) - u_1 \sin(\omega t_2)}{u_1 \cos(\omega t_2) - u_2 \cos(\omega t_1)} \right) \quad (6.7)$$

where a clear received signal is essential for accurately extracting A and θ . To achieve this, any DC offset present in the measured signals must be removed following the filter process [65], [66].

The two-time samples t_1 and t_2 can theoretically be chosen from any interval of the clear received signals. However, for more accurate modeling of A and θ , they should not be too close to each other. In the test tank measurement, it is observed that transducer transients are present in the initial part of the time gated measured signal while the wall reflections appear in the later portion. Therefore, selecting t_1 and t_2

from the middle part of the time gated measured signal allows the 2E-2U method to be more effectively applied for calibration projectors and hydrophones.

6.1.3.1. Measurement Setup

The same measurement setup described in Section 6.1.2.1 is used during the 2E-2U measurement. At each frequency, measurements are taken from the steady-state portion of a sinusoidal pulse (tone burst) signal. Considering the initial transients and the boundary conditions of the test tank, the received signals are windowed within a time interval of 2 ms to 4,8 ms to capture their steady-state portion. In this step, two important factors must be determined: the initial transient time and the test tank's echo-free time. These are critical for estimating the duration of the time-gated signal and selecting the appropriate time points, t_1 and t_2 . The T_{TG} , T_{it} , τ_{da} and τ_{ef} are represented in Figure 6.7.

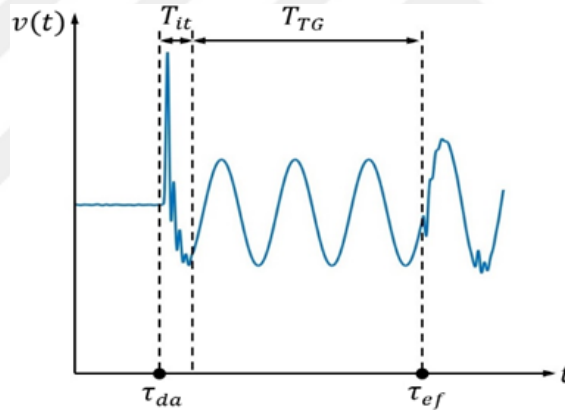


Figure 6.7: The representation graphic for T_{TG} .

- T_{it} : Estimation of the initial transient duration

The initial transient begins when the first direct signal reaches the receiver. The direct path arrival time is $\tau_{da} = dd/c$ where the dd is the direct distance between the segmented Class V Flextensional transducer element and the HBK 8104 Calibrated Hydrophone element. Following the arrival of the direct signal, the initial transients persist for a duration as T_{it} . Since t_1 and t_2 can be selected from any part of the received signal within the steady state after the initial transient duration (T_{it}), estimating T_{it} for the calibration measurements is not a critical concern for the 2E-2U method.

- τ_{ef} : Estimation of the tank echo-free time

There are numerous reflections caused by the boundaries of the open test tank's walls and surface. However, the arrival of the first reflected signal at the receiver, originating from the nearest surface – the water surface – defines the tank's echo free time. Knowing the acoustic wave propagation speed, c , in open test tank and the shortest two-way distance, ds , between the transducer and the nearest surface, the ending window time is calculated with the formula $T_{ef} = ds/c$, explained in Section 6.1.2.1.

Now, we can define a duration T_{TG} for the time gated signal

$$T_{TG} = \tau_{ef} - (\tau_{da} + T_{it}) \quad (6.8)$$

The open test tank echo free time (T_{ef}) and direct signal arrival time (τ_{da}) were calculated previously as 4,8 ms and 1,3 ms respectively. Additionally, by checking the measured time waveforms, (T_{it}) is set to 0,7 ms corresponding to $T_{it} \cong 0,175 T$ for 250 Hz, which will be the lower frequency calibration limit of the open test tank. This is achieved by applying the 2E-2U method, which is 1 kHz as previously explained (Section 6.1.2.1) with the current measurement setup. In order to minimize the effect of the broadband noises the measured signals are averaged 50 times before being used as an input for the 2E-2U method.

