Improved design and manufacturing of low frequency broadband underwater transducers

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Abstract — Wideband low frequency transducers are crucial enablers for building underwater communication networks. The use of low frequencies promises long range communication ranges, but most low-frequency transducers are large, lack directionality and have limited bandwidth. The aim of this study is to tackle these limitations. We take a novel approach at achieving directional radiation: A symmetric driving stack combined with a structure that is tailored to have an asymmetric mechanical response. Tuning the structure to have multiple mechanical resonances allows for an increase in usable bandwidth. Finite element analysis is used to predict the performance of a particular design. The concept is modeled for a shell made out of 3D printable plastic. If the radiation characteristics look promising the shell is then printed. Displacements are introduced in the printed shell using actuators, the resulting vibrations are evaluated in air using a microphone array and Laser Doppler Velocimetry. These concept models can be used to develop transducers made of metals.

Introduction

Wideband low frequency transducers are essential in building an underwater communication network and have attracted considerable interest over the past 20 years [1]. They facilitate long ranges, but bring their own set of problems with them. The main design impacts stem from the lack of directionality at small scales. Directional approaches are usually array-based, which increases their size and energy consumption dramatically. This hinders direct application of low-frequency modems in compact sensor nodes or in Unmanned Underwater Vehicles. The aim of this study is to tackle these limitations.

The field of low frequency, high power transducers is dominated by two distinct types: The free-flooded ring (FFR) and the flextensional transducer. The FFR is a ring type transducer that employs resonant modes within the ring and inside the ring cavity to create radiation. The flextensional transducer is a design that translates the extension of the piezoelectric material to a flexural motion of a surrounding shell, thereby greatly increasing the available displacement. Both types are omnidirectional sources. Directionality is generally achieved by arranging multiple transducers in an array. This leads to severe weight and power penalties. Recent research shows that a flextensional transducer is capable of directional output, either by adding acoustic mirrors or by careful exploitation of asymmetric driving conditions [2, 3]

A second design goal is the increase of usable bandwidth over current designs. FFR transducers achieve their high bandwidth by employing multiple resonances and profit directly from the use of PMN-PT material [4]. Resonance frequency and available bandwidth are directly linked to the material the ring is made from. In a flextensional design resonance frequencies and bandwidth are determined by the shell. This opens up a wide range of design possibilities to increase the available bandwidth. A design with multiple mechanical resonances is easily achievable. A second determining parameter for the bandwidth is the mechanical quality factor. For the FFR this is determined by the piezoelectric material used. In this case the quality factor can be related to the sharpness of the resonance frequency. It relates stored mechanical energy U_e to power dissipation P_d (equation (1)) [5].

$$Q_m = 2\pi f \frac{U_e}{P_d} \tag{1}$$

For the flextensional transducer the design and materials of the shell determines the quality factor and can be tuned in a wide range by using different shell materials. The resulting system is essentially a damped mass-spring arrangement with the corresponding quality factor definition (equation (2)).

$$Q = \frac{\sqrt{Mk}}{D} \tag{2}$$

M denotes the mass, k the spring constant and D the damping coefficient.

Design of a prototype

The structure presented in [2] is used as a basis for our prototype, as it exhibits pronounced directionality under asymmetric driving conditions in the frequency range between 3 kHz and 10 kHz. We recreate the presented model in COMSOL Multiphysics and modify it to show a similar deformation profile at 3 kHz, but as an eigenmode of the structure instead of a result of asymmetric driving conditions (**Fig 1**). While this comes at a cost of bandwidth, it vastly simplifies the driving circuit for a prototype structure. In addition, it allows for a small gain in active piezoelectric material, as the inactive section splitting the stack in two parts is no longer necessary. To achieve this, we have made a number of modifications. The design from [2] (**Fig 1**, left) uses a symmetrical shell together with two piezoelectric stacks that can be driven independently. Our design (**Fig 1**, right) takes the opposite approach. We only use a single piezoelectric stack. To make the design directional, we make one of the beams thinner and distribute the mass at the shell ends asymmetrically.

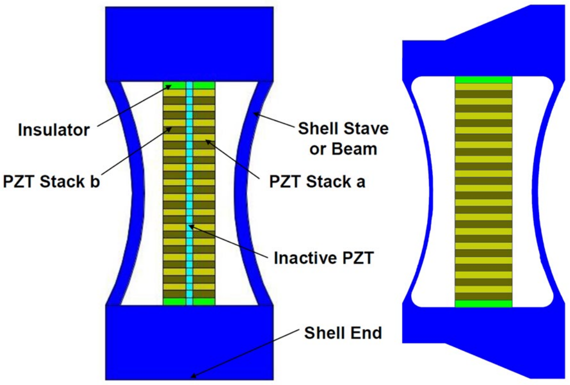

Fig 1: Comparison between the two stack design used in [2] (left) and our single stack design (right)

We translate the structure to a model system made of 3D printable plastic to facilitate rapid testing in air. The translation consists of two steps. Step 1 is to exchange the material in the simulation. While this is a fairly straightforward process for readily available materials, it is much more involved for 3D printable plastic. Material properties of such material vary by a large margin depending on the type of plastic, orientation, model of the printer and printing conditions [6–8]. As such, for each subpart of the structure mechanical testing has to be performed on appropriate testing specimens made under the exact same circumstances as the final printed structure.

