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Design, development and characterization of a mid-frequency (35 khz) tonpilz transducer array from 0.675PMN-0.325PT piezoceramics

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Abstract

A mid-frequency tonpilz transducer array was designed and analyzed by finite element method using commercial ATILA code and constructed using piezoceramic rings with lead magnesium niobate (PMN)-lead titanate (PT) composition. The morphotropic phase boundary (MPB) $0.675Pb(Mg_{1/3}Nb_{2/3})O_3$-$0.325PbTiO_3$ composition was chosen to obtain higher performance from the transducer due to the superior dielectric and electromechanical properties of the MPB compositions. A pure perovskite phase was obtained from the ceramics. Piezoelectric charge coefficient (d_{33}) was measured as 435 $pC\cdot N^{-1}$. Single tonpilz element and an array consisting of 7-unit array were constructed and later potted in polyurethane for underwater measurements. A second array was also constructed for comparison from commercial hard $Pb(Zr,Ti)O_3$-PZT ceramics. The longitudinal piston mode vibration frequency of the tonpilz transducer was measured around 33 kHz in air and around 35 kHz in water. The PMN-PT based array was found to have a comparable transmit performance and a superior receive performance compared to PZT.

1. Introduction

Since the middle of the 20th century with the emergence of materials with high dielectric constants, piezoceramics, a subgroup of dielectric ceramics have been used in many electronic applications. Due to their dielectric constant, electromechanical coupling coefficients and piezoelectric charge coefficient, piezoceramic materials can also be used in electromechanical applications for underwater imaging, listening, communications (sonar, hydrophone), and many other applications [1-3]. Transducers that operate at low to medium frequencies play a vital role in underwater naval applications for frigates and ships [4,5]. Tonpilz piezoelectric transducers are the most common type of transducers, especially in underwater applications, because they can be produced simply and at low cost [6,7]. The design and choice of piezoelectric materials of Tonpilz transducers directly affect their ability to generate high acoustic power in water in a wide band.

Tonpilz transducers generally consist of heavy tail mass, light head mass, a piezoceramic stack as a drive section in "33" mode. In the transducer assembly, these components are joined by a stress bolt, which is used in the center to fasten all the components and keep them under a prestress [8]. The drive section consists of piezoceramic that is in charge of generating vibration [9]. The selection of piezoceramics is vital, so ceramics must have high piezoelectric and electromechanical coupling coefficient. Consequently, lead zirconate titanate (PZT) is the main piezoceramic family used for Tonpilz transducers due to their higher electrical properties. In the recent studies, lead magnesium niobate-lead titanate (PMN-PT) single crystals [10-12], lead-free perovskite compositions based on barium titanate [11] were also used as candidates for enhancing of the electromechanical properties. It has been observed that PMN-PT single-crystals operate in a wider bandwidth than commercially used PZT ceramics due to their high piezoelectric coefficient and electromechanical coupling factor. However, production of the single crystal PMN-PT ceramics is difficult, as well as expensive. Crystallographically textured PMN-PT ceramics have also been investigated in the drive section and compared with the polycrystalline PMN-PT ceramics as cost-effective, alternative for single crystals [8]. In addition to changes that have been done in the active piezoelectric materials of the tonpilz, several design changes have also been investigated to increase the bandwidth and generated acoustic power of the device, such as using ceramic rings of non-uniform thickness [13] or driving the ceramics in segments [4].

The synthesis of pure perovskite phases of PMN-PT polycrystalline ceramic is exceedingly difficult; thus, various synthesis techniques have been developed [14]. The columbite - solid state calcination process was used to produce PMN-PT composition because this method prevents the undesired pyrochlore phase and promotes an increase in grain size without considerably changing density [14,15]. It is known that the composition with the highest piezoelectric and electromechanical coupling coefficients of PMN-PT is in the region called the morphotropic phase boundary [12].

In this study, a tonpilz transducer was designed for mid-frequency (~35 kHz) underwater applications, specifically for the acoustic head of unmanned underwater vehicles. The design was analyzed by finite elements analysis (FEA) using commercial ATILA code. As a novel device detail, the head mass of the transducer was designed with a hexagonal symmetry to achieve a larger acoustic radiation surface and a tighter packing in an array arrangement. The piezoceramic rings used in the drive section of the transducer was fabricated from a 0.675PMN-0.325PT composition that is located in the morphotropic phase boundary region for a higher piezoelectric performance. After the construction of the single transducer, a 7-unit array was also constructed, tested underwater. Finally, identical single elements and a 7-unit array were constructed from commercial PZT-4 class hard piezoceramics for comparison.

