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Design of a Low Frequency, Wideband Tonpilz Transducer for Sonar Applications

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Abstract:

Tonpilz transducers are the most widely used transducers for sonar applications due to their good acoustic performance, simple construction, ease of array formation and long service life. However, the large size and mass required for low-frequency transducers limit their typical use to frequencies above 2 kHz. Another limitation is its low bandwidth. In this paper, an attempt is made to design a transducer with a resonance frequency of 1 kHz and a source level of 190 dB or more with a useful bandwidth of more than two octaves. The finite element method is used to model the transducer and to study the effect of important parameters on Transmitting Voltage Response (TVR). Based on the study an optimum design is proposed. The studies reveal that the dimensions of the piezoceramic stack and head mass significantly affect TVR.

Keywords:

Tonpilz transducer, sonar, underwater transducer, low-frequency, finite element model

1 Introduction

Tonpilz transducers are the most widely used transducer for the sonar applications [1]. They are also used for underwater communications, echo sounders, oceanographic studies, and underwater calibrations. Tonpilz transducers are preferred because of their good transmitting and receiving characteristics, simple construction, reliability, and long life [2]. When the transducer is in the active mode, it generates acoustic pressure in the medium by the electrical excitation of the piezo ceramic stack and in the receiving mode it converts the acoustic pressure received to voltage. The transducer comprises of a piezoceramic stack assembled between two metallic masses called head mass and tail mass using a central bolt and it is assembled inside a housing to make it

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water-tight. Fig. 1 illustrates the schematic of a typical Tonpilz transducer. Due to their inherent weakness in tension, piezoceramic stacks are always subjected to a compressive bias through pre-stressing. This ensures that the transducer never experiences tensile loads during operation. Even though the transducers are simple in construction, as the frequency comes down, its mass and size increase drastically so the general use is restricted to above 2 kHz [3]. Another drawback of the transducer is its low bandwidth. However, low-frequencies and wide bandwidths are required for long-range detection and communication [4, 5].

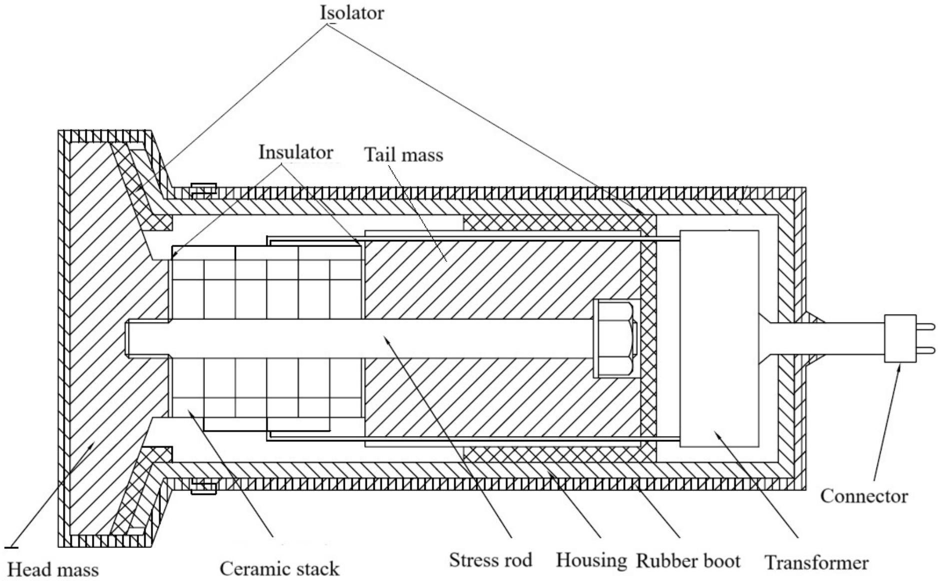

Fig. 1 Schematic of a Tonpilz transducer.

