Development of wide band underwater acoustic transducers

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This paper addresses the design and development of wide-band Tonpilz transducers and class V flextensional type hydrophones for oceanographic applications. A case study to lower resonant frequency from 6 to 4.5 kHz with a usable frequency range of 4–10 kHz without altering the dimension has been carried out. The transmitting response (151 dB at 5 kHz) and the receiving sensitivity (–163 dB re V/μPa@1 m) were retained. The development of a wideband (2–18 kHz) transducer for sub-bottom profiling and buried object detection has been presented. A hydrophone array (2–24 kHz) of receiving sensitivity of –155 dB re V/μPa@1 m was also developed.

Keywords: Hydrophones, piezoelectric, transceivers, wide-band transducers.

Introduction

SOUND Navigation and Ranging (SONAR) is an important tool in the investigation of underwater detection, navigation, communication as well as bathymetry. It has applications for defence as well as civilian use. Acoustic waves are most effective in underwater exploration compared to radio waves due to low attenuation. The demand of low-frequency light-weight and wide-band transducer is a challenge to a designer.

Transducers, in general, refer to projectors as well as hydrophones. An underwater transducer is an indispensible electro-acoustic device used in underwater communication, ocean exploration, collection of scientific data from ocean bottom stations, acoustic imaging in offshore oil industry. The challenge was to realize miniaturized and efficient low-frequency transducers with reasonable bandwidth. Larger the bandwidth, better it suits applications like long-range underwater communication and acoustic imaging without hampering resolution.

In the last few decades, intensive research works have realized design of multi-resonant transducers. Attempts have also been successful in utilizing piezoelectric as well as magnetostrictive transducers as a hybrid design for the realization of transducers in the frequency ranges of 2–9 kHz and 12–35 kHz. The most frequently used transducer designs are the conventional Tonpilz type and the flextensional transducer designs. Efforts have been focused on the design of low frequency, wide-band transducer with giant (more striction induced) magnetostrictive materials as well as conventional piezoelectric materials.

Wide-band in transducer design has been achieved by adopting different methodologies. Qingshan and Leif[1] suggested that by using the fundamental longitudinal mode and the flapping mode together, broadband can be achieved with a transmitting sensitivity response of ± 2 dB from 28.5 kHz to 41.8 kHz. Rajapan[2] and Srinivasan and Rajapan[3] designed a wide-band transducer in the frequency range of 2–10 kHz using multi-mode optimization method for achieving wideband assuming lumped parameter condition where simulations were not carried out. Ebenezer and Subash Chandra Bose[4] introduced a third mass between head and tail masses with two piezo ceramic stacks. This approach was first demonstrated for other frequencies by Butler[5] for achieving a wideband triply resonant transducer. Passive components were added to Tonpilz type to achieve a triply resonant transducer, and a wide bandwidth in the frequency range of 13–37 kHz. Hyunki and Yongrae[6] designed using a void head mass. The reduction in weight provided a low mechanical quality factor, and thus a wide bandwidth was achieved.

In the present paper, the modelling and performance of a light-weight, low-frequency bandwidth (2–18 kHz) transmitter for marine applications have been discussed. Following a similar procedure, Tonpilz transducers frequency ranges of 2–12 kHz and 33–43 kHz have been developed for which some results are presented. Hydrophone array of flex tensional type class V transducer has been discussed in detail.

A light weight low frequency bandwidth (2–18 kHz) transmitter

Geometry and construction of the transducer

The transducer comprises a head-mass made up of aluminium, a stainless steel stress bolt, a tail mass made up of brass material and a stack of piezo crystals. The head mass is circular in shape. Brass shims were used to provide electrical connectivity of the stack assembly. Conductive glue was used to bond the ceramic crystals to the shim for wiring. The stack assembly was connected in

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parallel using teflon wires. The stack assembly is sandwiched between the head mass and tail mass. The entire assembly is kept under pre-stress with the help of stainless steel bolt and nut instead of costly beryllium copper used in the conventional design. Optimum torque was applied for the stress rod. To induce longitudinal mechanical vibrations, the piezoelectric stack was excited with alternating voltage closer to its resonant frequency. The vibrations are transferred to the water medium and the coupling material of polyurethane material has been used for encapsulation. Encapsulation ensures electrical isolation between the transducer and water as well.

Modal analysis

This analysis was carried out to determine the modes of vibration. An axi-symmetry Finite Element Model (FEM) in-air was created using ATILA software. Table 1 presents the resonant, anti-resonant frequencies and the coupling coefficient values for the first three modes. Figure 1 displays the structured mesh model. The resonance frequencies of the first, second and third modes are 4.0, 11.8 and 15.9 kHz.