2. Experimental procedures

2.1 Ceramic fabrication

Ceramic powders with 0.675PMN-0.325PT composition were synthesized by the combination of solid-state calcination and columbite methods. Columbite method was applied to synthesize magnesium niobate ($MgNb_2O_6$) using Nb_2O_5 (Alfa Aesar, 99.5%) and $(MgCO_3)_4\cdot Mg(OH)_2\cdot 5H_2O$ (Sigma Aldrich, 98%) as source powders. The detailed information about synthesis of magnesium niobate by columbite method is accessible in our previous papers [16,17]. Titanium dioxide-TiO_2 (Degussa, P25) and lead (II) oxide-PbO (Alfa Aesar, 99.9%) were used as titanium and lead sources, respectively. Source powders were weighed according to stochiometric ratio and ball-milled for 24 h. The mixture was dried at 70°C and calcinated at 750°C for 2 h. The particle size of the powders was measured as 0.177 µm ($d_{0.5}$). Powders were uniaxially pressed into a ring-shape. The green ceramic rings were sintered at 1200°C for 4 h in air atmosphere and then rings were lapped and polished. Calcination and sintering conditions were chosen according to our previous papers [16,17]. The final dimensions of the rings after lapping were given in Figure 1(a). The rings were coated with silver paste electrodes on two parallel surfaces for electrical measurements and for poling. Poling along the thickness direction was done at 80°C for 10 min under an electric field of 24 $kV\cdot cm^{-1}$. Identical rings were also fabricated from commercial PZT-4 class hard piezoceramics (TP4, T&Partners Praha, Czech Republic).

2.2 Transducer design and construction

Two ceramic rings were used in the single element tonpilz design. A 6013-aluminum head mass with hexagonal cross-section was used for a close-packing of the transducers in the array to generate higher acoustic power. A 1040 plain steel with conical shape was used as the tail mass. The three-dimensional cross-sectional representative drawing of a single element was given in Figure 1(b). Single element tonpilz transducers were fabricated using two rings and during the assembly, the pre-stress is applied with a stress bolt. After cabling, they were covered with polyurethane from outside for electrical isolation.