There are different techniques that can be adopted to improve the bandwidth like matching layers [6, 7], head mass with cavity [8] or double head mass concept [9, 10]. Matching layer concept utilises multiple layers of quarter wavelength thick impedance matching materials in front of the radiating head mass. This cannot be adopted for low-frequency because of bulkiness of layers. In the case of head mass with a cavity, the internal space of the head mass is hollowed out to significantly reduce weight, resulting in a low mechanical quality factor and a wide bandwidth. The double-head mass Tonpilz transducer design incorporates a central mass positioned between the tail and head masses. A compliant material or an additional ceramic stack is assembled between the middle and head masses, resulting in dual resonance frequencies and enhanced bandwidth. Thompson et al. and Butler [11, 12] also reported doubly resonant wideband transducers with the addition of inactive materials in the driver portion of a Tonpilz transducer. Broad bandwidth is also achieved by using non-uniform piezo ceramic drive sections [13].

Transducer head flexure is generally considered detrimental to transducer performance [14] but proper design of the head mass can convert the head flexure advantageously [15]. The conventional method of Tonpilz transducer design consider it as a spring mass system [1] and leads to a heavy transducer. Size of low-frequency transducers are much lower than the wavelengths to make them compact to use in transducer arrays [16]. Polat et al. studied the Tonpilz transducer design using simple lumped parameter method, equivalent circuit method, and finite element method. They found that the finite element modelling studies results matched well with the experimental results of transducers manufactured and tested based on the studies [17]. In the present study COMSOL Multiphysics [18], a commercial finite element software is used to model a compact, low-frequency broadband Tonpilz transducer.

2 Objective of the Study

The objective of this study is to design a multi-resonant Tonpilz transducer that incorporates both length mode and flexural resonance frequencies to achieve low-frequency operation and a wide bandwidth. The transducer design is intended with a length mode resonance at 1 kHz and head flexure around 4 kHz, aiming for a useful bandwidth exceeding two octaves and a Source Level (*SL*) of 190 dB or higher. Source level refers to the intensity of a radiated wave in a specific direction, measured in decibels. It is defined relative to a plane wave with an RMS pressure of 1 µPa and is referenced at 1 meter from the transducer's acoustic centre along its maximum response axis [19]. The key parameters of the transducer, such as the dimensions of the piezoceramic ring, head mass, and tail mass, are analysed to determine their influence on the Transmitting Voltage Response (*TVR*). The Transmitting Voltage Response of a transducer represents the ratio of the acoustic pressure amplitude (P), projected back from the far field to 1 meter from the source, to the amplitude of the applied driving voltage (V). It is expressed in decibels relative to a reference response (S_{ref}) of 1 µPa/V as, $TVR = 20\log[(P/V)/S_{\mathrm{ref}}]$ dB re 1 µPa/V at 1 m [19].

3 Transducer Details and Methodology

The transducer consists of a lightweight head mass made of aluminium alloy and a tail mass made of stainless steel. The piezoceramic stack is made of axially polarised rings of PZT4. The stack is assembled with brass electrodes between the rings for electrical connections and FRP sheets at the ends to electrically isolate it from the end masses. The rings are assembled in such a way that alternate rings are poled along opposite directions to get the maximum in-phase strain from the piezoceramic stack. The head mass is rubber moulded to match the impedance of seawater. The total assembly is housed inside a rubber moulded metallic housing to prevent water ingress. The transducer assembly is structurally decoupled from the metallic housing using rubber isolators as shown in Fig. 1. A transformer is used to match the impedance of the transducer and driving power amplifier. Based on conventional design practices, 1 kHz transducer head mass dimension is 750 mm (i.e. 0.5 λ where λ is the wavelength of sound) and tail mass needs to be 2 to 4 times the weight of head mass [1]. Transducer dimensions based on conventional design practices will lead to large size and mass. So, to achieve a compact design, low-frequency transducers are made much smaller than the wavelength [16].

To make a compact light weight transducer, the head mass outer diameter was initially fixed as 400 mm i.e. 0.266 λ. To get a bandwidth of two octaves, utilising head flexural frequency is fixed around 4 kHz. The flexural frequency of a circular head mass can be calculated using the relation [1]

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$$f_{\text{flex}} = \frac{1.65ct_{\text{h}}}{a^2\sqrt{1-\upsilon^2}} \tag{1}$$

where c is the velocity of sound in the head mass material, t_{h} is the head mass thickness, a is the diameter of head mass and υ is the poissons ratio of head mass material. For an aluminium head mass of 55 mm thickness and 400 mm diameter, flexural frequency is 3.9 kHz. The dimensions of the transducer can be decided based on an iterative modelling study to get the required *TVR* and bandwidth. By manipulating the size of different components, an optimum transducer design can be arrived at.

