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$Pb(Ni_{1/3}Sb_{2/3})O_3$-$PbZrTiO_3$ Ceramic Sensors for Underwater Transducer Application

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ABSTRACT

Cymbal is a class-V flextensional transducer that consists of thickness poled ceramic disc sandwiched between the two metal end caps which acts as a mechanical transformer. Cymbal transducers were fabricated using piezoceramic discs of compositions $Pb_{0.988}(Zr_{0.52}Ti_{0.48})_{0.976}Nb_{0.024}O_3$ (PZT type 5A) and $Pb_{0.98}La_{0.02}(NiSb)_{0.05}[(Zr_{0.52}\,Ti_{0.48})_{0.995}]_{0.95}O_3$ (PNS-PZT). Piezoelectric and hydrostatic constants for PNS-PZT composition were on higher side. End caps were made up of brass sheet having thickness 0.5 mm. Underwater testing of the polyurethane moulded cymbal hydrophones were carried out in acoustic tank and compared. The resonance frequency for both the hydrophones was 10.1 kHz. PNS-PZT hydrophone shows higher sensitivity (-183.2 dB re 1V/µPa) compared to PZT type 5A (-191.2 dB re 1V/µPa) at resonance frequency. Directivity pattern observed for PNS-PZT is omni-directional near resonance frequency.

Keywords: PNS-PZT piezoceramics, cymbal hydrophone, receiving sensitivity, directivity pattern

1. INTRODUCTION

Over large distances, acoustic energy is the single most effective source for communication in underwater systems like SONAR, passive sonobouy, homing torpedo, and towed arrays[1]. Hydrophone is a device used as a passive sensor to listen or pick up the underwater acoustic energy. Most of the hydrophones consist of piezoelectric devices or components of various geometry and design depending upon the requirement. In response to pressure generated due to acoustic energy, piezoelectric element in the hydrophone produces analog voltage which is further amplified and processed for detection and analysis[2]. Cymbal hydrophone is class-V flextensional transducer consists of thickness poled ceramic disc sandwiched between the cymbal end caps which amplifies the applied stress due to its geometry[3]. Receiving sensitivity of the hydrophones is highly influenced by the cymbal design and piezoceramic material used to fabricate the cymbal transducers[4]. The receiving sensitivity (M) of a piezoelectric disc is equal to product of piezoelectric voltage constant (g_{ij}) and thickness (t) of the piezoceramic disc[5]. Considering the hydrostatic mode the receiving sensitivity is given by Eqns (1) and (2)

$$M_0 = g_h * t = (g_{33} + g_{32} + g_{31}) * t \tag{1}$$

since

$g_{31}=g_{32}$

$$M_0 = (g_{33} + 2g_{31}) * t \tag{2}$$

where g_{33} and g_{31} are opposite in sign hence g_h values are much lesser for bulk piezoceramics. Due to cavities in a cymbal, metal caps transform and amplify a portion of the incident axial stress into radial stresses of opposite sign. Thus, the g_{33} and g_{31}, contributions of the piezoceramic are now added together instead of subtraction, in the effective g_h value of the hydrophone. The amplification factor is approximately equal to the radius of the cavity divided by the height of the cavity[6]. Considering the hydrostatic constants, hydrostatic voltage constant (g_h) is related to hydrostatic charge constant (d_h) and dielectric constant (K_3^T) and permittivity of free space(ε_0) according to Eqn (3)[7]

$$g_h = \frac{d_h}{\varepsilon_0 K_3^T} \tag{3}$$

This relationship indicates that the higher g_h values are possible for higher d_h and lower K_3^T. Since g_h and d_h are respectively proportional to g_{33} and d_{33} of the bulk piezoceramic material, the piezoceramic materials with higher g_{33} and d_{33} can be suitable for hydrophone applications[8]. It is reported that, due to lanthanum substitutions domain wall motion is improved leading to higher piezoelectric properties[9-11].

In the present work, PNS-PZT and PZT type 5A materials were synthesized. Cymbal hydrophones were fabricated. Comparative study of receiving sensitivity and electromechanical properties were carried. Directivity of the PNS-PZT hydrophone at various frequencies was also analysed.

