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Parametric Studies of a Low-Frequency Underwater Transducer

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ABSTRACT

Low-frequency active transducers are essential for applications like active sonar, underwater communications, oceanographic studies, and underwater acoustic measurements. Different transducers, including free flooded rings, flextensional, flexural disks, Janus Helmholtz, and Janus Hammer Bell (JHB), are employed as low-frequency transducers. The JHB transducer features a double-headed Tonpilz transducer, known as a Janus driver, housed within a cylindrical structure. This transducer exhibits two resonances corresponding to the Janus driver's length mode resonance and the cylindrical housing's breathing mode resonance caused by the excitation of water trapped inside the cylinder. By adjusting these two resonances, a broad operating band can be achieved. This paper presents the modelling of a low-frequency JHB transducer with a resonance frequency below 1 kHz using commercial finite element software COMSOL. A comprehensive analysis was performed to investigate how changes in key parameters like the outer diameter of the piezoceramic stack, head mass, tail mass, housing, and the gap between the head mass and housing affect the transducer's transmitting voltage response (TVR). The studies reveal that the outer diameter of the piezoceramic stack, head mass, and housing significantly influence the resonances. An optimised design was also arrived at based on parametric studies. The designed transducer can produce a 200 dB or higher source level at resonances.

Keywords: Janus helmholtz; Janus hammer bell; Cavity resonance; Underwater transducer; FEM model; COMSOL

NOMENCLATURE

a	: Radius of housing
c	: Speed of sound
f_r	: Resonance frequency of housing
f_s	: Resonance frequency of Janus driver
ID	: Inner Diameter
JH	: Janus Helmholtz
JHB	: Janus Hammer Bell
K	: Stiffness of ceramic stack
L	: Length of housing
M	: Effective mass
OD	: Outer Diameter
SL	: Source Level
t	: Thickness of housing
TVR	: Transmitting Voltage Response
V	: Voltage
ρ	: Density of housing material
ρ_0	: Density of seawater

1. INTRODUCTION

Submarines are becoming increasingly silent due to advanced technologies, detecting them with passive sonar is difficult. In this context, anti-submarine platforms need to utilise low-frequency active sonar to locate submarines[1]. Various low-frequency active transducers, such as free flooded rings, flextensional devices, flexural disks, Janus Helmholtz (JH), and Janus Hammer Bell (JHB), are employed for this purpose[2,3]. Free-flooded ring transducers are advantageous due to their wide frequency band, ability to handle high power and suitability for use in deep ocean environments[4-5]. However, they need elaborate tooling for assembly, pre-stressing and making them watertight[6]. Flexural disk transducers are typically used for low-power, shallow-depth applications but suffer from low bandwidth and delamination of piezoceramics[7]. Different types of flextensional transducers[8] are used for high-power, low-frequency applications[9], but their bandwidth and depth capabilities are limited, generally not employed beyond 200-300 meters of water[10]. The Janus Helmholtz transducer provides broad bandwidth, high power, deep-sea operational capability, and high efficiency[11-12], with variants such as multi-cavity and outer cavity transducers[13-14]. The Janus Hammer Bell transducer, similar to the Janus Helmholtz transducer, offers high power and broadband capabilities[15-16]. While both the JH and JHB transducers use a Janus driver, the JH transducer relies on the coupling of Helmholtz resonance of the entrapped fluid with length mode resonance.

In contrast, the JHB transducer uses the shell's breathing mode resonance excited by the length mode resonance of the Janus driver[17-18]. The JHB transducer is also more compact for the same resonance frequency than the JH transducer[19]. There are very few publications in the open literature on the design of JHB transducers. The study presented here focuses on a JHB transducer operating at frequencies below 1 kHz for underwater communication and oceanographic studies. A detailed parametric analysis was conducted to investigate

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the influence of key design parameters on the transducer's Transmitting Voltage Response (TVR), enabling optimised design choices.