Step 2 is scaling of the model. The low stiffness of the 3D printable plastic leads to very low frequencies for the eigenmodes. This shifts the frequency of the targeted eigenmode to an easily accessible range.

Fig 2 shows eigenmodes predicted by simulations for the structure after the scaling has been done. On the left side is the eigenmode at 897 Hz, which is the targeted mode for directionality in forward direction. The right side shows a mode at 1002 Hz which can be used to gain directionality in backwards direction.

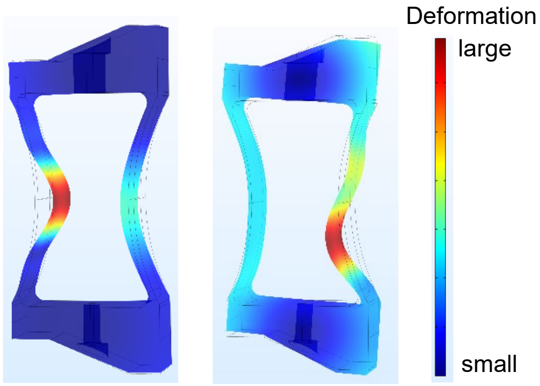

Fig 2: COMSOL eigenmode simulations of the prototype structure, left: 897 Hz, right 1002 Hz

Measuring directionality

The shape of the prototype structure allows for a definition of directionality. The setup used for the measurements on the prototype is shown in **Fig 3**.

In the center is the prototype structure, which is excited into vibrations using piezoelectric actuators from the top and bottom. The directionality is probed at several points on a horizontal plane with the structure in the middle and the actuators above and below. The Laser Doppler Velocimetry (LDV) measurements (using a Polytec PDV100) are carried out in the center of the two curved surfaces (forward and backwards direction). The sideways direction is measured on the upper part of the structure, which is joining the two vibrating beams.

For the LDV measurements, directionality is defined as in equations (3) and (4).

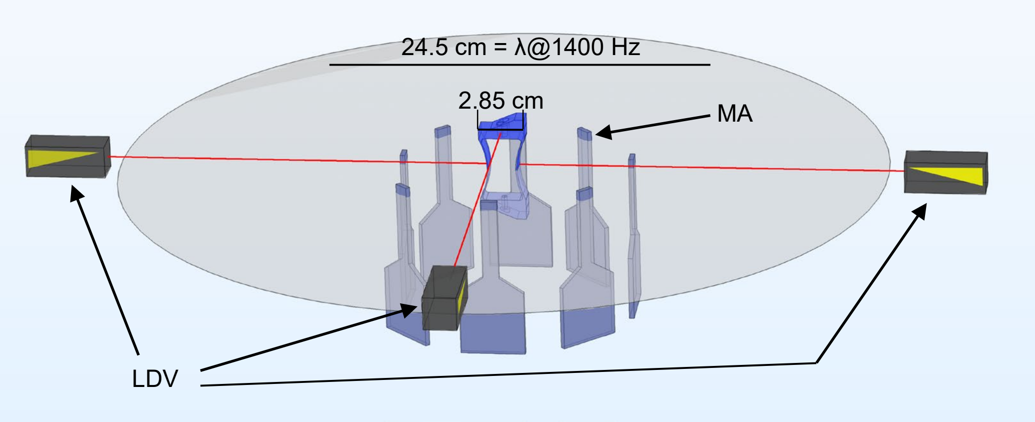

Figure 3: Schematic of the measurement setups used. The probed structure is the same in all cases, while the detector changes (Laser Doppler Vibrometer (LDV) vs Microphone Array (MA)).

$$D_{LDV,f} = 20 * \log_{10}\left(\frac{Amplitude_{forward}}{Amplitude_{sideways}}\right) \qquad (3)$$

$$D_{LDV,b} = 20 * \log_{10}\left(\frac{Amplitude_{backwards}}{Amplitude_{sideways}}\right) \qquad (4)$$

For each direction separately the amplitude of vibrations over frequency is recorded using LDV. From this data the directionality D_{LDV} is calculated by comparing the amplitude in the desired direction (forward/backwards) against the spurious amplitude in the sideways direction.

A second set of measurements is done using an array of microphones (MA) placed around the prototype structure (**Fig 3**, center). The array is developed at the University of Amsterdam and allows for parallel, phase synchronous recording of currently up to eight signals using wideband MEMS microphones. The microphones are all at a distance of about 7 cm from the center of the structure and equally spread over the circumference.