2. EXPERIMENT

Ferroelectric compositions $Pb_{0.988}(Zr_{0.52}Ti_{0.48})_{0.976}Nb_{0.024}O_3$ (PZT type 5A)[12] and $Pb_{0.98}La_{0.02}(NiSb)_{0.05}[(Zr_{0.52}Ti_{0.48})_{0.995}]_{0.95}O_3$ were selected. Stoichiometric compositions were processed through mixed oxide route. The raw materials in the form of

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oxides of Lead (Waldies Ltd., Kolkata, 99.5 per cent), Zirconium (Loba Chemie, 99.37 per cent), Titanium (Travancore Titanium Products, 98.5 per cent), Niobium (Loba Chemie, 99.9 per cent), Nickel (Acros, 97 per cent), Antimony (Loba Chemie, 99 per cent), and Lanthanum (Indian Rare Earths Ltd., 99.99 per cent) were wet milled for 24 h. De-mineralized water was used as a solvent (Millipore, Elix-10) and zirconia balls as grinding media. Calcination was performed at 1060 °C and wet milled for 24 h to obtain the fine powder of particle size about 1.2 ± 0.2 µm. Poly Vinyl Alcohol was added 10 per cent by volume to the weight of the powder. Granulated powder was compacted in the form of round discs using double ended die punch machine (Make-GMT) maintaining green density about 4.8 g/cc. Sintering was carried out at 1270 °C for 90 min in the lead rich environment. Discs were lapped, electroded and poled in oil bath.

Capacitance (C), tan δ (measured at 1 kHz), resonance frequency (f_r), anti resonance frequency (f_a), Impedance (Z_m) were measured using Hioki Hi-tester (model 3532). Piezoelectric charge constant (d_{33}) was measured by Berlincourt d_{33} meter (CPDT-3330). Standard mathematical relations were used to compute dielectric constant (K_3^T),voltage constant (g_{33}), coupling factor (k_p) and mechanical quality factor (Q_m)[13,14]. Hydrostatic voltage constant (g_h) and hydrostatic charge constant (d_h) were measured by 'Piezo Meter' Make-Take Control (PM35), UK.

Low frequency cymbal transducers as per the schematic in Fig. 1 and physical dimensions in Table 1 were fabricated out of PNS-PZT and PZT type 5A discs and pair of brass metal caps, 3M adhesive was used and allowed to cure for 48 h at ambient temperature. Further, they were moulded in acoustically transparent poly-urethane and cured for 72 h as shown in Fig. 2.

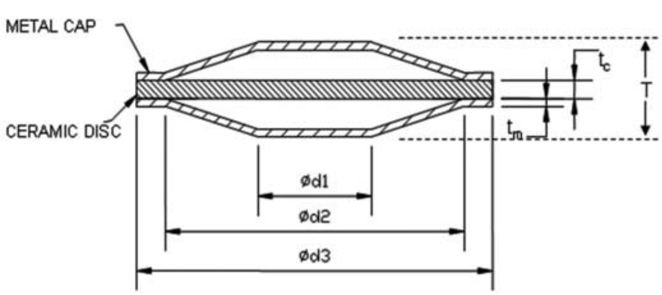

Figure 1. Schematic of the cymbal transducer.

Table 1. Physical dimensions of cymbal transducer

Dimension	mm
d_1	8.0
d_2	21.0
d_3	25.0
t_c	1.2
t_m	0.5
T	6.0

Cymbal hydrophones fabricated out of PNS-PZT and PZT-5A were tested in cubical acoustic tank, 8 m x 8 m x 8

Figure 2. Moulded cymbal hydrophone.

m at NSTL, Visakhapatnam. Standard hydrophone calibration was carried out using calibration setup make– Brüel and Kjær model-9718 and the data obtained was used to measure the receiving sensitivity of PNS-PZT and PZT type 5A cymbal hydrophones. Standard hydrophone and test hydrophone were mounted at 1 m depth and 1 m apart. Receiving sensitivity was measured from 2 kHz to 40 kHz. The beam patterns were obtained at 10 kHz, 20 kHz, 30 kHz and 40 kHz.