2. OBJECTIVE OF THE STUDY

In the current study, a finite element model of a low-frequency Janus Hammer Bell (JHB) transducer, resonating below 1 kHz and capable of generating a source level exceeding 190 dB re 1 µPa at 1 m, was developed using COMSOL Multiphysics[20] software. A comprehensive parametric study was conducted to determine how major design parameters affect the transducer's transmitting voltage response (TVR). The parameters investigated included the outer diameter of the piezoceramic stack, tail mass, head mass, housing, and the radial clearance between the head mass and housing inner diameter. The study will facilitate design optimisation to achieve maximum acoustic performance from the transducer.

3. DESCRIPTION OF THE TRANSDUCER

The JHB transducer comprises two piezoceramic stacks positioned between two head masses and a shared tail mass, forming what is known as a Janus driver, housed within a cylindrical structure as depicted in Fig. 1. Thin FRP sheets are used to electrically isolate the stacks from the metallic head mass and tail mass. The housing is secured to the tail mass using special studs and bolts. The gap between the housing and head mass allows water to free-flood the horizontally maintained transducer. This transducer exhibits two resonances: one associated with the length mode resonance of the Janus driver and the other with the breathing mode resonance of the metallic cylinder induced by the water trapped inside. By adjusting these two resonances, a broad operating band can be achieved.

The following expression[19,21] can be used to obtain the breathing mode resonance frequency, f_r of a free-flooded cylinder in the water.

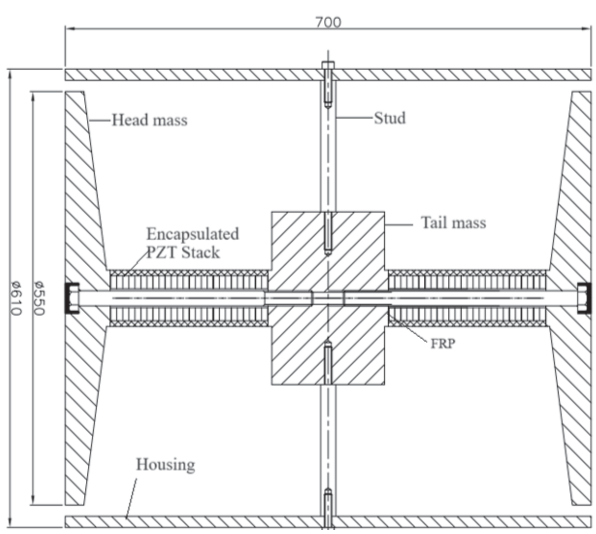

Figure 1. Schematic of the JHB transducer.

$$f_r = \frac{c}{2\pi a}\left(1+\frac{\rho_0\sqrt{\frac{aL}{2}}}{\rho t}\right)^{-1/2} \tag{1}$$

In the above equation, a represents the radius of the housing, L is its length, t is the thickness of the housing, ρ is the density of the material used for the housing, ρ_0 is the density of seawater, and c represents the speed at which sound travels through the housing material. Using the above equation, the resonance frequency of an aluminium cylinder of 575 mm diameter, 700 mm length, and 15 mm thickness can be calculated as 948 Hz.

An approximate relation for the resonance frequency, f_s of the Janus portion of the transducer, is given by[21]

$$f_s = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \tag{2}$$

where, K is the stack's stiffness, and M is the effective mass of the transducer. An initial estimate of the dimensions of the Janus portion of the transducer resonating below 1 kHz can be obtained using this expression.

4. MODEL AND BOUNDARY CONDITIONS

Due to symmetry, only one-eighth of the transducer requires 3D modelling. Symmetric/infinite sound hard boundary conditions are applied in the symmetry plane at $x=x_0$, $y=y_0$, and $z=z_0$. COMSOL's pressure acoustics interface models sound waves in water, the solid mechanics interface handles the behaviour of structural components, and the electrostatics interface simulates the piezoelectric material's response[20].

The model uses positive Z-axis polarisation for the piezoelectric material. Negative Z polarisation requires defining a custom coordinate system. During assembly, the piezoceramic rings are oriented with alternating polarisation directions. This configuration facilitates the generation of maximum in-phase strain from the resulting stack. Piezoceramic rings in the stack are excited with an electrical potential of 1 V_{rms}. The transducer, surrounding water, and a perfectly matched layer (PML) outside the water layer simulate a non-reflecting infinite water domain, as illustrated in Fig. 2.