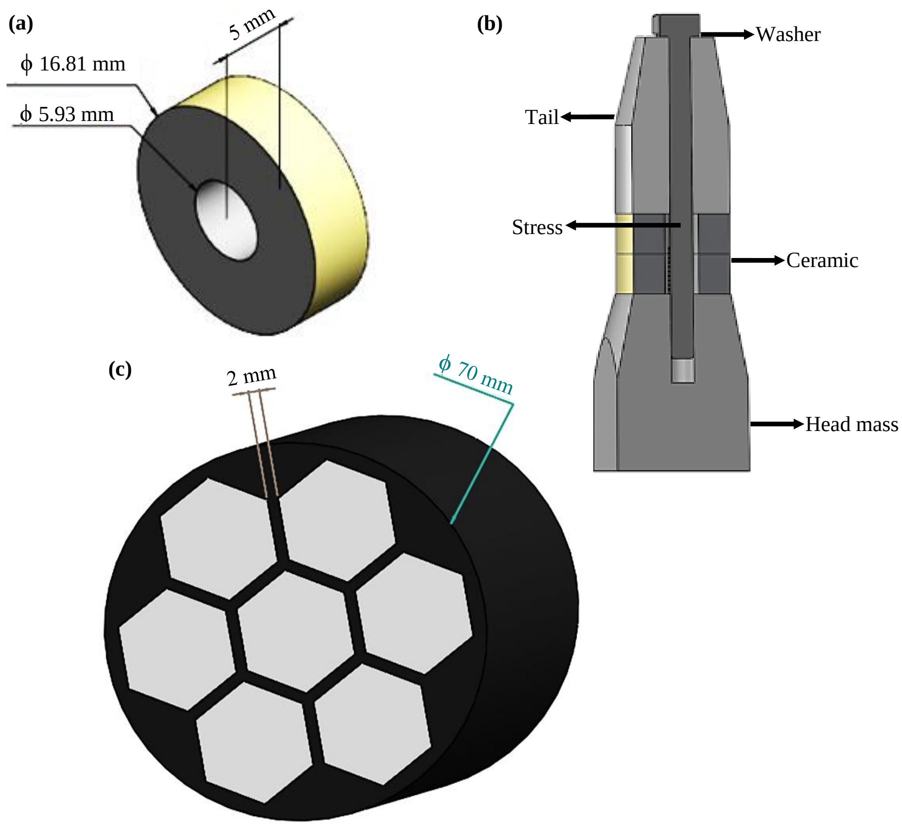

Figure 1. (a) The size of a ring, (b) cross-sectional view of a single element transducer and (c) the transducer with 7 element transducer array in a closed-packed hexagonal order where the units are electrically connected either in series or in parallel.

2.3 Characterization

The phase analysis of the powders and rings was done by X-ray diffractometer (XRD) (D8 Advanced, Bruker, Germany) using a Cu-Kα. The microstructure of the sintered ceramics was examined by a scanning electron microscope (SEM) (XL30, FEI Co., USA). Piezoelectric charge coefficient (d33) of the rings were measured by a piezo-d33 meter (APC International Ltd., USA). Resonance spectra of the rings and the transducers were measured with Hioki 3520 LCR meter (Hioki, Japan) between 1 kHz to 200 kHz frequency range at room temperature. The materials property matrix of the PMN-PT ceramics for FEA was used from our previous studies [16,17] which were determined by the resonance method using the IEEE standards. Underwater performance of the single element transducers and arrays was evaluated through the calculation of transmitting voltage response (TVR) and free field voltage sensitivity (FFVS) from underwater admittance vs. frequency measurements [18].

3. Results and discussion

3.1 Structural and electrical properties of ceramic rings

Figure 2 shows the comparison of the XRD pattern of powder and sintered ceramic ring. The pure perovskite structure was observed in the samples without untransformed or residual secondary phase. SEM micrograph of the fracture cross-section of the sintered PMN-PT ring is given in Figure 3 and as seen in this figure, the microstructure is dense without any porosity with a rather uniform grain size distribution in the range of 2 μm to 5 μm.

Piezoelectric charge coefficient (d_{33}) was measured as 435 $pC{\cdot}N^{-1}$ after poling. Figure 4 shows admittance and phase angle graphs of poled PMN-PT ring. Resonance frequency (f_R) of the main radial mode was found as 93 kHz and as seen from the phase angle curve, ceramics were found to be effectively poled.

3.2 Electrical properties and underwater measurement of single transducer

The comparison of the admittance and phase angle vs. frequency curves of a single element tonpilz taken in air prior to polyurethane coating and taken in air and in water after polyurethane coating was given in Figure 5. The resonance peaks belong to the longitudinal extension, i.e., the piston mode of the transducer and it was measured as 33 kHz in air before coating with polyurethane. Resonance behavior was found to be slightly damped and shifted to higher frequencies after coating with polyurethane and resonance peaks were further damped due to the mass loading and hydrostatic pressure of the water when the measurements were taken underwater.

The performance of the underwater projector is evaluated by underwater admittance vs. frequency measurements of the transducer and then by calculating the transmitting voltage response (TVR) from this data using the approach reported by Kaya *et al.* [18]. Comparison of the experimentally measured graphs of admittance and TVR in terms of frequency with the results obtained from the ATILA FEA analysis were given in Figure 6. The results are generally comparable in form, although variations in the numerical values were unavoidable due to the limitations of the FEA method in modeling a device under pre-stress, where the full materials property matrix under mechanical stress is required for a more realistic analysis.

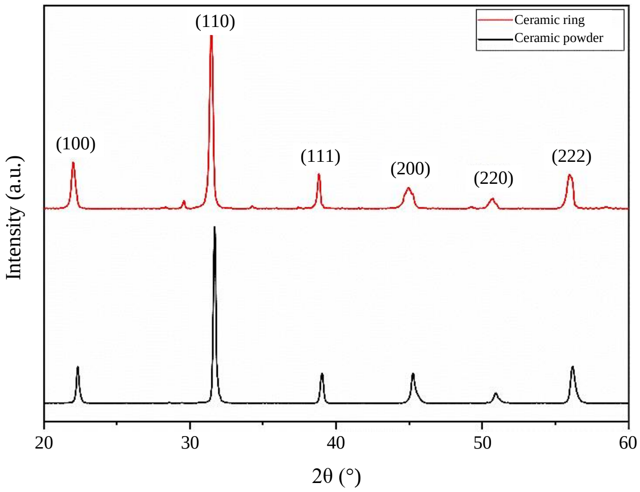

Figure 2. XRD analysis from ceramic powder and ring.