3. RESULTS AND DISCUSSIONS

Electromechanical and hydrostatic properties of the discs are listed at Table 2. Charge constant (d_{33}), voltage constant (g_{33}) and figure of merit ($d_{33*}g_{33}$) for PNS-PZT are superior over PZT type 5A. This indicates that PNS-PZT will have better charge generating ability having higher potential. Higher hydrostatic charge constant (d_h), hydrostatic voltage (g_h) and hydrostatic figure of merit ($d_{h*}g_h$) for PNS-PZT indicates the suitability of the material for hydrophone applications. Higher Q_m and lower tan δ for the same indicates the higher power handling capacity with minimum dielectric losses. Higher k_p for PNS-PZT indicate the comparatively higher energy conversion capability.

Receiving response, for both the hydrophones, is shown in Fig 3. Resonance frequency was found to be same (10.1 kHz) for both the hydrophones. At resonance frequency, PNS-PZT hydrophone shows sensitivity -183.2 dB re 1V/µPa which

Table 2. Dielectric, piezoelectric and hydrostatic properties of piezoceramic discs

Property of disc samples	PZT type 5A	PNS-PZT
Charge constant (d_{33}) X 10^{-12} C/N	368	450
Voltage constant (g_{33}) X 10^{-3} Vm/N	24.02	36.8
Figure of merit ($d_{33*}g_{33}$) X 10^{-12} CVm/N^2	8.84	16.57
Dielectric constant (K^T_3)	1730	1380
Dielectric loss factor (tan δ)	0.020	0.013
Hydrostatic charge constant (d_h) X 10^{-12} C/N	46.1	77.0
Hydrostatic voltage constant (g_h) Vm/N	2.8	5.9
Hydrostatic figure of merit ($d_{h*}g_h$) X 10^{-12} CVm/N^2	129.08	454.3
Mechanical quality factor (Q_m)	86	130
Coupling coefficient (k_p)	0.56	0.64

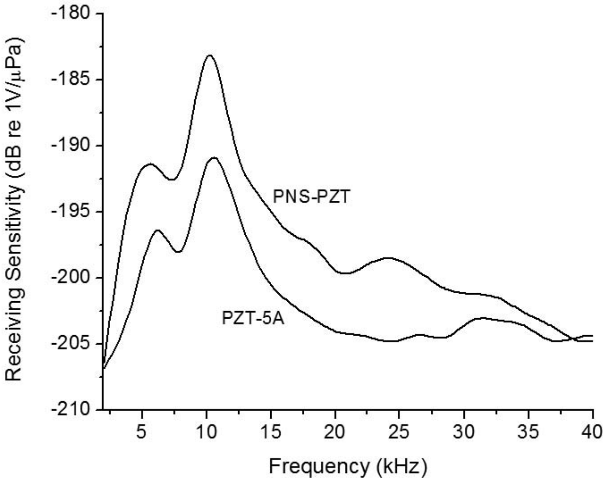

Figure 3. Receiving sensitivity.

is higher by 8 dB compared to PZT type 5A (-191.2 dB re 1V/μPa). It is also higher over the frequency range 2 kHz to 38 kHz. This is attributed to higher $d_{h,}$ g_h and $d_{h*}g_h$ for PNS-PZT.

Directivity patterns for PNS-PZT composition are shown in Fig 4. Very close to resonance frequency, i.e. at 10 kHz, the pattern is perfectly omni-directional. Beyond resonance frequency, patterns are distorted. Main lobes are along the flat face of the hydrophone.