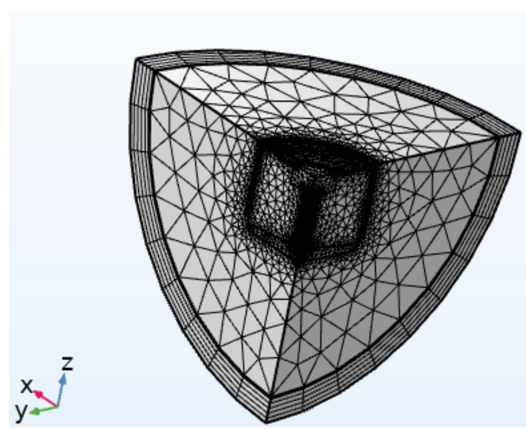

Figure 2. 3D model of 1/8th transducer.

The maximum element size in the mesh is specified as 1/5th of the smallest wavelength corresponding to the highest frequency of analysis (i.e. 1.5 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 free tetrahedral mesh and the outer structured prism mesh elements, ensuring an accurate calculation of the exterior field.

Preliminary dimensions for the transducer model are determined using Eqn. 1 and Eqn. 2. Subsequently, an iterative modelling study in the frequency domain was conducted to refine these dimensions and achieve resonance frequencies below 1 kHz. The base model has piezoceramic stacks with 26 axially poled PZT4 rings. Steel is used for the transducer head mass, tail mass, and studs, while the housing is aluminium, and the central bolt is beryllium copper. The material properties from COMSOL's material library used for the modelling studies are listed in Table 1.

Table 1. Material properties

Material	Young's modulus (GPa)	Density (kg/m^3)	Poisson's ratio
Steel, AISI 4340	205	7850	0.28
Aluminium, 3003H18	70	2700	0.33
Titanium Gr.21S	105	4910	0.33
Beryllium copper, C17200	128	8250	0.30

Table 2. Dimensional details of JHB transducer

Parameter	Dimension (mm)
Head mass outer diameter	550
Thickness of head mass	55
Tail mass outer diameter	250
Tail mass length	150
Housing outer diameter	610
Radial clearance between the housing and head mass	15
Housing wall thickness	15
Piezoceramic stack outer diameter	60
Number of PZTs in each stack	26
FRP sheet thickness	0.5

Table 2 presents the dimensions of the base transducer model, which has first and second resonances at 750 Hz and 950 Hz, respectively. Parametric studies were then conducted using this base model to examine the influence of key parameters on transmitting voltage response. These parameters include the outer diameter of the piezoceramic stack, head mass, tail mass, housing, and the radial clearance between the head mass's outer diameter and the housing's inner diameter. Parametric studies are conducted by systematically varying one parameter at a time while holding all other dimensions constant. This approach quantifies each parameter's influence on the Transmitting Voltage Response.

5. RESULTS AND DISCUSSIONS

Figure 3 illustrates the transmitting voltage response (TVR) of the base model of the transducer. The TVR indicates that the transducer exhibits its primary resonance at 750 Hz and a secondary resonance at 950 Hz, with corresponding TVR values of 139 and 149 dB re 1 µPa at 1 m, respectively. The transducer demonstrates a useful operating frequency band exceeding one octave, ranging from 650 Hz to 1300 Hz, with a TVR of 130 dB or higher within this band.

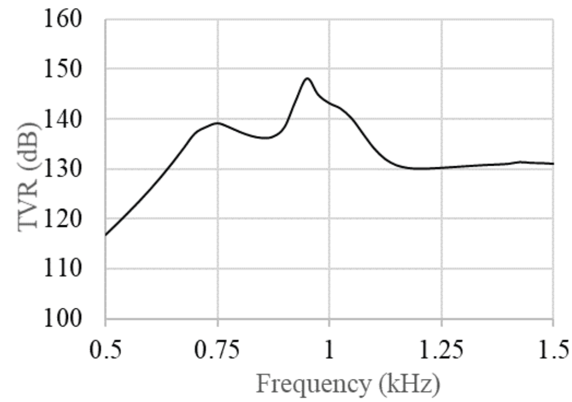

Figure 3. Transmitting voltage response.