6.1.3.2. Measurement Result

The reconstructed time waveforms using the 2E-2U method from the measured signals for the segmented Class V Flextensional transducer element, from 250 Hz to 1 kHz, are shown in the Figure 6.8. The blue signals represent the received signals captured by the HBK 8104 Reference Hydrophone element when the segmented Class V Flextensional transducer element emits tone burst signals, while the red signals represent the reconstructed signals obtained using the 2E-2U method.

As the main focus of the 2E-2U method is on low frequencies, where the necessary number of oscillations cannot fit within the dimensions of the open test tank facility for calibration measurements, the time waveforms from 250 Hz to 1kHz representing the lower calibration range, which cannot be achieved with the current measurement setup in the laboratory are presented here.

As observed in the Figure 6.8, the measured and the constructed time waveforms align very well and increasing frequency results in a better signal to noise ratio at the receiver. This is primarily due to the segmented Class V Flextensional transducer's improved performance above 500 Hz.

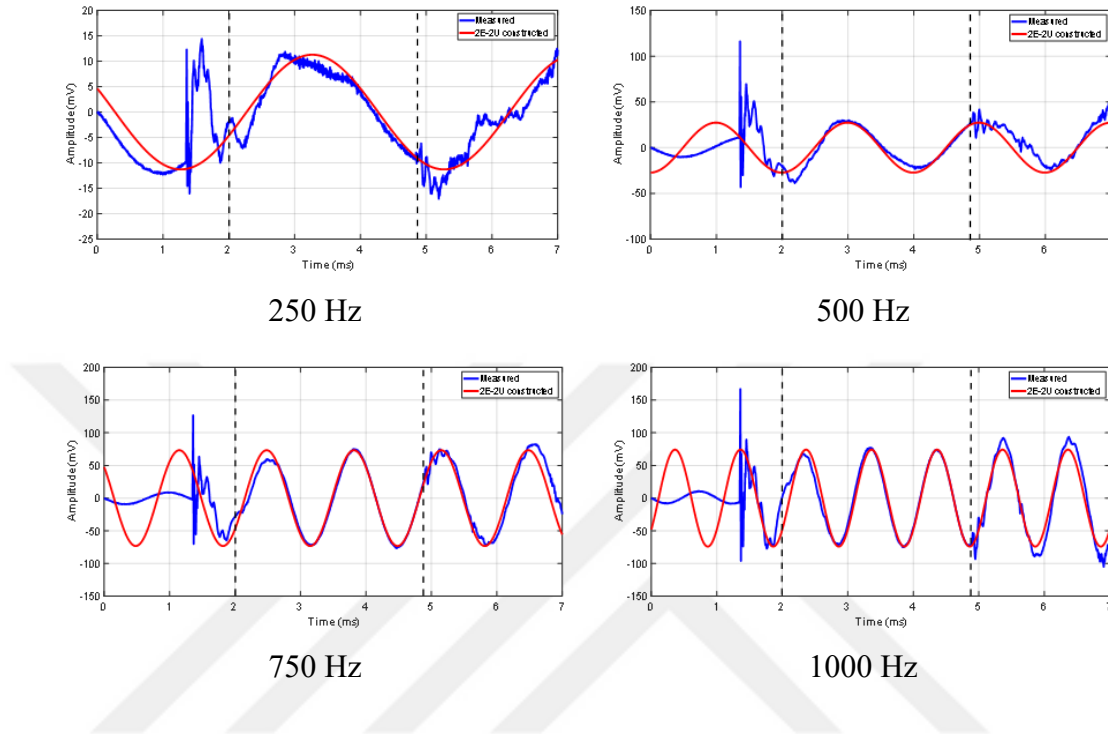


Figure 6.8: The measured and constructed waveforms at the receiver when the segmented Class V Flextensional transducer element transmits sound waves.

The 2E-2U method is also applied to calibrate another hydrophone available in the laboratory, demonstrating the method's efficiency for hydrophone calibration as well. The reconstructed time waveforms using the 2E-2U method from the measured signals for the HBK brand 8104 model hydrophone (Serial Number: 3087933), from 250 Hz to 1 kHz, are shown in the Figure 6.9. The results, compared with those obtained using a pressure chamber for frequencies ranging from 250 Hz to 1,4 kHz are given in paper [64].

