DEVELOPMENT OF A HEXAGONAL HEAD TONPILZ TRANSDUCER FOR UNDERWATER APPLICATIONS

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1 INTRODUCTION

A large number of acoustic systems are currently used for variety of underwater applications in the defense and civil sectors. Some potential applications are underwater surveillance, navigation, target detection and classifications etc.[1]. In all these systems the terminal element is an electro-acoustic transducer. Many of these applications require the transducer with wide bandwidth, high power handling capability and high electro-acoustic efficiency. Some of these are conflicting requirements and therefore a compromise is to be made in the design of transducer. Piston type pre-stressed sandwich transducer with the piezoelectric ceramic as driving stack can be used in most of the sonar applications. Tonpilz transducer (figure-1) is the most popular type of sonar transducer commonly used for high power applications due to their superior acoustic performance and rigid structure [2,3]. Generally, these are grouped into arrays for sonar applications to increase power radiation and for required beam steering. Basically, sonar design begins with the design of a single transducer. It consists a stack of piezoelectric ceramic rings connected mechanically in series and electrically parallel. The ceramic stack is sandwiched between heavy tail mass and a light head mass.

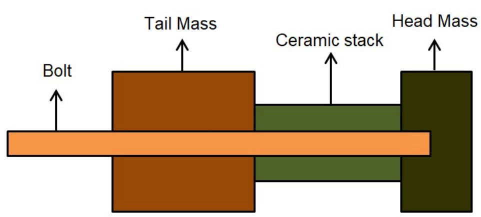

Figure-1: Schematic diagram of a Tonpilz transducer.

The head mass is an essential component in the transducer design. It is made to be much lighter than the tail mass, as it has to vibrate at high frequency in order to radiate pulses. Hence metals like Aluminium (Density: 2,712kg/m^3) or Titanium (Density: 4,500kg/m^3) are preferred for underwater applications, as they have low density and high strength [4]. The material used in head mass is required to have an acoustic impedance between the ceramic and water. The surface of the head mass is the place where the energy is transmitted / received through acoustic medium. Thus, it is called the active surface. The shape of the active surface varies according to functional requirements. Circle shape is very common but not very useful in the array applications as the packing fraction is less which in turn reduces the acoustic output. Therefore, a square or hexagonal shaped piston is preferred.Also, the conventional Tonpilz transducer as a longitudinal vibrator has a limited bandwidth [5]. However, there is a need for wideband, high power Tonpilz transducers for detection and classification of underwater objects. The size and shape of the head mass play a vital role in bandwidth of the transducer.

Various authors studied on the optimization of the head shape for wide bandwidth, effect of head shape on beam pattern, selection of head mass and active material to achieve improvement in the performance of Tonpilz transducer. Yao and Leif explored the possibilities of achieving a broadband Tonpilz transducer using different vibrational modes [6]. Saosometh et al. designed a multimode Tonpilz transducer with a cavity inside the head mass [7]. Afzal et al. used a side acoustic window to increase the bandwidth [8]. Wang, Lan and Cao described the effect of head mass material on the transducer performance [9]. Pyo et al. used non-uniform piezoceramic stack to maximize the operational bandwidth [10]. The impact of surface geometry that is in contact with water on the radiation pattern was discussed by Roh et al.[11]. Recently MerveNur et al. designed a seven element array of Tonpilz transducer with hexagonal radiating head and PMN-PT piezoceramics as driving stack [12].

With Finite Element Analysis (FEA) software programs such as COMSOL and ATILA, performance of transducers can be described very precisely. In this paper a Tonpilz transducer with hexagonal radiating head is designed for low frequency sonar application. The theoretical design parameters are verified using FEA package COMSOL.A prototype transducer is developed and tested for transmitting voltage response (TVR), receiving sensitivity (RS) and beam pattern. The results of prototype transducer shows the maximum TVR 142.6 dB ref. 1μPa/V@1m and RS -175.7 dB ref.1V/μPa.

2 METHODOLOGY

A Tonpilz transducer with hexagonal radiating head was designed for low frequency sonar application. The design parameters were calculated using standard formulae and shown in the table 1.