The transducer's source level (SL) can be calculated from the predicted TVR and the voltage (V_{rms}) applied using the Eqn. 3[22],

$$SL = TVR + 20 \log (V_{rms}) \quad (3)$$

Considering a safe field of 200 V_{rms}/mm[21,23], 1600V_{rms} can be applied across the ceramic ring of 8 mm thickness. The SL for the transducer at 750 Hz, 950 Hz and across the 650-1500 Hz band can be computed as 203, 213 and 194 dB re 1 µPa at 1 m, respectively. Since losses are not included in the model, a few dB reductions in transmitting voltage response and source level can be expected [24]. Parametric studies are carried out using the base model.

The impact of the PZT stack's outer diameter (OD) on resonance frequencies was investigated by varying the outer diameter of the stack to 50, 55, 60, and 65 mm. As illustrated in Fig. 4, the results indicate that resonance frequencies decrease with a reduction in the transducer's stack outer diameter. This decrease in outer diameter reduces the stack's stiffness, resulting in lower resonance frequencies. Additionally, a decrease in the outer diameter reduces the transmitting voltage response (TVR) level, attributable to the reduced ceramic volume.

The impact of the outer diameter of the head mass and housing on the TVR was analysed by altering the head mass diameter to 450, 500, 550, and 600 mm while maintaining the exact radial clearance between the head mass and housing. So, along with the outer diameter of the head mass, the outer diameter of the housing also changes. The TVR plot for change in head mass and housing outer diameter is shown in Fig 5. With the increase in head mass diameter, the effective mass of the Janus driver increases and reduces the resonance frequency. Since radial clearance is kept constant, the diameter of the housing also increases along with an increase in head mass diameter, leading to a larger entrapped volume of water and causing the reduction in breathing mode resonance of the housing.

The impact of radial clearance between the head mass and housing was examined by altering the housing's inner diameter. The findings in Fig. 6 reveal that variations between 5 mm and 20 mm have no significant effect on the resonance frequencies or the corresponding TVR values. However, some variations are observed beyond the second resonance, which may be attributed to changes in water flow through the clearances.

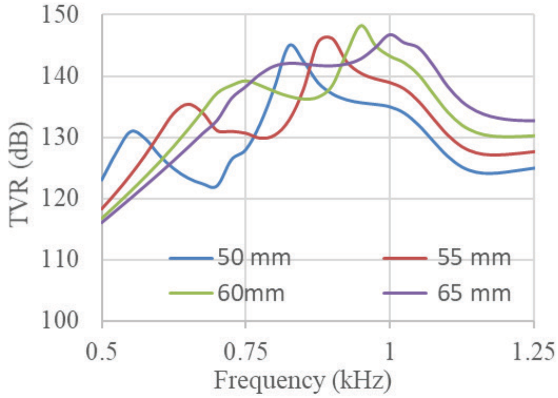

Figure 4. Effect of PZT stack OD on TVR.

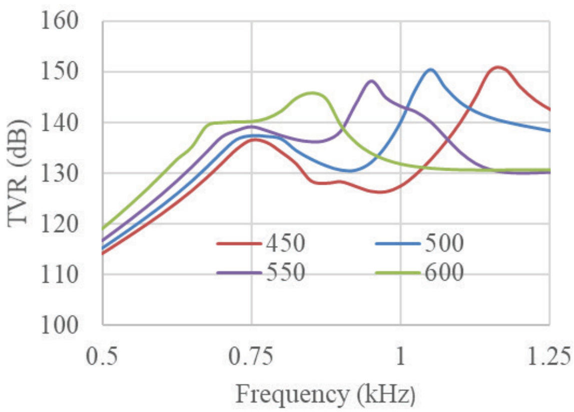

Figure 5. Effect of Head mass OD on TVR.