4 Transducer Model

Due to the axisymmetric nature of the transducer, a 2D axisymmetric model was employed for simulation using the COMSOL Multiphysics software package. As shown in Fig. 2, the axisymmetric model allows the transducer to be accurately represented by modelling only one-half of its structure in 2D. This approach significantly reduces computational complexity while maintaining the accuracy of the simulation results. Symmetric/infinite sound hard boundary conditions are applied in the symmetry plane at $z = z_0$. In the COMSOL model, the piezoelectric material is polarized along the positive Z-axis direction. For the negative Z polarization, a new coordinate system is defined. Due to the decoupling of the housing from the transducer's head and tail masses, the housing was excluded from the simulation model.

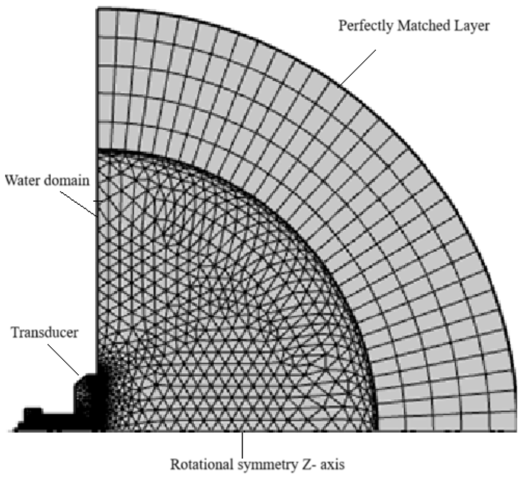

Fig. 2 2D axisymmetric model of the Tonpilz transducer

In COMSOL Multi physics, the Tonpilz transducer is modelled by combining solid mechanics, electrostatics, and pressure acoustics physics interfaces to simulate the mechanical deformation, piezoelectric effect, and acoustic radiation. The pressure acoustics interface in COMSOL models sound waves in water, while the solid mechanics interface handles the behaviour of structural components, and the electrostatics interface simulates the piezoelectric material's response. Piezoceramic rings in the stack are excited with an electrical potential of 1 V_{rms} on the positive surfaces and the other surfaces are grounded. Fixed boundary conditions are applied on tail mass outer diameter. The transducer, along with the surrounding water and a perfectly matched layer (PML) outside the water layer, simulates a non-reflecting infinite water domain, as illustrated in Fig. 2. PMLs allows simulations to be performed within a finite computational space without artificial reflections arising from the boundaries. The detailed mathematical model and governing equations for the simulation are given in the COMSOL Multiphysics, reference manual [18].

The maximum element size of the mesh is fixed as 1/5th of the smallest wavelength, corresponding to the highest frequency of interest (i.e. 6 kHz), to resolve the pressure waves within the inner water domain. Five layers of structured mesh are created in the PML using the Swept feature of COMSOL. A boundary layer mesh is generated within the inner water domain, adjacent to the external field boundaries. This boundary layer facilitates a smooth transition between the inner triangular mesh and the outer quadrilateral mesh elements, ensuring an accurate calculation of the exterior field. The material properties available in COMSOL's materials library used for the transducer model are shown in Tab. 1. The model determines the radiated pressure field, sound pressure level, and the transmitting voltage response (*TVR*) of the transducer. The modelling studies were conducted in the frequency domain in the range of 500 Hz to 6 kHz with a step size of 25 Hz. The dimensions arrived for a 1 kHz transducer based on the modelling studies are given in Tab. 2. Using this as the base model, the effect of important parameters on Transmitting Voltage Response (*TVR*) was studied by varying one parameter at a time.

