Acoustic Impedance Matching of PMN-PT/epoxy 1-3 Composites for Underwater Transducers with Usable Bandwidth Restricted by Electrical Power Factor

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This is an Accepted Manuscript of an article published by IEEE Online in *2019 IEEE International Ultrasonics Symposium (IUS)* on December 8, 2019, available online: https://doi.org/10.1109/ULTSYM.2019.8926034

Røed, E. S., Andersen, K. K., Bring, M., Tichy, F., Åsjord, E. M., & Hoff, L. (2019, October 6-9). Acoustic Impedance Matching of PMN-PT/epoxy 1-3 Composites for Underwater Transducers with Usable Bandwidth Restricted by Electrical Power Factor [Conference presentation]. 2019 IEEE International Ultrasonics Symposium (IUS). Glasgow. https://doi.org/10.1109/ULTSYM.2019.8926034

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***Abstract*— Volume cost has limited the use of single crystals in underwater applications, but reported performance of PMN-PT sonar transducers now motivates the design of commercial prototypes. This work addresses optimization of the matching layer for maximum bandwidth of underwater transducers made from PMN-PT/epoxy 1-3 composite plates. Bandwidth is here defined by both the electromechanical transfer function and the electrical power factor. The electrical power factor is the ratio of real to apparent power and must be taken into account for systems with transmitter volt-ampere limitations. PMN-PT single crystals has a higher electromechanical coupling coefficient than commonly used PZT. This requires a lower mechanical quality factor of the transducer design to avoid increased fluctuation of the tuned power factor. For a PMN-PT/epoxy composite with air backing and one matching layer it is challenging to achieve optimum mechanical quality factor, resulting in possible power factor limitation of bandwidth.**

Keywords—single crystal, matching layer, 1-3 composite

I. Introduction

Single crystals in the relaxor-ferroelectric lead magnesium niobate (PMN)-lead titanate (PT) system provide advantages over conventional lead zirconate titanate (PZT) ceramics when used as the active material in piezoelectric transducers [1]. PMN-PT single crystals have superior piezoelectric coefficients and electromechanical coupling coefficients to PZT, offering potential for larger acoustic source levels and broader frequency bandwidth [2]. While frequency bandwidth is important for resolution in most transducers, high source level is of particular importance for underwater detection of distant objects. PMN-PT has become a widely used material in high-end medical transducers, but its high cost per unit volume has limited its use in underwater transduces. However, results from naval research [2][3] now show transducer performance that motivates design of commercial prototypes. Motivation also comes from recent developments of so-called textured ceramics, showing that these may provide piezoelectric coefficients and electro mechanical coupling coefficients close to those of single crystals, but at a lower cost [4].

The reported underwater designs with single crystals are mostly of the tonpilz or cylinder type. A few composite designs are also reported [5][6][7], but the reports do not include matching details. This paper addresses matching of composite plates.

II. Definition of Bandwidth

The focus of the paper is frequency bandwidth. One definition of bandwidth is based on the electromechanical transfer function *H(f)*,

$$H(f) = \frac{u(f)}{V(f)}, \quad (1)$$

where f is the frequency, *u(f)* is the normal velocity at the face of the transducer, and *V(f)* is the voltage at the electrical terminal of the transducer. The transfer function bandwidth, Δf_H, is the range of frequencies where

$$20 \log\frac{|H(f)|}{|H(f_0)|} \geq -3\ dB\ , \quad (2)$$

with f_0 being the frequency where the transfer function *H(f)* has its maximum value.

Underwater transducers operate at lower frequency and higher power than medical transducers, and for some systems the transfer function will not be the only factor limiting the usable bandwidth. The electrical phase can also be a limitation. The cosine of the phase is called the electrical power factor, and is the ratio of real to apparent power. Especially for transducers mounted on small vehicles operated on batteries, low power consumption and compact design are essential. For effective operation, the capacitive part of the transducers' electrical

Funded by the Research Council of Norway, Grant no. 290462

impedance at the resonance frequency should be tuned out. However, this requires large inductors to handle the large currents and low frequencies involved, resulting in a less compact design. A definition of bandwidth also including the phase was given by Stansfield, [8] chapter 5, and in this paper we define bandwidth in a similar way:

The total bandwidth is the range of frequencies where the transfer function is within -3 dB of its maximum value, and where the electrical phase after parallel tuning is within ±37º, i.e. power factor > 0.8.