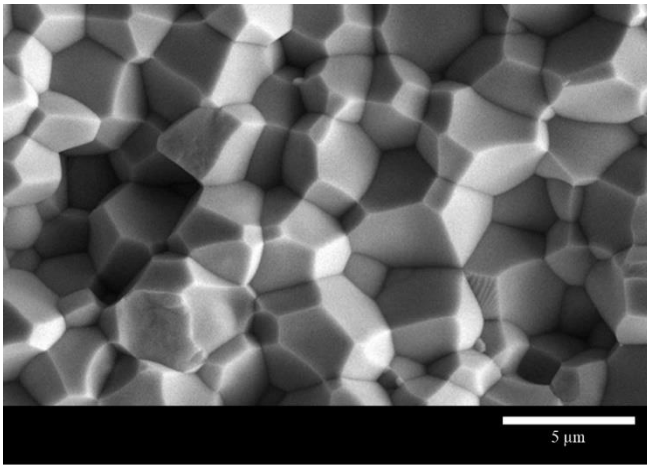

Figure 3. SEM micrograph taken from the fracture surface of the PMN-PT ceramic.

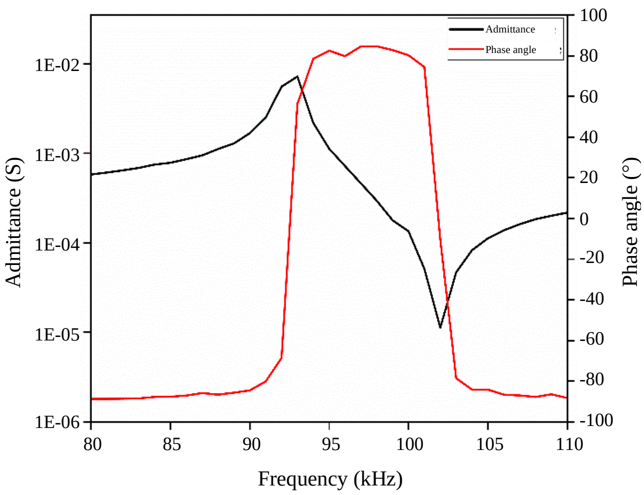

Figure 4. Admittance and phase angle graphs of PMN-PT ring.

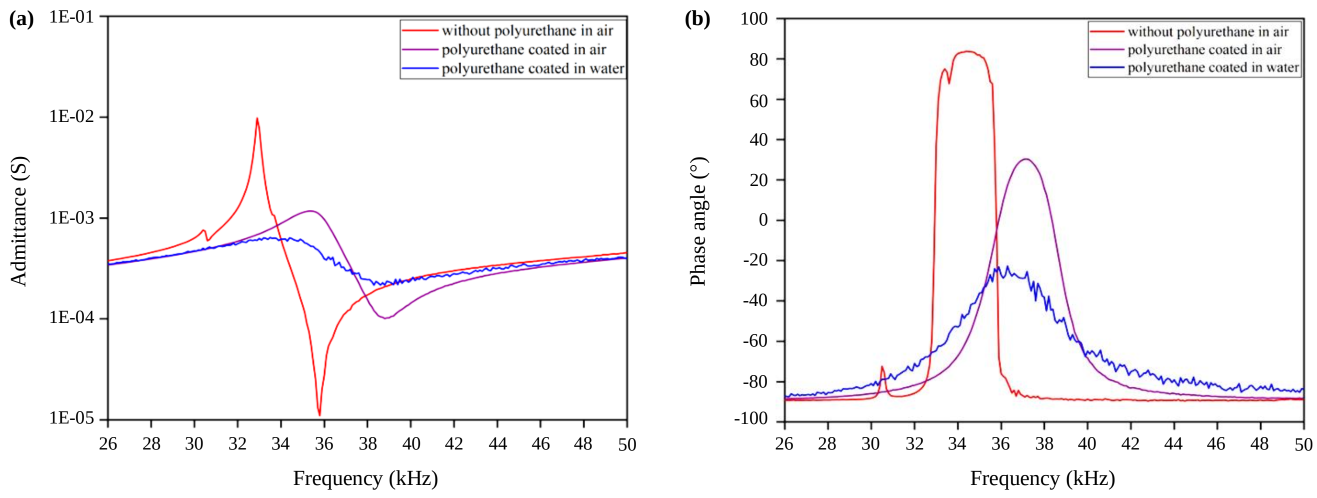

Figure 5. (a) Admittance and (b) phase angle graphs of a single element transducer in different conditions and environment.