The first mode of vibration is the fundamental longitudinal piston vibration. In the present model, the second mode of vibration is the longitudinal displacement of bolt and the third mode of vibration involves flapping of the head. Flapping mode of the head mass is usually avoided in Tonpilz-type transducers as it reduces the average velocity of the head mass[7]. However in the present design, in phase motion occurs at the edges and the centre

Table 1. Vibration frequencies and its coupling coefficient for the first three modes

Mode	Resonant frequency (kHz)	Anti-resonant frequency (kHz)	Effective coupling coefficient efficiency (%)
First	4.0	4.8	54.9
Second	11.8	11.8	4.8
Third	15.9	16.2	15.5

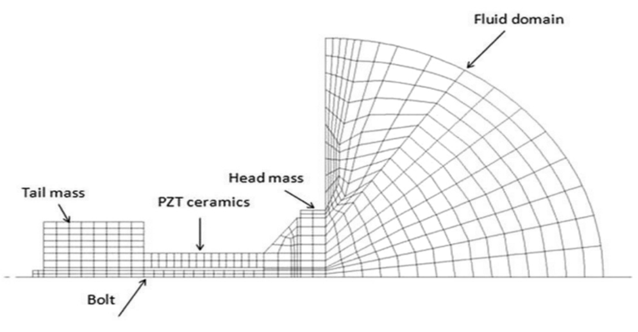

Figure 1. Structured mesh of the acoustic Tonpilz Transmitter using ATILA.

of the head mass, and the modes are optimized. In-phase motion occurs, because of the appropriate selection of cone angle of head mass[1]. All the three modes were verified using harmonic analysis.

The coupling coefficient is defined as a measure of efficiency in conversion and it indicates the amount of electrical energy converted into mechanical energy and vice versa which is given by[3,8]

$$k^2 = 1 - \left(\frac{f_r}{f_a}\right)^2, \tag{1}$$

where k is the effective coupling coefficient, f_r the resonant frequency and f_a is the anti-resonant frequency. A coupling coefficient for first mode has the highest efficiency of 54.9% which is the fundamental resonance (4 kHz).

Harmonic analysis

Harmonic analysis was carried out to determine the electrical impedance and the transmitting response of the transducer. For this purpose, initially a 2D axi-symmetry model geometry was created. Appropriate material properties were assigned and boundary conditions were imposed upon the model with electrical excitation of 1 V to the stack for characterizing electrical impedance and transmitting sensitivity. The water radius was modelled for half of the wavelength of resonant frequency. The circumference of the radius of water was modelled with damping elements[9]. Brass shims were used as electrodes for electrical connectivity of the piezo crystals and glue was not included in the model as their wavelengths are negligible compared to the working frequency range. The resonance values are in agreement with the three modes of vibration of modal analysis values as shown in Table 1.

The modelled transducer was fabricated, assembled and tested for its performance. Figure 2 *a* provides the comparison between the simulated and the measured response. From the figure, it is observed that resonance frequency occurs at 3.4 kHz for simulation, whereas practically measured resonance is at 2.4 kHz. This is because, when carrying out modelling, brass shims glue and encapsulation were not modelled and was assumed to be negligible when compared to the wavelength.

An Indian Patent was awarded for the wide band transmitter using multimode optimization[10].

Broad band transceiver in the frequency range of 4–12 kHz

To increase the range of SONAR, lowering of the frequency becomes essential which however, increases the transducer dimensions. Lowering the frequency and

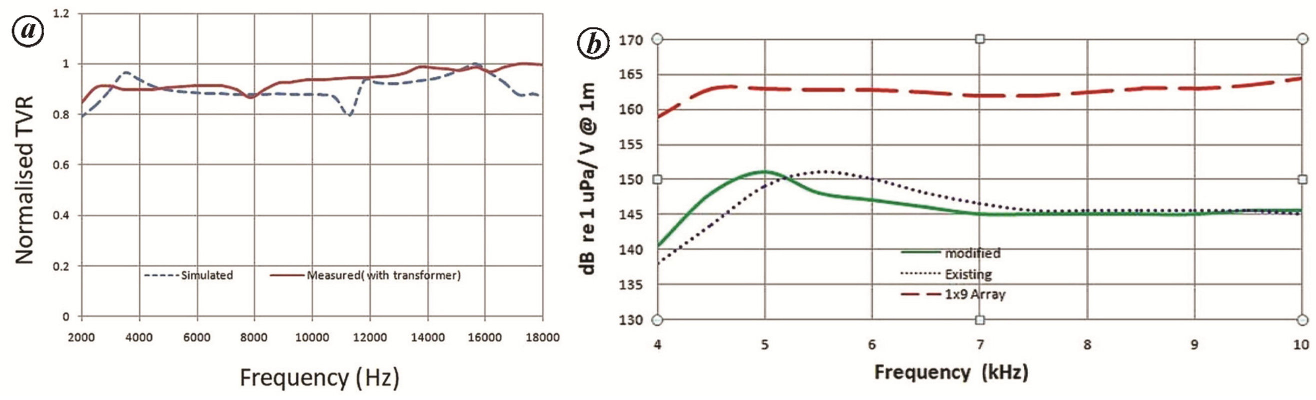

Figure 2. ***a***, Comparison of transmitter characteristics for simulated and measured transducer (2–18 kHz). ***b***, Transmitting frequency response of the broad band transceiver.