The power factor bandwidth, Δf_{PF}, is calculated by shunting the transducer by an inductor that cancels the capacitive part of the impedance at the resonance frequency, and then finding the range of frequencies where

$$PF(f) = \cos(\theta(f)) > 0.8\,, \tag{3}$$

with $PF(f)$ being the power factor for the tuned phase $\theta(f)$. The usable bandwidth, Δf, is the smallest of the power factor bandwidth Δf_{PF} and the transfer function bandwidth Δf_H.

III. Theory

A. Optimum mechanical quality factor

The bandwidth of a transducer according to the above definition will depend on both the electrical and the mechanical quality factor. The electrical quality factor, Q_e, is the ratio of susceptance to conductance at resonance. The lower the Q_e, the higher the power factor at resonance. The mechanical quality factor, Q_m, is defined as [9], p.380:

$$Q_m = \omega_r \frac{U_s(\omega_r)}{W_d(\omega_r)}\,, \tag{3}$$

where $U_s(\omega_r)$ is the peak kinetic energy at angular resonance frequency ω_r and $W_d(\omega_r)$ is the time average dissipated power at ω_r. A low Q_m is commonly achieved by matching the acoustic impedance of the transducer to the load. Optimum Q_m for broadband transducer response is derived in [8] and [9], minimizing the sum of the mechanical and the electrical quality factors. This optimum Q_m is given by the electromechanical coupling coefficient, k ,[9] p.63:

$$Q_{m,optimum} = \frac{\sqrt{1-k^2}}{k} \tag{4}$$

For $k = 0.7$, which is typical for the conventional piezoelectric material PZT, optimum quality factor is $Q_{m,optimum} = 1$. Single crystal materials can have coupling coefficients above $k = 0.9$. For k=0.9, $Q_{m,\,optimum} = 0.5$. Note however that the effective k of a transducer will be lower than the k of the active material.

As Q_m rises above $Q_{m,optimum}$, fluctuation of the tuned power factor increases [9]. This is shown in fig.1 which corresponds to figure 2.12 in [9].

B. Acoustic impedance matching

Many of the successful single crystal designs from naval research is of the tonpilz type. Moffett et al. [10] show how the Q_m of a tonpilz design can be reduced. A Q_m of 1.17 was achieved in [10] by three means: The motional resistance and the motional compliance were increased by a large head area against the load compared to the area of the piezoelectric

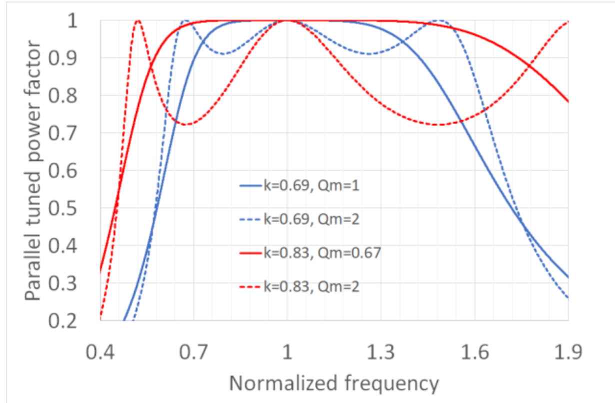

Fig. 1. Parallel tuned power factor for different combinations of coupling coefficient k and mechanical quality factor Q_m. The figure corresponds to figure 2.12 in [9].

material, and the motional mass was reduced by reducing head density and head thickness, all compared to conventional tonpilz designs.

The design considered in this paper is a composite transducer. Reduction of Q_m for composite designs are conventionally done by adding matching layers with quarter wavelength thicknesses, following guidelines for the acoustic impedances of the layers, e.g. by DeSilets et al. [11]. The concept of optimal quality factor is treated in [11], and it is shown that the material lead metaniobate with thickness mode coupling coefficient $k_t = 0.3$ is nearly optimally matched with one matching layer, while PZT-5A with $k_t = 0.5$ requires two matching layers for optimal matching.

IV. The transducer

The transducer treated here is comprised of a 1-3 composite plate vibrating in the thickness mode. It is air-backed and matched to the water load with one matching layer. The composite plate consists of the materials PMN-28%PT and epoxy CY1301/HY1300, with 50% volume fraction PMN-PT. This transducer is compared to a transducer comprised of a 1-3 composite plate with 50% volume fraction PZT-5H and the same epoxy. The effective material parameters are calculated in accordance with [12] and given in table 1. Elastic loss is included by assuming a value of $Q = 40$ at resonance for the composites and a value of $Q = 10$ for the matching layers.