Table-: 1 Design parameters for hexagonal head Tonpilz transducer

Component	Structural parameter	Dimension (mm)
Head mass	Side	16.6
	thickness	7
Tail mass	Length	5.5
	Outer diameter	17
PZT ring	Thickness	4
	Outer diameter	14
	Inner diameter	6
Stress bolt	Diameter	4

The details of the material properties used in the design calculation are shown in the table 2.

Table 2: Material properties used for FEA.

Components	Material	Poisson's ratio	Density (kg/m3)	Young's Modulus (Pa)	Sound speed (m/s)
Head	Aluminum alloy	0.344	2780	7.14×10^{10}	5067
Tail	Naval Brass	0.33	8270	9.2×10^{10}	3335
Stress bolt	Be Cu alloy	0.3	8250	12.8×10^{10}	3938
Stack	PZT-4	-	7500	6.6×10^{10}	2966
Radiation medium	Water	-	1000	-	1500

2.1 Analysis in COMSOL

The design parameters are verified using FEA in COMSOL. Here, a 3-D axi-symmetric quarter model along with water (figure-2) was constructed for the frequency domain analysis. Radius of the radiating sphere was set to sufficiently high to meet the far field condition. Perfectly Matched Layer boundary condition was applied to absorb the radiated acoustic energy. The front hexagonal surface of the head mass is interfaced with the water medium for fluid structure interaction. The finite elements are tetrahedral-shaped with maximum distance between two nodes as one fourth of the wavelength corresponds to the highest frequency of interest. Here, the front thickness of the head mass was optimized to maximize the operational bandwidth. Analysis was done for three different front thicknesses, 1.0 mm, 1.5 mm and 2.0 mmmaintaining the same mass. TVR for the three cases are shown in figure-3. The 3 dB TVR bandwidth is $0.552f_0$, $0.296f_0$ and $0.304f_0$ for 1.0 mm, 1.5 mm and 2.0 mm front thickness respectively. Based on the above result the front thickness of the radiating head was finalized to 1.0 mm. The performance factors analyzed are the conductance (G), transmitting voltage response (TVR), receiving sensitivity (RS) and beam pattern in the frequency band of interest.

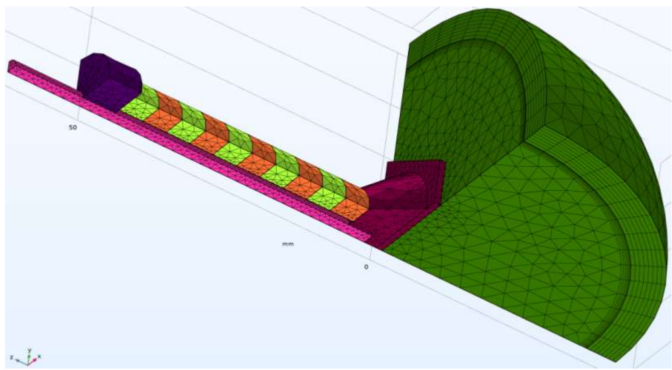

Figure 2: Three dimensional axi-symmetric model of the transducer along with water and mesh.

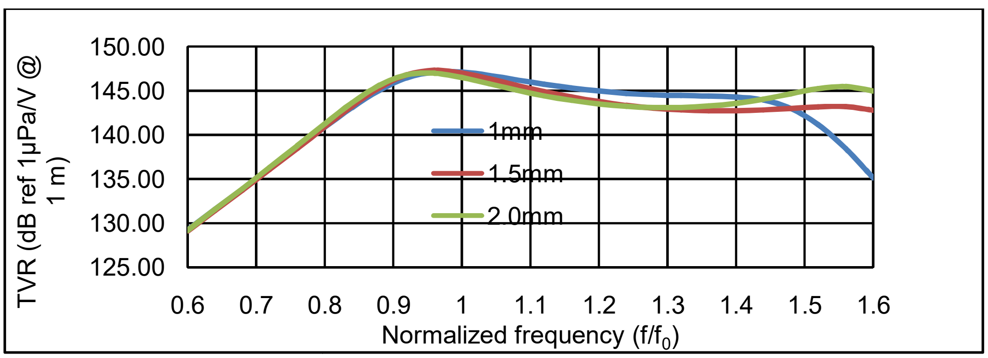

Figure 3: TVR for three different front thicknesses.