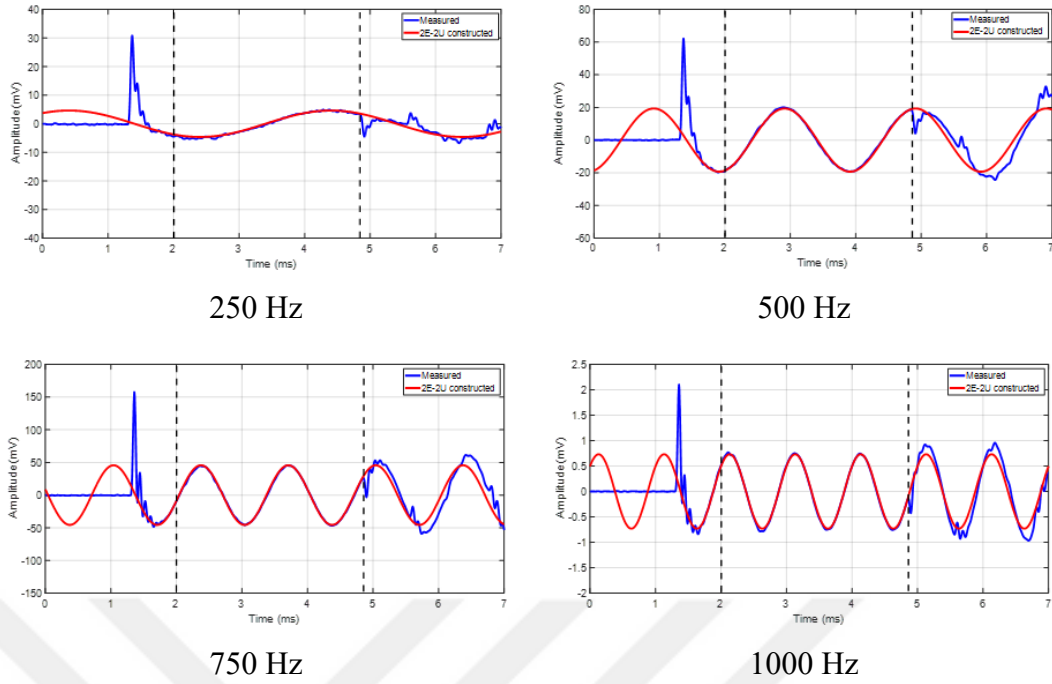


Figure 6.9: The measured and constructed waveforms at the HBK 8104 (Serial Number: 3087933) when an on the shelf projector element transmits sound waves.

The TVR ($S_{V,p}$) of the segmented Class V Flextensional transducer element is measured from 250 Hz to 11 kHz and the results are shown in the Figure 6.10 with a maximum uncertainty of 1,7 dB. The error bars in the figure indicate uncertainties for a cover factor of $k = 2$ [63].

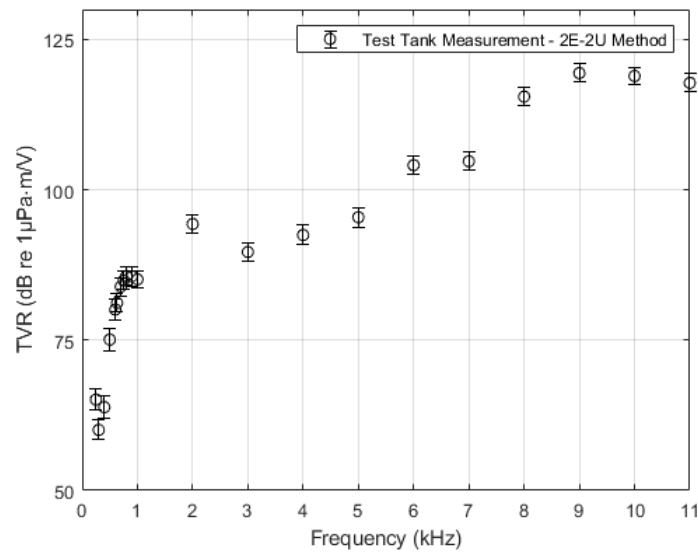


Figure 6.10: TVR of the segmented Class V Flextensional transducer element measurement in the test tank using the 2E-2U method.