V. Optimization

For the PMN-PT-composite, the effective coupling coefficient k_t is 0.83, and according to (4), optimum Q_m is 0.67. Designing a transducer with Q_m close to this value is challenging if only one matching layer is used. The broadband matching method described [11] is optimized at low transfer function ripple. However, in general more ripple can be accepted for underwater transducers than for medical transducers, and allowing more ripple opens up for designs with reduced Q_m. In this paper we want to find the optimum matching layer impedance and thickness for maximum bandwidth. The bandwidth definition is given at the end of chapter II. This definition has no specific restrictions for ripple, it is only limited by the -3 dB limits for the transfer function and the power factor being larger than 0.8. We have optimized bandwidth under this definition, using the gradient-based numerical algorithm implemented in MATLAB's *Global Optimization Toolbox*, as previously described for different optimization criteria [13].

The air-backed and water-loaded transducer is modelled by the one dimensional distributed Mason model [14], using one acoustic matching layer. Effective material parameters for the composite are shown in table 1. The electrical impedance and the electromechanical transfer function, $H(f)$, is calculated for various matching layer thicknesses and impedances. The electrical impedance is tuned by a parallel inductor and the tuned electrical phase is used to calculate $PF(f)$. The resulting bandwidth, Δf, is set to the smallest of the transfer function bandwidth, Δf_H, and and the power factor bandwidth Δf_{PF}. The optimization algorithm is run to minimize a cost function E set to:

$$E = \frac{1}{\Delta f}$$

VI. RESULTS AND DISCUSSION

In fig. 2, the curves labeled "PMN-PT" show transfer function and tuned power factor versus frequency for the PMN-PT composite with one matching layer that has thickness and impedance as given by [11]. The matching layer thickness t is $\lambda/4$, where λ is the wavelength at the resonance frequency, and the acoustic impedance is $Z_m = (Z_c Z_l^2)^{1/3}$, where subscript m denotes matching, c composite and l load. The frequency axis in the figure is normalized with respect to the resonance frequency. Note the skewing of the transfer function, as also mentioned in [11]. For the curves labeled "PMN-PT adjusted" in fig.2, this skewing is compensated for by adjusting the matching layer thickness to $1.09\lambda/4$. This adjustment is larger than what was needed in [11], possibly because of the high coupling coefficient of PMN-PT.

In fig. 3 the PMN-PT composite is compared to the PZT composite, both of them with one matching layer with acoustic impedance $Z_m = (Z_c Z_l^2)^{1/3}$ and adjusted thickness. The thickness of the matching layer of the PZT composite needed less adjustment, $t = 1.07\lambda/4$, compared to what was needed for the PMN-PT composite. This supports the assumption that less adjustment is needed for plates with lower coupling coefficient. The tuned power factor limits the bandwidth in fig. 3, resulting in only a small improvement of bandwidth for the PMN-PT transducer compared to the PZT transducer, despite the larger coupling coefficient of PMN-PT. The PMN-PT transducer has a fractional bandwidth of 0.51 and the PZT transducer has a fractional bandwidth of 0.46.

To reduce fluctuation of the power factor, the PMN-PT transducer must be designed in such a way that its mechanical quality factor approaches the optimum value, as illustrated in fig. 1. The matching layer thickness and impedance that maximizes bandwidth for the PMN-PT composite with one matching layer was found by the optimization algorithm to $t = 1.15\lambda/4$ and $Z_m = 1.4(Z_c Z_l^2)^{1/3}$. The transfer function and power factor with this matching layer are shown in fig. 4. The fractional bandwidth of the PMN-PT transducer is now 0.65. The larger matching layer impedance reduced the mechanical quality factor compared to the conventional impedance. This larger impedance could be introduced because there are no ripple restrictions in the bandwidth definition. The increased bandwidth comes at the cost of more ripple, a full -3 dB in the passband of the transfer function. Note that the values for optimum t and Z_m found here are for the given composite and should not be taken as general design guidelines.

The mechanical quality factor of the transducer should be further reduced for the design to reach the potential maximum bandwidth for coupling coefficient $k_t = 0.83$ [10]. Adding more matching layers or reducing the volume fraction PMN-PT are possible means worth considering for further reduction of Q_m.