Tab. 1 Material properties

Material	Young's modulus [GPa]	Density [kg/m^3]	Poisson's ratio [–]
Steel, AISI 4340	205	7 850	0.28
Aluminium, 3003H18	70	2 700	0.33
Beryllium Copper, C17200	128	8 250	0.30

Tab. 2 Dimensional details of the base transducer

Parameter	Dimension [mm]
Outer diameter of head mass	400
Thickness of head mass	75
Tail mass outer diameter	150
Tail mass length	150
Bolt diameter	20
Piezoceramic ring size	100(OD) × 50(ID) × 6(T)
Number of PZTs in the stack	22

5 Results and Discussions

The conductance plot of the transducer base model is shown in Fig. 3 and it shows that the transducer has its length mode resonance at 1 kHz and the flexural mode resonance at 3.7 kHz. The *TVR* of the base model is shown in Fig. 4 and it shows that the transducer has *TVR* of 139 dB and 140 dB at its first and second resonances. *TVR* of the transducer in the band of 800 Hz to 5.5 kHz is 131 dB or more. The peak *TVR* is expected to come down by a few dB's at both the resonances since material losses are not included in the model [10]. So, the transducer has a useful bandwidth of more than two octaves.

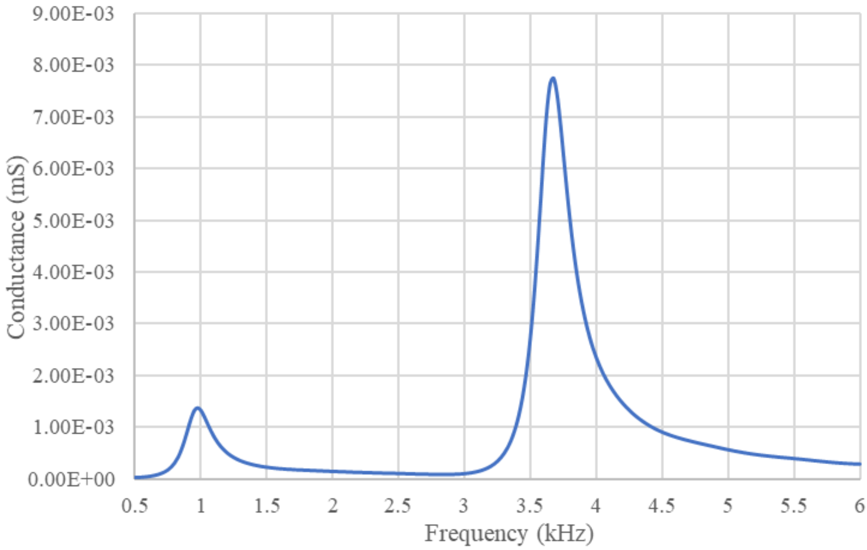

Fig. 3 Conductance plot of the base model

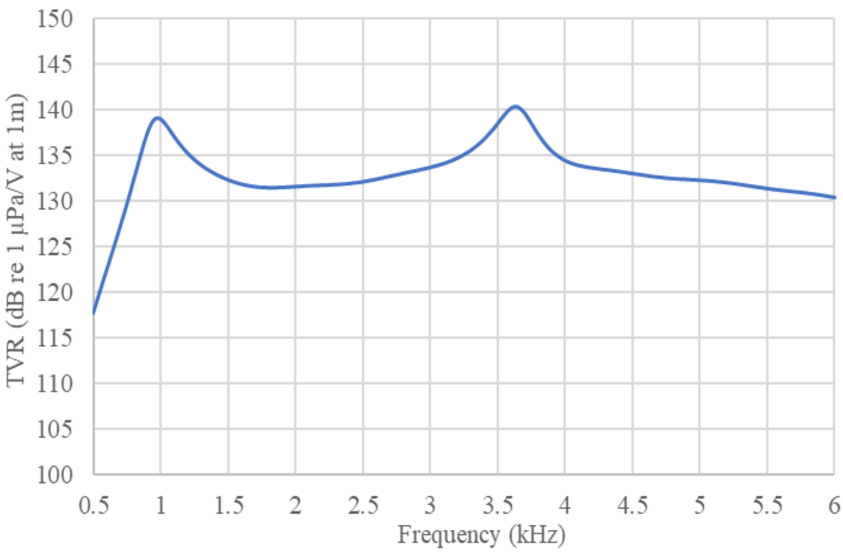

Fig. 4 TVR of the base model

The effect of important parameters like ceramic stack's inner diameter (*ID*), outer diameter (*OD*), thickness (*T*), head mass *OD*, thickness, and tail mass length on the Transmitting Voltage Response of the transducer were studied by varying one parameter at a time, keeping all other dimensions