6.2. Comparison of the Measurement Results with the Modeling Study

In this section, the results obtained from measurements and Finite Element Analysis are discussed. Firstly, the electrical impedance measurement of the segmented Class V Flextensional transducer element is analyzed by comparing Finite Element Analysis and Test Tank Measurements up to 11 kHz. Secondly, the Transmission Voltage Response of the segmented Class V Flextensional transducer element is compared using the 2E-2U method, the Comparison Calibration method, and Finite Element Analysis study starting from 250 Hz (for the applicable methods) up to 11 kHz.

In the Figure 6.11, the electrical impedance curves of the segmented Class V Flextensional transducer element are displayed. Good agreement between the FEA and the Test Tank Measurement is observed for the electrical impedance measurement. The two results align very well across the frequency range of interest.

The FEA shows that the Segmented Class V Flextensional transducer element has a resonance frequency between 4 kHz and 5 kHz, where a dip and a peak appear, which are not visible in the Test Tank Measurements. The behavior of this resonance observed in Finite Element Analysis will also be illustrated more apparently in the TVR graphs.

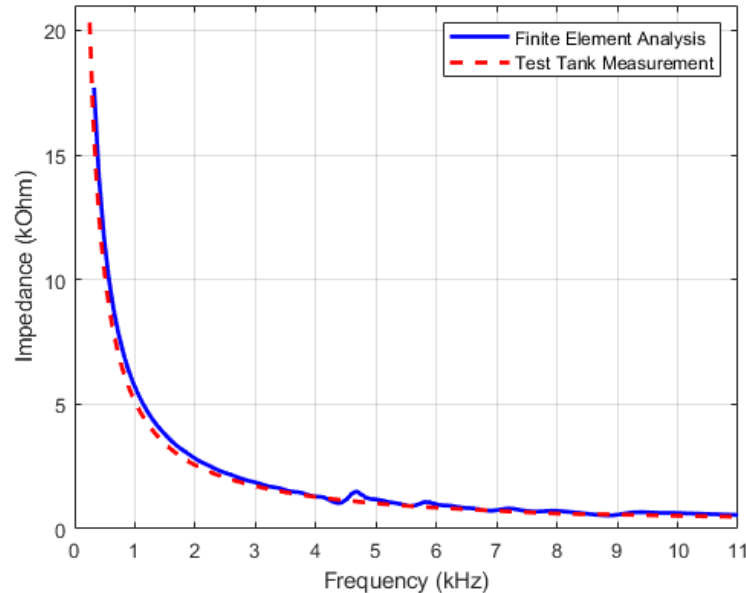


Figure 6.11: Electrical impedance plot of the segmented Class V Flextensional transducer element: test tank measurement and FEA results.

As mentioned earlier, one of the key parameters for describing the performance of an underwater acoustic projector element is the Transmitting Voltage Response (TVR). The TVR of the segmented Class V Flextensional transducer element is analyzed in detail using three characterization methods: Test Tank Measurement by the 2E-2U method, Test Tank Measurement by the Comparison method, and the FEA study. The results are presented graphically in Figure 6.12 and in tabular form in Table 6.3.

In general, the three approaches exhibit similar behavior in the frequency range between 1 kHz and 11 kHz except in the range from 3 kHz to 5 kHz, where the FEA shows a higher TVR. The reason for this behavior is discussed later in this section.

It is evident that the two test tank measurement methods match very well with each other in this range, with a maximum difference of 1,1 dB and an uncertainty of 1,6 dB. Below 1 kHz, a comparison of the 2E-2U method with other methods cannot be conducted due to the lack of additional infrastructure for comparison, unlike the setup used for the calibration of the hydrophone element below 1 kHz as presented in the Appendices.