VII. CONCLUSIONS

The frequency bandwidth of a transducer with mechanical quality factor far from the optimum value $Q_{m,optimum} = \sqrt{1-k^2}/k$ may be limited by the electrical power factor. For composites with high coupling coefficient k, a transducer with optimum Q_m is challenging to design. We used a numerical optimization algorithm to find the matching layer thickness and impedance that maximize bandwidth for a PMN-28%PT/epoxy 1-3 composite in an air-backed and water-loaded transducer. Compared to designs with conventional matching layers, the mechanical quality factor for the optimized design is reduced

TABLE I. EFFECTIVE COMPOSITE PARAMETERS

Parameter	Symbol (unit)	PMN-28%PT composite	PZT-5H-composite
Piezoelectric constant	h_{33}(10^8V/m)	33.4	21.0
Electrical permittivity	ε_{33}^S (ε_0)	536	759
Acoustic impedance	Z_c (MRayl)	18.8	16.4
Longitudinal velocity	c (m/s)	4080	3800
Electromechanical coupling coefficient	k_t	0.83	0.69

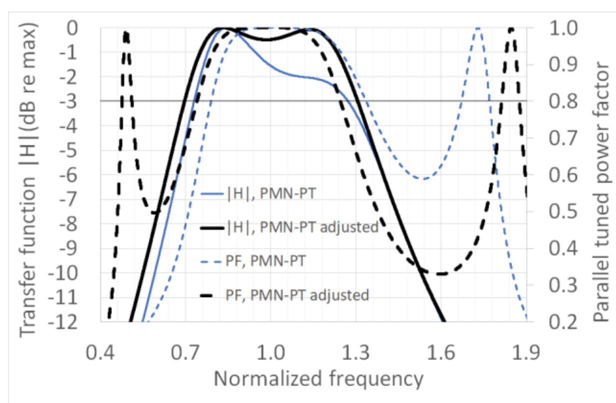

Fig. 2. Transfer function and parallel tuned power factor vs. normalized frequency for the PMN-28%PT composite with one matching layer. Blue, thin curves: Conventional thickness and impedance, $t=\lambda/4$ and $Z_m=(Z_c Z_l^2)^{1/3}$. Black, thick curves: Conventional impedance, adjusted thickness, $t=1.09\lambda/4$.

by using a matching layer with 40% increased impedance. The expense is larger transfer function ripple.

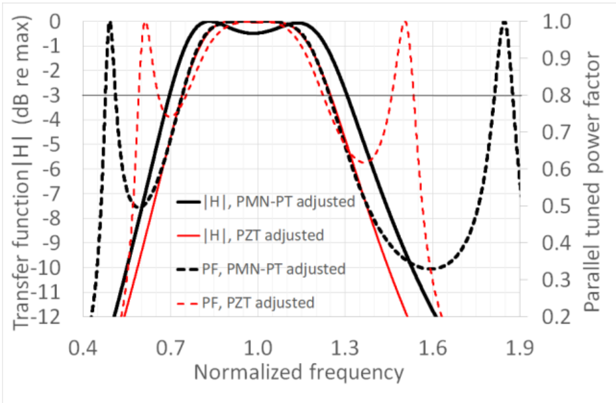

Fig. 3. Transfer function and parallel tuned power factor vs. normalized frequency for composites with one matching layer with conventional impedance $Z_m=(Z_cZ_l^2)^{1/3}$ and adjusted thickness. Black, thick curves: PMN-28%PT composite, t=1.09λ/4. Red, thin curves: PZT composite. t=1.07λ/4.

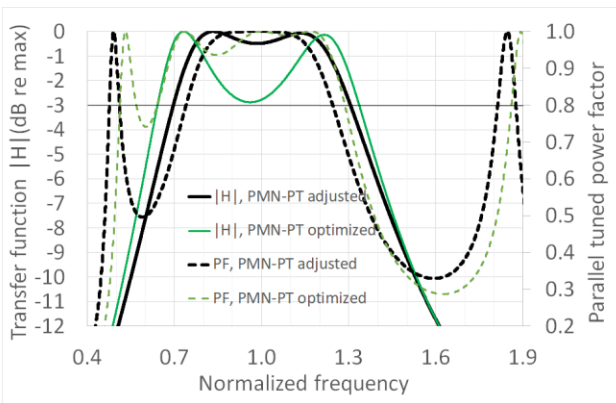

Fig. 4. Transfer function and parallel tuned power factor vs. normalized frequency for the PMN-28%PT composite with one matching layer. Black, thick curves: Conventional impedance $Z_m=(Z_cZ_l^2)^{1/3}$ and adjusted thickness t=1.09λ/4. Green, thin curves: Impedance and thickness optimized for maximum bandwidth, $Z_m=1.4(Z_cZ_l^2)^{1/3}$ and adjusted thickness t=1.15λ/4.

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