the same. The effect of inner diameter of the ceramic stack on *TVR* is shown in Fig. 5. The study was carried out by varying the inner diameter from 40 to 70 mm. As the inner diameter increased from 40 mm to 70 mm, the stiffness of the stack decreased, causing the resonance frequency to drop from 1 kHz to 0.875 kHz. Additionally, the larger inner diameter reduced the ceramic volume, resulting in lower *TVR* values across the frequency band.

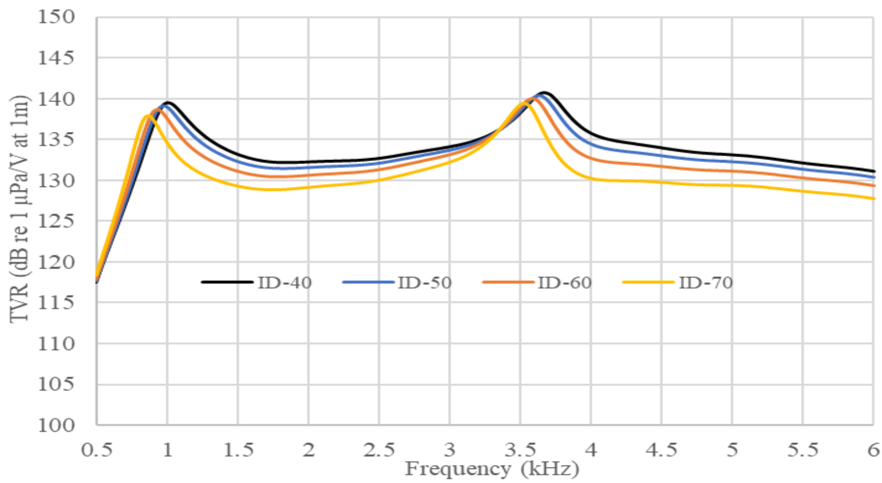

Fig. 5 Effect of piezoceramic ring inner diameter on TVR

The effect of piezoceramic stack *OD* was studied by varying it from 100 mm to 130 mm and the results are shown in Fig. 6. Increasing the ceramic's outer diameter resulted in a stiffer stack and a larger ceramic volume. This, in turn, led to a higher resonance frequency and *TVR*. When the ceramic *OD* increased from 100 mm to 130 mm, resonance frequency increased from 1.0 to 1.275 kHz and the overall *TVR* value increased up to 6 dB, except near the resonances, for the transducer with resonance of 1.275 kHz.

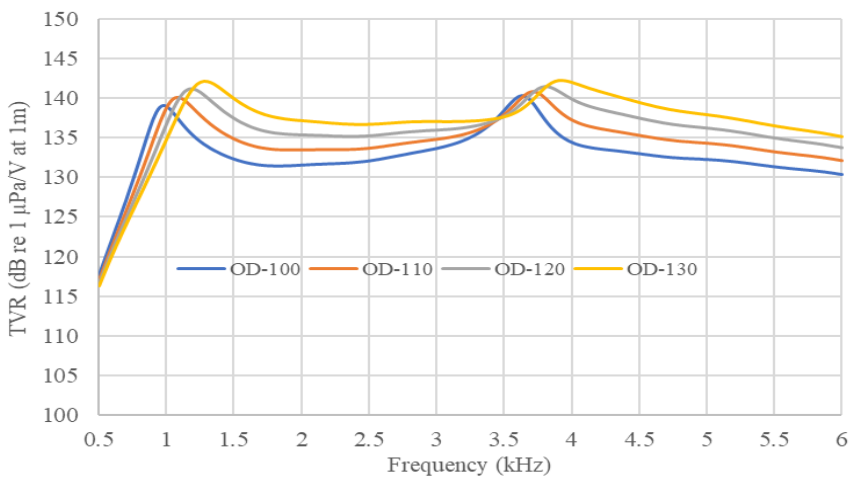

Fig. 6 Effect of piezoceramic ring outer diameter on TVR

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The effect of ceramic thickness was studied by varying the thickness from 6 to 10 mm. As the thickness of ceramic increases, stack length also increases, leading to a reduction in stiffness and thereby the resonance frequency comes down. But when the ceramic thickness increases, the field across it reduces and *TVR* also reduces as shown in Fig. 7.