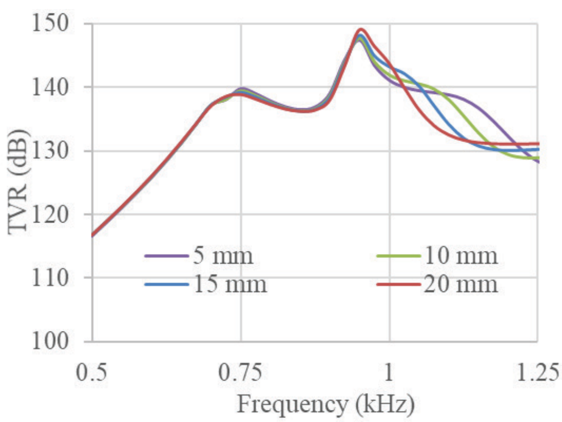

Figure 6. Effect of radial clearance on TVR.

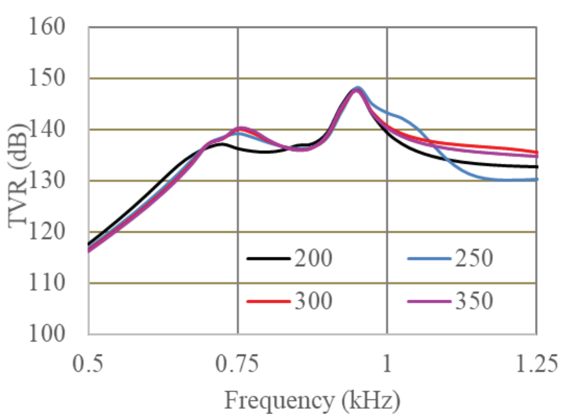

Figure 7. Effect of tail mass OD on TVR.

The impact of the tail mass's outer diameter on the transmitting voltage response (TVR) was investigated by adjusting the diameter to 200 mm, 250 mm, 300 mm, and 350 mm. The results, shown in Fig. 7, demonstrate that an increase in the outer diameter leads to a rise in the first resonance frequency and a higher TVR.

The impact of head mass material on the transmitting voltage response (TVR) was investigated using steel, titanium, and aluminium as the head mass materials. The results illustrated in Fig. 8 indicate that the first resonance frequency remains unaffected by the material change. However, the second resonance frequency is influenced by the material density. The transducer with steel head mass has the lowest resonance frequency due to its higher density. The transducer incorporating a steel head mass demonstrates a transmitting voltage response (TVR) approximately 5 dB higher at the lower resonance frequency than the transducer equipped with an aluminium head mass.

The effect of housing length on TVR was studied by changing the length to 700, 600, 500 and 400 mm while keeping all other dimensions the same. The results are shown in Fig 9. The resonance frequencies have not changed with the reduction in length. Still, below the first resonance and immediately after the second resonance, TVR values have reduced by about 2 dB to 3 dB when the housing length is reduced from 700 mm

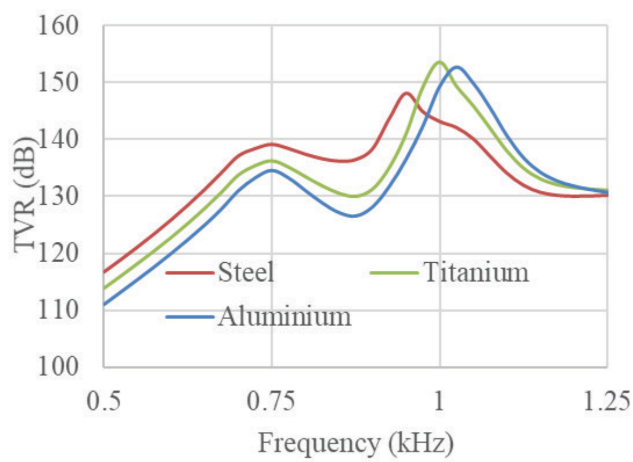

Figure 8. Effect of head mass material on TVR.