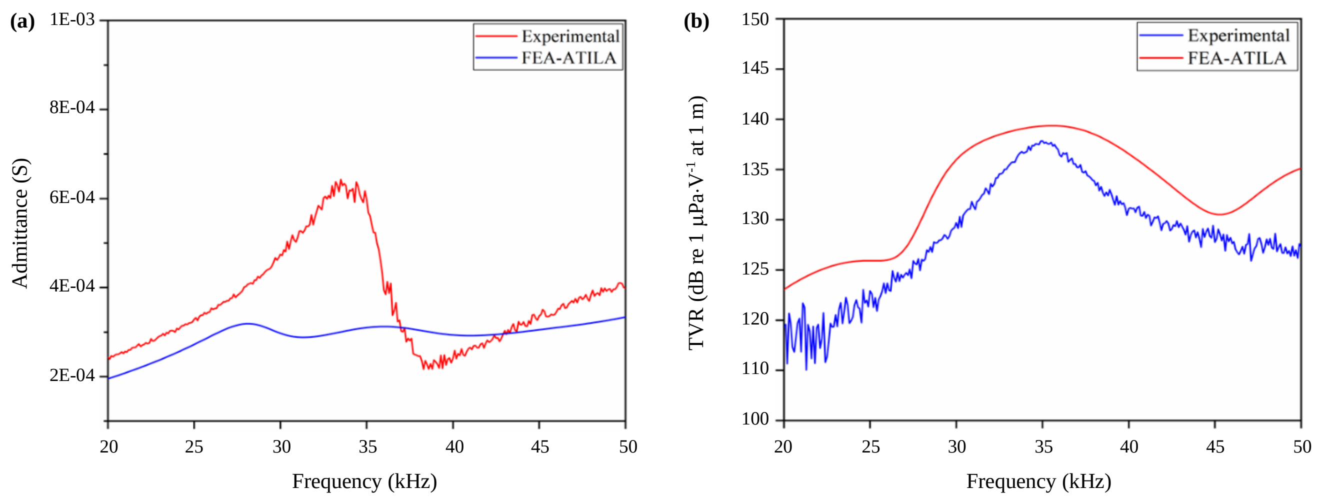

Figure 6. Comparison of finite elements analysis and experimental result of (a) admittance, and (b)TVR measurement in water.

3.3 Comparison of the underwater performance of the single element and 7-unit PMN-PT transducer array with that of PZT transducers

Underwater performance of the single element transducers and the seven-unit transducer arrays prepared from the PMN-PT ceramics were compared with that of the transducers and arrays constructed from the commercial PZT-4 piezoceramics. In the underwater measurements of the 7-unit transducer arrays, the units were electrically connected in either series or in parallel. The reason for connecting the transducers in parallel is to increase the TVR value, and the reason for the series connection is to increase the acoustic sensitivity or FFVS [19]. The results of these measurements were given in Figure 7. As seen in Figure 7(a), the single PMN-PT based transducer had a slightly higher (>1 dB) peak TVR value compared to the PZT based transducer. The TVR shows the active use, projector performance of the transducer and the array. Arranging seven units into an array and connecting them in parallel led to a drastic increase (>6 dB) of the peak TVR value, because when the transducers are connected in parallel, this gives a higher current and boosts up the TVR, in return. The PMN-PT and PZT based arrays had a comparable projector performance with peak values of TVR reaching 143 dB to 144 dB re 1 μPa·V^{-1} at 1 m.