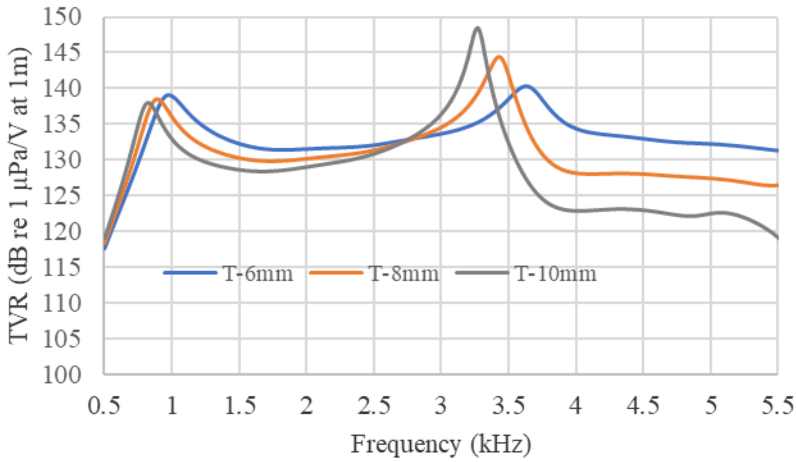

Fig. 7 Effect of piezoceramic ring thickness on TVR

The effect of the outer diameter of head mass was studied by varying it from 360 to 420 mm and the results are shown in Fig. 8. With the increase in diameter its mass goes up and resonance comes down. The *TVR* value also comes down with the reduction in frequency as the transducer needs higher volume displacement. The effect of tail mass length was studied by varying it from 100 to 200 mm and the results are shown in Fig. 9. With the increase in length its mass goes up but the *TVR* is not changed significantly so the tail mass length can be fixed to 100 mm to reduce the transducer weight.

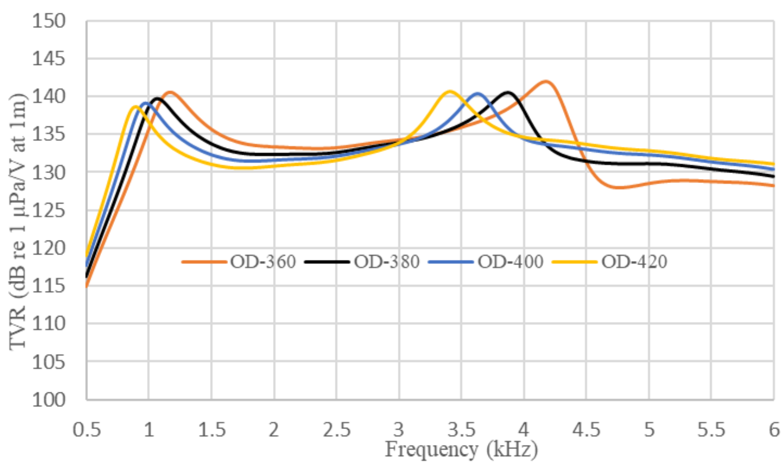

Fig. 8 Effect of head mass outer diameter on TVR

Based on the results of the parametric study, an optimised transducer was modelled and its results in comparison to the base model are shown in Fig. 10. The optimised transducer has similar resonance as that of the base model, but its *TVR* value has improved up to 2.5 dB in the band of 1 to 6 kHz except close to resonances. The *TVR* variation of the optimised transducer is about 7 dB in the band of 800 Hz to 5.5 kHz, so the useful band is more than two octaves with a minimum *TVR* of 133 dB across the band. The corresponding source level (*SL*) with a safe field of 200 V_{rms}/mm [3] can be calculated using the relation $SL = TVR + 20 \log (V_{rms})$ [20] as 194.5 dB. Thus, the optimised transducer meets all the design objectives of frequency, bandwidth and source level specified.