4. CONCLUSIONS

PZT Type 5A and PNS-PZT piezoceramic compositions were synthesized by mixed oxide route. Discs of dia 25 mm x 1.2 mm thick were fabricated from these compositions and characterized for dielectric, piezoelectric and hydrostatic properties. Cymbal hydrophones were fabricated. Hydrophones were tested for underwater acoustic performance. The resonance frequency for both the hydrophones was 10.1 kHz. At resonance frequency, PNS-PZT hydrophone shows higher sensitivity (-183.2 dB re 1V/μPa) compared to PZT 5A (-191.2 dB re 1V/μPa) attributed to the higher piezoelectric (d_{33}, g_{33}, Qm, k_p, FoM) and higher hydrostatic properties (d_h, g_h, FoM). Directivity of PNS-PZT hydrophone was found to be perfect omni-directional at resonance frequency.

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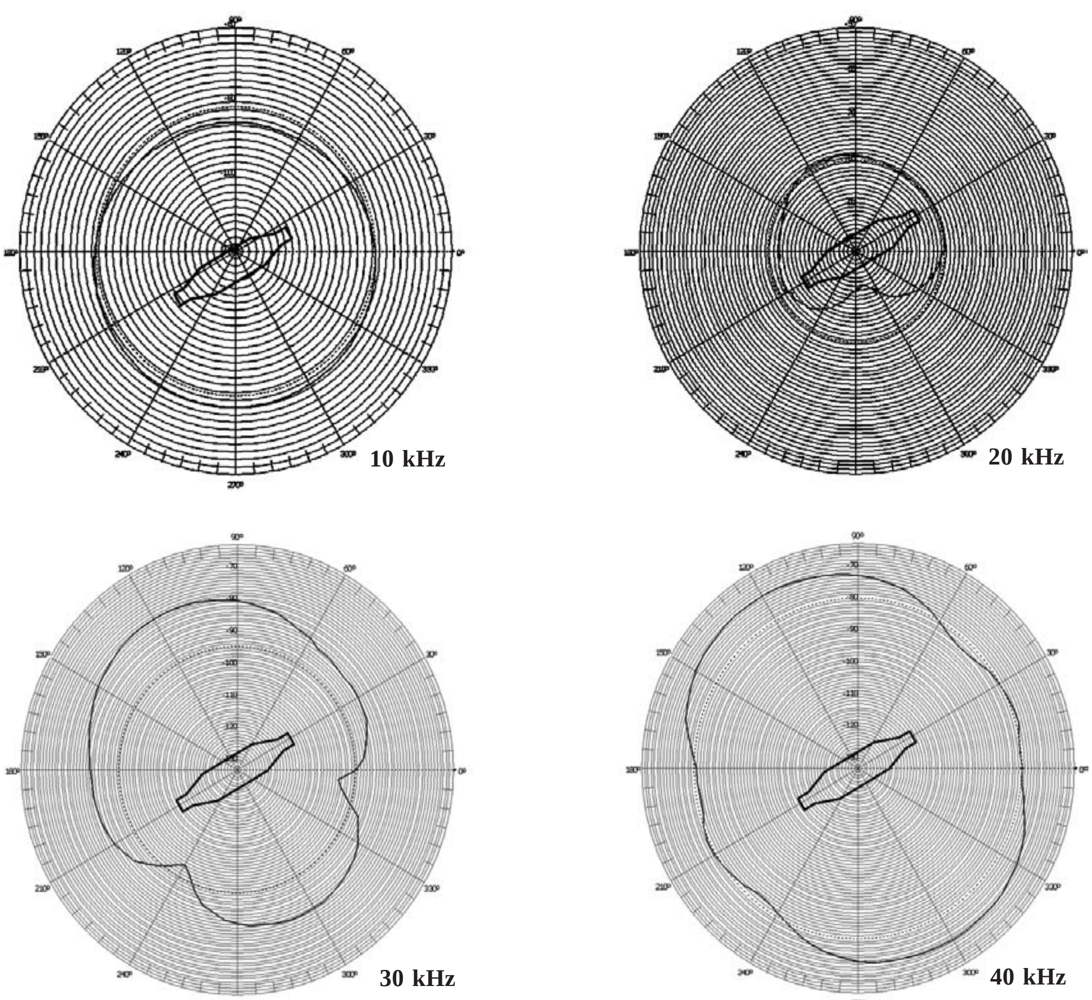

Figure 4. Receiving directivity of PNS-PZT hydrophone.

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