Results

In **Fig 4**, D_{LDV} is plotted over the excitation frequency. The left side of the figure shows $D_{LDV,f}$, the right side $D_{LDV,b}$.

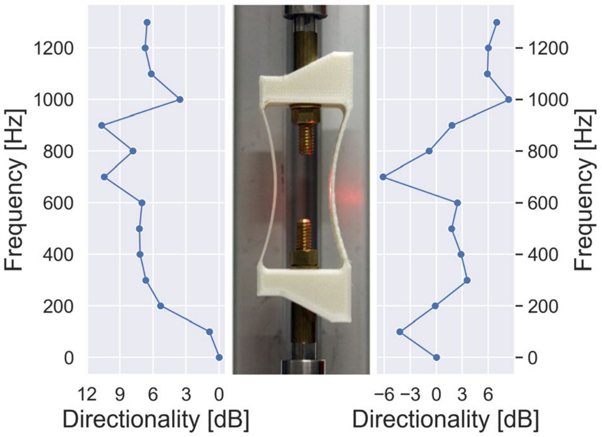

Figure 4: Directionality (Amplitude forward vs backward direction) as frequency response measured using Laser Doppler velocimetry.

Over the whole frequency regime we find a preference of the forward and backwards direction over the sides. Between 0 and 900 Hz we find a larger amplitude in the forward direction than backwards. This effect is changes at and above 1 kHz. At 1 kHz we find a pronounced directionality in the backwards direction and at frequencies above that we see similar amplitudes in both directions. **Fig 5** shows the same frequency range probed with the MA. Frequencies below 500 Hz are omitted to improve readability. Each Frequency is distinguished by color, the distance from the center indicates relative amplitude, with points further outwards corresponding to higher values.

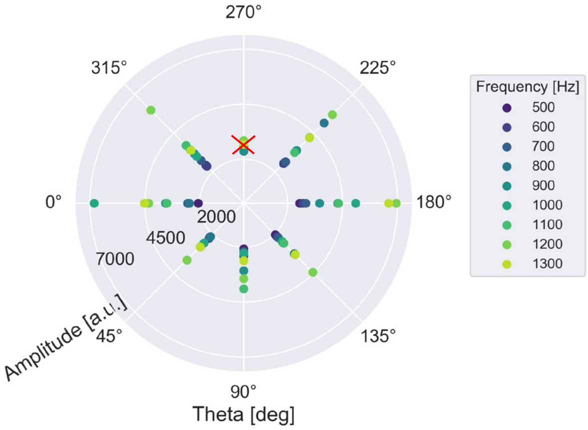

Figure 5: Near-field pressure distribution around the prototype structure, recorded with the microphone array.

We find maximum amplitude in forward direction (0°) at 900 Hz, as shown with LDV and predicted with the simulations. The direction θ = 270° is to be disregarded, as it is blocked by the mounting beam for the structure. In general the directionality is much less pronounced than measured with LDV.

Conclusions

We have designed a new type of flextensional transducer shell using a model structure that has been 3D printed in PLA. The structure exhibits pronounced directionality at 750 to 900 Hz as evidenced by Laser Doppler Vibrometer measurements. The measurements using the microphone array further support this. We find strong acoustic radiation in the forward and backward direction combined with much lower radiation to the sides. We suspect reflections and environmental noise to be the reason for the high amplitudes to the sides.

With a characteristic length of less than 3 cm the prototype is smaller than one tenth of the wavelength at maximum directionality.

Outlook

The next step to be done is to manufacture a prototype in metal. This prototype will subjected to the same tests in air to test the modelling assumptions. Afterwards the prototype will be sealed and tested in water to obtain performance data at the relevant frequencies for communication use.

Acknowledgements

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Biography

Andreas Behringer graduated in Material Sciences in Berlin, Germany (B.Sc.) and Ilmenau, Germany (M.Sc.), specializing in light metallic alloys, glasses and piezoelectric ceramics. He is currently working towards his PhD at the University of Amsterdam, Netherlands, cooperating closely with the Acoustics and Sonar department of TNO. The topic of his research are wideband sonar transducers based on new materials.

Dr. S. Peter Beerens graduated in theoretical physics at the University of Amsterdam and received his PhD in 1995 at the Royal Netherlands Institute for Sea Research.

In 1996 he joins the Sonar Department of TNO. Currently he is senior scientist and programme manager. He has specialised in sonar signal processing and sea trials.

E. (Ernest) van der Spek started his career as an engineer at Technical University of Delft, after which he entered the armed forces, first as an engineer at the Royal Netherlands Air Force, later at the Royal Netherlands Navy and is currently part of the Defence Materiel Organisation where he is responsible for the SSTD project.

Dr. Rudolf Sprik obtained his graduation and PhD in experimental physics at the University of Amsterdam. His current research includes the fundamental and applied physics of wave propagation in strongly scattering and complex systems. In particular the use of elastic and acoustic waves in non-destructive testing and imaging. He is an associate professor at the University of Amsterdam.