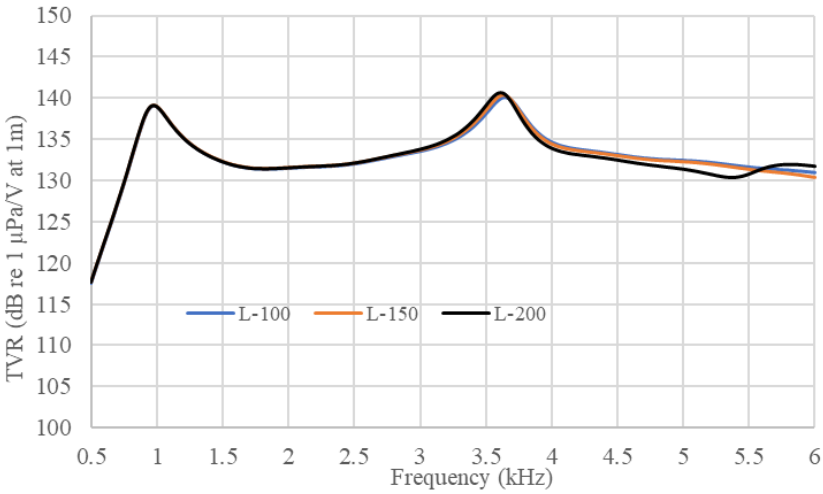

Fig. 9 Effect of tail mass length on TVR

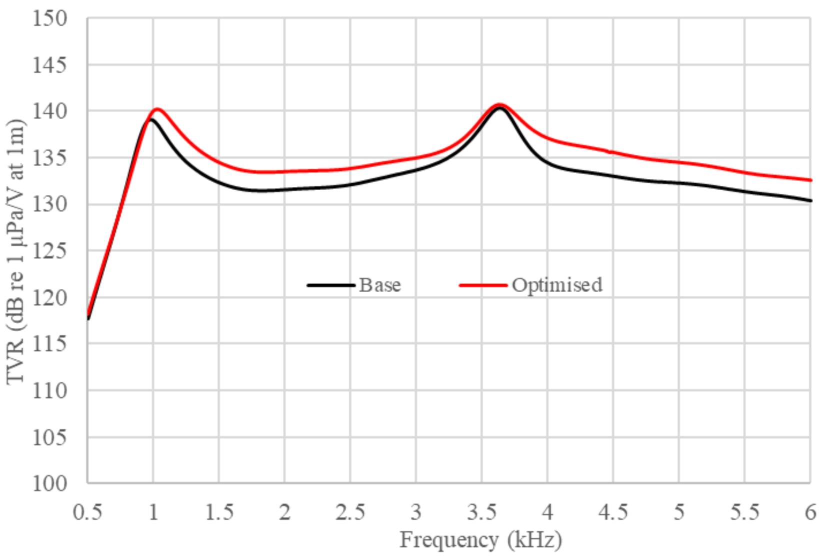

Fig. 10 TVR of the base model and optimised transducer model

6 Conclusions

Low-frequency, broadband Tonpilz transducers were modelled using a finite element software COMSOL Multiphysics. Along with length mode resonance, head flexure of the transducer was used advantageously to get a useful bandwidth of more than two octaves. The optimised transducer exhibited its first resonance at 1 kHz and second resonance at 3.7 kHz, with a *TVR* of 140 dB at resonances and 133 dB or more in the useful frequency band. The transducer achieved a useful bandwidth of more than two octaves and a minimum source level of 194 dB in the band from 800 Hz to 5.5 kHz. The effect of major component dimensions, including the ceramic stack, head mass, and tail mass, on the transducer's *TVR* was studied. It was found that the head mass outer diameter, ceramic *OD*, *ID*, and thickness had considerable effects on both the resonance frequency and *TVR* levels.

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