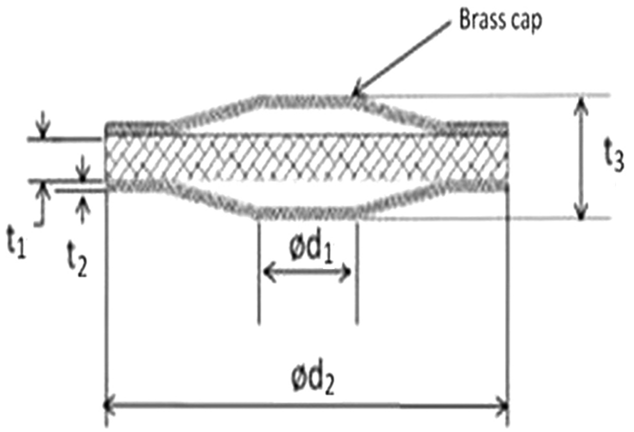

Figure 3. Schematic of the cymbal transducer.

Table 2. Source level for various frequencies

Frequency (kHz)	Source level (dB)
4.5	209
5	209
6	211
7.5	213

retaining the dimensions, along with improved performance was a major challenge to a designer. This design has been awarded with a patent[11]. This has also led to advantage of retaining the hull dimensions same and platform unaltered which in turn saves cost. Hence the existing SONAR transducer was modified to lower the frequency without any variation in the existing dimensions of the transducer. The transducer is basically an electromechanical device. The mechanical system which is analogous to electrical circuit is a tank circuit which comprises resistance 'R', inductance 'L', and capacitance 'C' and oscillates at a frequency 'f' which is given by

$$f = 1/(2\pi\sqrt{LC}). \tag{2}$$

Lowering of the frequency is achieved by doubling the piezoceramic stack length. Since capacitance 'C' is doubled, frequency is reduced by square root two times. To accommodate the increase of length in piezo stack, the tail mass dimension needs reduction. To retain weight with lesser dimension, higher density material (copper tungsten) was chosen as the tail mass material.

An existing hull mounted SONAR Tonpilz type transducer which had a frequency response is shown as dotted line in Figure 2*b*. The modified response which was practically measured is shown in solid line in Figure 2*b*. The dashed line shows the performance of the 1 × 9 linear arrays of transducers which is the measured value. Resonant frequency was lowered from 6 to 4.5 kHz and the transmitting response of modified transducer at 5 kHz was 151 dB re 1 μPa/V@1 m. 1 × 9 Array transmitting response has an average gain of 17 dB in the frequency range of 4–10 kHz. Table 2 shows the source level values for various frequencies. The transducer had a receiving sensitivity of –163 dB re V/μPa @ 1 m.

A wideband transducer

The development of transducer in the frequency range of 33–43 kHz is of Tonpilz type. This transducer was developed for echo-sounding application[12]. The echo sounder is used for bathymetry applications.

Development of hydrophones

Miniaturized flex tensional class V hydrophones were designed using finite element software ATILA. Cymbal element geometry consists of a piezoceramic sandwiched between cymbal end caps which performs like a mechanical transformer[13,14]. The advantage of this design is that tailor-made hydrophones of various frequency ranges can be realized by varying the apex dimensions ø d_1, ceramic thickness 't_1' with diameter ø d_2 and brass cap thickness 't_2' as shown in Figure 3. The total thickness of the