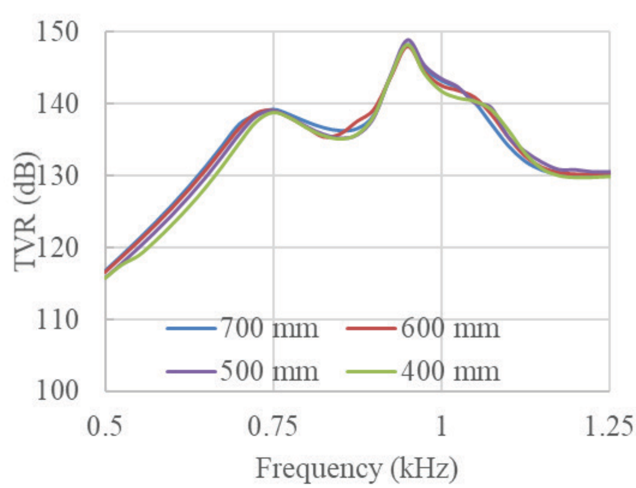

Figure 9. Effect of housing length on TVR.

to 400 mm. However, we can reduce the housing length from 700 mm to 600 mm without much reduction in TVR.

Based on the design requirement, parameters can be modified to get higher TVR and bandwidth in the frequency of interest by changing one or more of the parameters studied. Since the current study focuses on frequencies below 1 kHz, an attempt was made to optimise the response in the frequency band of 750 to 950 Hz. A few iterations by changing the parameters resulted in the response shown in Fig.10. The optimised transducer has up to 7 dB higher TVR in the 750 to 950 Hz band. The parameters changed from the base model are tail mass OD to 300 mm, head mass OD to 575 mm, housing OD to 625 mm, radial clearance to 10 mm and PZT OD to 64 mm, keeping all other dimensions the same.

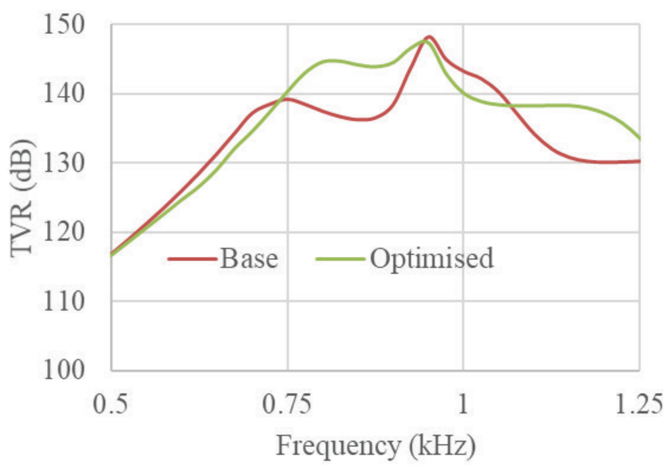

Figure 10. TVR of the optimised transducer.

6. CONCLUSIONS

A low-frequency Janus Hammer Bell (JHB) transducer with resonance frequencies below 1 kHz was modelled using the commercial finite element software COMSOL. The transducer exhibits its first resonance at 750 Hz and its second resonance at 950 Hz, with corresponding transmitting voltage response (TVR) values of 139 dB and 149 dB, respectively, for the base modal. It has a useful operating frequency band spanning over one octave, from 650 Hz to 1300 Hz, maintaining a TVR of 130 dB or higher within this band. Comprehensive parametric studies were conducted to investigate the influence of key parameters such as the outer diameter of the piezoceramic stack, head mass, housing, and the radial clearance between the head mass outer diameter and the housing inner diameter on the TVR of the transducer. The studies revealed that the head mass material, piezoceramic stack outer diameter, head mass outer diameter, and housing outer diameter predominantly affect the transducer's resonances and TVR. The base model was optimised to improve the TVR in the 750-950 Hz band, and an increase of up to 7 dB in TVR was obtained. The designed transducers can produce a source level exceeding 200 dB at resonances and more than 190 dB across the frequency band of 650 Hz to 1300 Hz.

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He has guided the present work and reviewed the manuscript.