In the frequency range between 3 kHz and 5 kHz the result of the 2E-2U Method and the Comparison Method agree very well with each other. However, Finite Element Analysis shows a peak in this range, which also appears in the Impedance Measurement. It is considered that during the manufacturing process of the segmented Class V Flextensional transducer element, the mechanical resonance of the element is damped, which explains why this peak does not appear at the measurements.

It seems that the damping mechanism that occurred during the manufacturing process could not be replicated similarly in the model work, which should be addressed in future work. Specifically, the mechanical jointing, such as the screws used to assemble the octagonal structure of the stacks and the cap, needs to be implemented in the model with particular attention and effort.

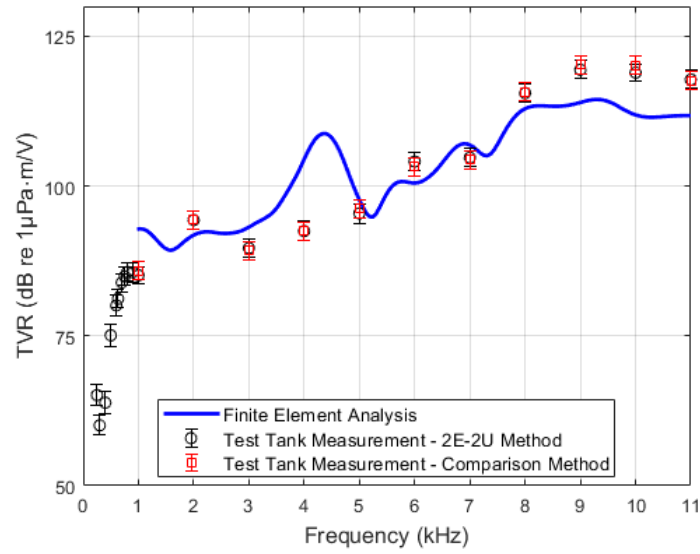


Figure 6.12: Graphical representation of transmitting voltage response of the segmented Class V Flextensional transducer element response: measurement in the test tank using the 2E-2U method, the comparison method, and finite element analysis.

Table 6.3: Tabular representation of TVR of the segmented Class V Flextensional transducer element response: measurement in the test tank using the 2E-2U method, comparison method and finite element analysis.

Finite Element Analysis		Test Tank Measurement 2E-2E Method			Test Tank Measurement Comparison Method		
f Hz	TVR dB	f Hz	TVR dB	U $\pm$ dB	f Hz	TVR dB	U $\pm$ dB
-	-	250	65,1	1,7	-	-	-
-	-	300	60,1	1,6	-	-	-
-	-	400	63,9	1,8	-	-	-
-	-	500	75,1	1,8	-	-	-
-	-	600	80,1	1,7	-	-	-
-	-	630	81,2	1,5	-	-	-
-	-	700	83,9	1,5	-	-	-
-	-	750	84,9	1,5	-	-	-
-	-	800	85,7	1,5	-	-	-
-	-	900	85,6	1,6	-	-	-
1000	92,8	1000	85,1	1,5	1000	85,9	1,5
2000	91,9	2000	94,3	1,5	2000	94,3	1,5
3000	93,2	3000	89,7	1,6	3000	89,3	1,5
4000	104,3	4000	92,5	1,6	4000	92,5	1,5
5000	97,2	5000	95,4	1,6	5000	96,3	1,5
6000	100,5	6000	104,1	1,5	6000	103,2	1,5
7000	106,9	7000	104,8	1,5	7000	104,4	1,5
8000	113,0	8000	115,5	1,5	8000	115,7	1,5
9000	114,0	9000	119,4	1,5	9000	120,2	1,5
10000	112,0	10000	119,0	1,5	10000	120,1	1,5
11000	111,8	11000	117,8	1,5	11000	117,6	1,5

7. CONCLUSION

In this thesis, a novel design for an underwater electro-acoustic projector element is studied in detail. The Class V Flextensional transducer design, commonly used in ultrasonic and medical applications, served as the baseline for this study. While the existing Class V Flextensional transducer design has occasionally been applied to underwater acoustic applications, it has primarily been used for mid- or high-frequency operations. To date, the Class V Flextensional transducer has not been utilized for low-frequency applications below 10 kHz as a projector unit in the field of underwater acoustics due to size-related challenges. These challenges include difficulties in manufacturing piezoelectric materials with the required dimensions and complications in the assembly process.