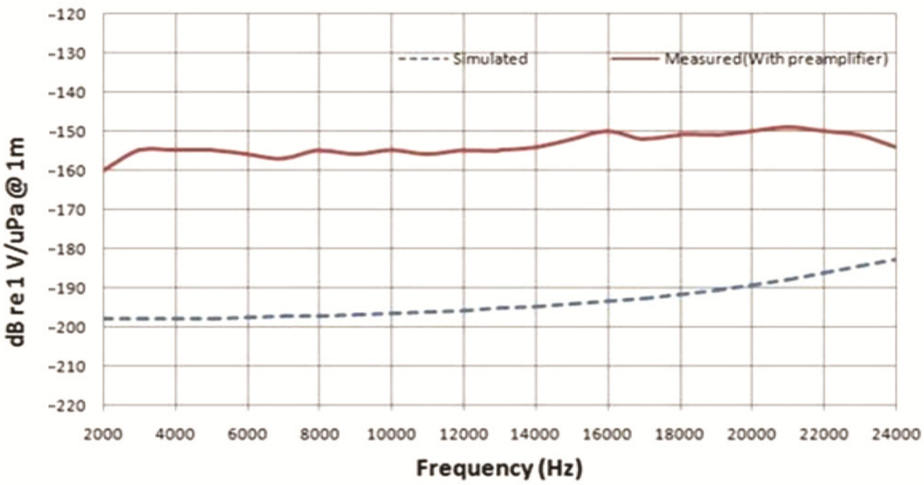

Figure 4. Typical receiving sensitivity response of hydrophone of simulated and measured response.

element is t_3. The resonant frequency depends upon the end cap dimensions, cavity depth and the dimension, and properties of the ceramic disc[15]. Moreover, since it is a miniaturized type of transducer, fabrication and assembly of cymbal transducers have posed major challenges. A transmitter was developed using Cymbal array with 5×10 elements[16] which delivered a power of 750–1000 W.

In the present design, end caps used are made up of brass material. Performance of cymbal element varies depending upon the selection of end cap material. Simulated receiving sensitivity is shown as a dotted line in Figure 4. A receiving sensitivity of –198 dB re V/μPa was observed at 2 kHz. A 3 dB variation was observed in the three octave frequency range.

The model was realized by efficient method of fabrication. Cymbal hydrophone was integrated with preamplifier (60 dB gain) and was placed in an acoustic transparent tube filled with oil. The hydrophones were characterized[17] in Acoustic Test facility. The measured receiving sensitivity values are shown as a solid line in Figure 4. A 10 dB variation in the frequency range of 2–24 kHz was observed. The potting material is polyurethane and oil filled tube provides damping and makes the receiving response flatter. A 20 dB variation is seen from 2 to 24 kHz for the modelled cymbal element because vibration of free elements was considered without any encapsulation.

A 32 element planar array was formed and the developed hydrophone array was used for buried object detection SONAR which detected buried objects hidden in the seabed. Miniaturized hydrophone arrays with high sensitivity of the order of –155 dB re 1 V/μPa@ 1 m were realized. These transmitters and hydrophones have been utilized in the realization of buried object detection sonar for shallow water applications. A prototype multichannel sub-bottom profiler for shallow water applications was the spinoff of the first phase of the acoustic imaging programme. Next challenge is to collaborate with an industry for commercial use. Efforts have been initialized for a Transfer of Technology to an industry through National Research Development Corporation, New Delhi. The future programme includes the development of 2D/3D imaging sonar which has applications in turbulent and muddy water where normal optical imaging systems fail.

To summarize, prototype low-frequency, light-weight, wide-band projectors in the frequency region 4–10 kHz, 2–18 kHz, 33–43 kHz and a hydrophone array working in the frequency range 2–24 kHz have been successfully developed. All the indigenized transducers developed were tested in the field for its performance.

Conclusion

Four different frequency ranges of transmitters, transceivers were designed and were tested. The challenges in achieving wideband Tonpilz type transducer in the frequency range of 2–18 kHz were met with modal, harmonic analysis and with practical results. The results are in agreement with the modelled results. Wideband was achieved by careful selection of head mass geometry and the bolt diameter. The developed transducer was used as an acoustic transmitter in buried object detection SONAR and for sub-bottom profiling applications.

A broad-band transceiver of Tonpilz type was redesigned to lower the resonant frequency without modification of the external dimensions of the transducer which was the real challenge. Resonant frequency was lowered by material selection for tail mass and by increasing the stack length but maintaining the external dimensions. A source level of 209–213 dB was achieved for a frequency range of 4.5–7.5 kHz. This has led to a significant achievement of using an existing platform for the usage in a wide frequency range with improved performance of the SONAR system.

Echo sounder transducer has a working frequency range of 33–43 kHz with a power handling capability of 1 kW. An array of 32 elements produced a directivity of 20 degree beam width around 33 kHz. Wide-bandwidth was achieved using design configuration and mounting mechanism.

A miniaturized Cymbal transducer of class V was demonstrated by modelling and realizing for real time application. The developed hydrophone was used for buried object detection. Results were encouraging as it worked in field trials in Royapuram harbour off coast Chennai. A flat response with a variation of 10 dB in the frequency range of 2–24 kHz was achieved which was the challenge in designing a miniaturized version.

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