2.2 Prototype Development

A prototype Tonpilz transducer with hexagonal radiating head was developed using the finalized dimensions as shown in table-1. PZT-4 rings are sandwiched between the hexagonal head and cylindrical tail mass. Electrodes are placed between the rings and electrical connections are made. The prototype transducer fabricated is shown in figure-4.

Figure 4: Prototype Tonpilz transducer with hexagonal radiating head.

3 EXPERIMENTAL EVALUATION

To verify the design parameters, the prototype transducer was evaluated experimentally for its acoustic performance and compared with that from FEA. The experiment was carried out in acoustic tank using tone burst technique [13] in the frequency band of interest. The experimental setup is shown in figure 5. The transducer was assembled with watertight rubber dome and the entire assembly was mounted on the test fixture and positioned at a depth of 4 m in water. Conductance(G) spectra was measured using Wayne Kerr 6500B impedance analyzer. A hydrophone (ITC1032) was positioned at same depth with a horizontal separation of 1m along the maximum response axis. The acoustic performances were measured using Transducer Calibration System (TCS) having signal generator, power amplifier, pre-amplifier, data acquisition system and post processing modules. TVR and RS spectrum was measured over the required frequency band at a intervals of 1 kHz and beam pattern was measured at $0.8f_0$ and f_0.

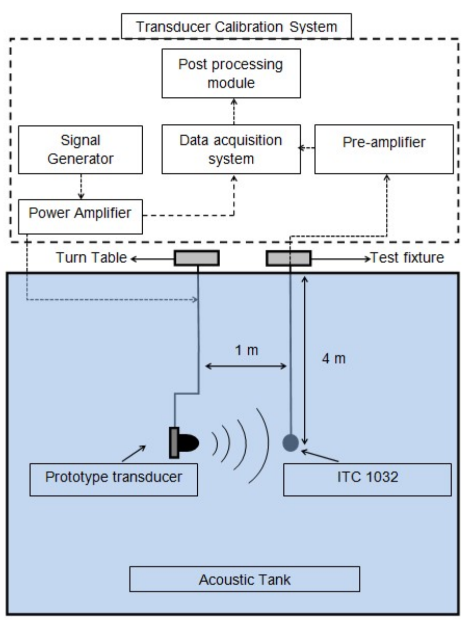

Figure-5: Schematic diagram of the experimental setup for TVR spectra.

4 RESULTS AND DISCUSSION

The experimental results were compared with that from FEA and shown in the figures 6-10. Figure-6 shows measured conductance compared with that from FEA. The measured maximum G is 0.54

mS compared to 0.76 mS from FEA. The longitudinal resonance frequencies are at $0.904f_0$ and $0.968f_0$ respectively for experiment and FEA. The flexural mode of vibration is merged with the longitudinal mode in G spectra.