This thesis introduces a novel design concept to the literature, enabling the application of the Class V Flextensional transducer design to low-frequency underwater acoustic applications. A segmented octagonal stack assembly structure is designed and developed to eliminate the need for manufacturing a monolithic piezoelectric plate with a disc-shaped geometry equivalent to the octagonal stack assembly's diameter and thickness. The manufacturing of a monolithic piezoelectric plate with a diameter (100 mm) and thickness (3 mm) equivalent to the octagonal stack assembly is very challenging task from a production perspective. Additionally, a cap design suitable for the octagonal stack assembly is created, along with an assembly and encapsulation process, resulting in the segmented Class V Flextensional transducer element.

The CAD model of the segmented Class V Flextensional transducer element is developed for Finite Element Analysis (FEA) using OnScale FEA software, and simulations of the transducer element are conducted. A prototype of the segmented Class V Flextensional transducer element is subsequently characterized and calibrated at the TÜBİTAK MAM Underwater Acoustic Laboratory using the comparison method and the 2E-2U Method. The measurement results are then compared with the findings from the modeling study. This thesis successfully demonstrates that the 2E-2U method allows calibration measurements to be conducted down to 250 Hz, compared to the previous limit of around 1 kHz.

The results are promising and demonstrate strong agreement between the measurement methods and the simulation results except the discrepancy observed between the 3 kHz to 5 kHz in the simulation results, which has been explained in detail. This thesis represents a comprehensive study, covering the conceptual design through to the characterization of an end product, with the unique aspects discussed in detail in Section 2.3. It has been demonstrated that the segmentation of the piezoelectric material in the transducer design provides a significant advancement to the field. The lightweight structure and dimensionally compact transducer design, relative to its operating frequency make it suitable for use on stationary or mobile platforms. For higher sound power levels, array structures can be designed and manufactured, enabling the beam to be steered both horizontally and vertically to focus on other bearings.

The current prototype design also allows the transducer element to be driven with different signal phases due to the individual electrical connections of each stack, something that is not possible with a single, monolithic PZT disc-shaped plate.

Future work can focus on transmitting voltage response below 1 kHz and improving the mechanical assembly of the stacks with the cap structure as part of a modeling study. This will further enhance the modelling performance of a single transducer element.

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BIOGRAPHY

Ata Can ÇORAKÇI, completed his high school education at Lycée Saint Joseph with a science degree in 2002. He received his Bachelor of Science degree from FMV Işık University's Faculty of Engineering, Department of Electronic Engineering, in 2007 in Istanbul, TÜRKİYE, and his Master of Science in Sound and Vibration Engineering from Chalmers University of Technology in 2009 in Gothenburg, SWEDEN.

He worked as an intern engineer at Bombardier Transportation in Västerås, SWEDEN, where he focused on interior acoustic modeling of train compartments, carrying out both measurements and ray-tracing modeling during his Master thesis work.

After completing his graduate studies, he returned to TÜRKİYE in the early summer of 2010 and fulfilled his mandatory military service for six months in Çorlu, TÜRKİYE. Following his military service, he began his career as a researcher at TÜBİTAK MAM's Underwater Acoustic Laboratory in the autumn of 2010.

During his duration at TÜBİTAK MAM, he worked primarily on projects aimed at meeting the needs of the Turkish Navy Forces. He held positions as researcher, deputy project manager and project manager for both national and international projects.

At the end of 2023, Ata Can ÇORAKÇI decided to pursue an international career and joined the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO-a United Nations-affiliated organization) in Vienna, AUSTRIA, as the Project Manager of the Hydroacoustic Team in the International Monitoring System Division.

PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

[1] Çorakçı A. C., Biber A., Saydam T., Aksoy S., (2024), “Application of 2E-2U method for free field underwater calibrations of hydrophones and projectors in a reverberant laboratory test tank,” Measurement Science and Technology, 35 (8), 1-7.

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