On the other hand, the free field voltage sensitivity (FFVS) of the single element transducers and the 7-unit arrays where the units are connected either in parallel or in series were also calculated from the underwater admittance vs. frequency data and presented in Figure 7(b). The FFVS shows the passive use, hydrophone sensitivity of the transducer and the array. From Figure 7(b), although the sensitivity of the PMN-PT based single element lags behind PZT based transducer by about 2 dB, the serially connected array of PMN-PT transducers outperforms PZT based array for about 9 dB in most of the frequency range of interest. A higher sensitivity is obtained when the transducers are connected in series compared to the single transducer, because the series connection sums up the voltages. The FFVS of the serially connected array of PMN-PT based transducers achieved a rather very high sensitivity value of -163 dB re 1 V·μPa^{-1} at 1 m at its peak point. These results clearly indicate that connecting PMN-PT based transducers parallel achieved comparable performance with that of PZT based ones in projector performance, whereas the hydrophone performance of the PMN-PT based transducers clearly outperformed the commercial PZT based compositions in terms of sensitivity.

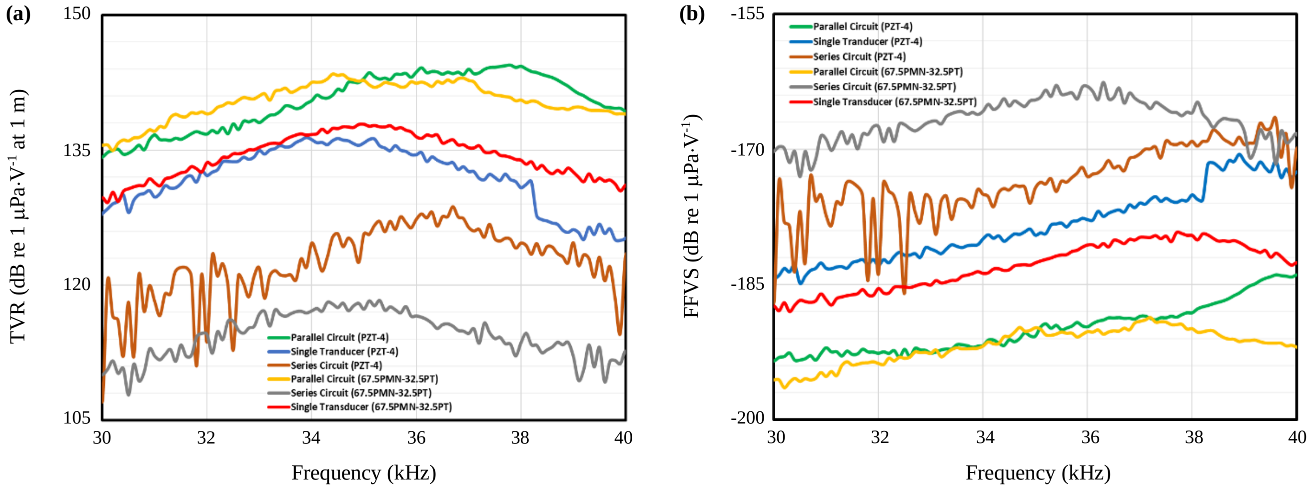

Figure 7. Comparison of the underwater performance of PMN-PT and commercial PZT based single element transducers and 7-unit transducer arrays where the units are electrically connected in series or in parallel. (a) TVR, and (b) FFVS results.

4. Conclusion

Tonpilz transducers based on 67.5PMN-32.5PT was fabricated and characterized for an enhanced underwater performance. As modelled by ATILA FEA program, the operational resonance frequency of the transducer was centered around ~35 kHz. The TVR of the transducer was calculated to be 137.62 dB at 35.1 kHz and the FFVS was calculated as -179 dB re 1 V·μPa^{-1} at 1 m from experimental data. The PMN-PT based transducer performed slightly better (>1 dB) as a projector compared to the PZT based counterpart. The 7-unit array connected in parallel displayed a >6 dB higher peak TVR value compared to the single element and the PMN-PT and PZT based arrays had a comparable projector performance with peak values of TVR reaching 143 dB to 144 dB re 1 μPa·V^{-1} at 1 m.

In the case of FFVS, the sensitivity of the PMN-PT based single element transducer was about 2 dB lower compared to the PZT based counterpart, however, the serially connected seven-unit array of PMN-PT transducers outperforms PZT based array by about 9 dB in most of the frequency range of interest. The FFVS of the serially connected array of PMN-PT based transducers was -163 dB re 1 V·μPa^{-1} at 1 m at its peak point which is 12 dB higher compared to the single element. In conclusion, a unique tonpilz transducer operating in a wide band has successfully been designed and produced from PMN-PT ceramics and arrays of this transducer was demonstrated to have a comparable projector performance and superior hydrophone performance compared to commercial PZT based counterpart.

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