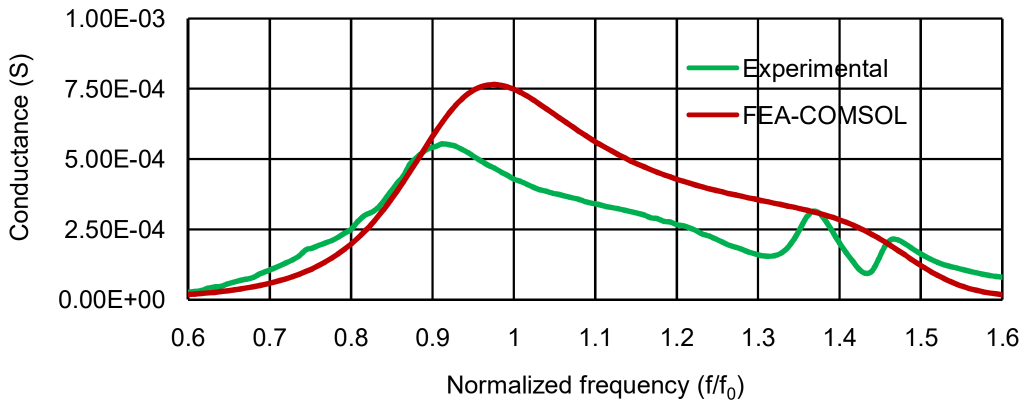

Figure-6: Comparison of conductance as a function of normalized frequency of the prototype Tonpilz transducer with hexagonal radiating head from FEA and experimental measurements.

Figure-7 compares measured TVR spectrum of the prototype transducer with estimation from FEA. The measured peak value of TVR for longitudinal resonance is 142.7 dB compared to 147.2 dB from FEA, resulting a deviation of 4.5 dB. The longitudinal mode frequencies for the measured and FEA TVR spectra are $0.92f_0$ and $0.976f_0$ respectively. The TVR levels for the flexural mode are 142.0 dB and 144.4 dB for experiment and FEA respectively, resulting a deviation of 2.4 dB. The flexural frequencies are at $1.16f_0$ and $1.384f_0$for experiment and FEA respectively.

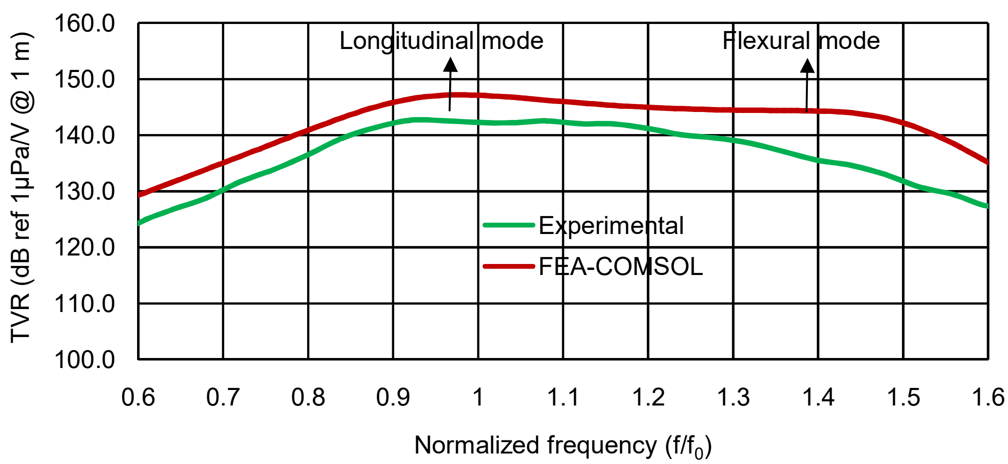

Figure-7: Comparison of TVR.

In experimental measurement of G and TVR spectra both longitudinal and flexural modes are shifted towards lower frequency compared to FEA. This is due to the presence of mechanical loading imposed on the transducer by the rubber dome assembly. Absence of loading in FEA model caused higher G and TVR value at slightly higher frequency.RS spectra from experiment and FEA are shown in figure-8. Peak RS value for experiment is -175.7 dB at f_0 compared to -178.9 dB from

FEA at 1.512f_0. Here also the effect of rubber dome assembly influences the RS spectra. The results for TVR and RS spectra are tabulated in table-3.

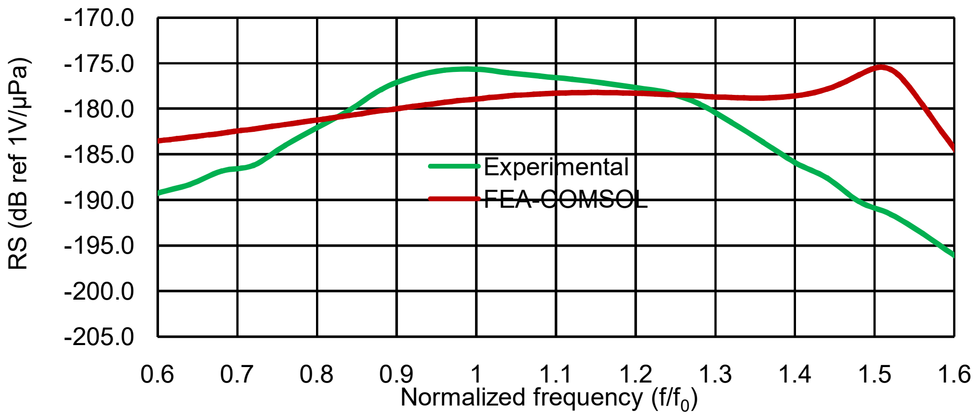

Figure-8: Comparison of RS.

Table-3: Comparison of longitudinal and flexural mode as per FEA and experimental measurements.

Method	Longitudinal mode TVR (dB)	Flexural mode TVR (dB)	Longitudinal resonance frequency	Flexural resonance frequency	Bandwidth (3 dB)	
					TVR	RS
FEA	147.2	144.4	0.976f_0	1.384f_0	0.552f_0	0.624f_0
Experimental measurement	142.7	142.0	0.92f_0	1.16f_0	0.44f_0	0.36f_0

The beam pattern at 0.8f_0 and f_0 are shown in figure-9 and 10. The -3 dB beam width from experiment at 0.8f_0 is 80 degree compared to 77 degree from FEA and at f_0 the values are 77 degree and 73 degree respectively.

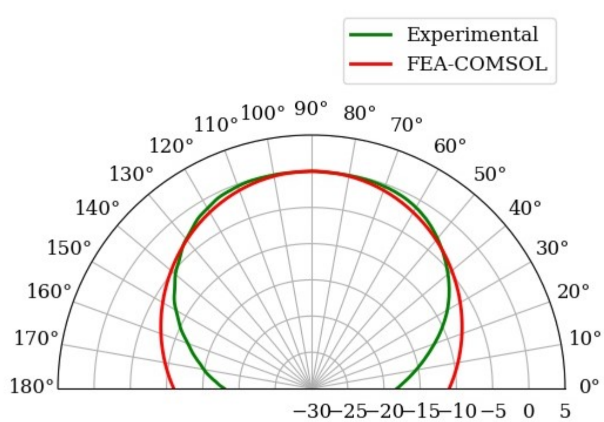

Figure-9: Comparison of beam pattern of the transducer at 0.8f_0 from FEA and experiment.

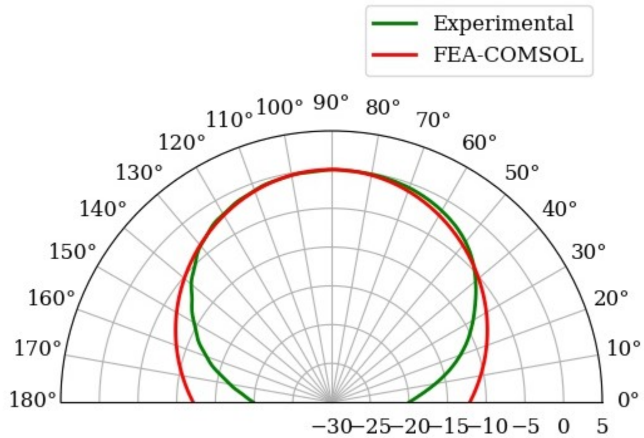

Figure-10: Comparison of beam pattern of the transducer at f_0 from FEA and experiment.

From figures 6-10 we can say that results are comparable. The deviation could be due to the inaccuracy of material properties of the components used for FEA and the mounting arrangement of the transducer for calibration, which could not be modelled.

5 CONCLUSION

A prototype Tonpilz transducer with hexagonal radiating head was designed, developed and characterized for its acoustic performances. The experimental results are compared with that from FEA. As modeled by the COMSOL FEA program, the G, TVR, RS spectra and beam pattern of the transducer are in good agreement with the experimental data in the required frequency band.

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