Less gives more: on the optimal filling fraction of piezoelectric acoustic power receivers

M Gorostiaga, M C Wapler and U Wallrabe

Department of Micro-actuators, IMTEK-University of Freiburg, Georges-Koehler Alle 102-02, D-79110, Freiburg im Breisgau, Germany
E-mail: wallrabe@imtek.uni-freiburg.de

Abstract. In this paper, we investigate the suitability of 1-3 composite transducers as receivers in acoustic power transfer applications. In contrast to the commonly used PZT transducers, the composites allow us to modify the acoustic impedance, the losses and the electromechanical coupling factor, and hence analyse their influence on the efficiency of acoustic power receivers. Comparing composite receivers with 40%, 60% and 80% filling factors, we find that the lowest filling fraction gives the highest efficiency. This is due to its lower acoustic mismatch with water, which compensates its lower electromechanical coupling and mechanical quality factor.

1. Introduction

Wireless acoustic power transfer has attracted some attention recently as an alternative to the inductive approach to, for example, recharge the depleted batteries of biomedical implants. In the literature, PZT pure plate transducers have been usually used as acoustic power receivers [1], but so far, their suitability as receivers has not been discussed.

Pure hard PZT plates have a very large mechanical quality factor \( Q_m \), and are fully made of piezoelectric material, which might be ideal to harvest as much energy as possible from the incoming acoustic waves. However, their reflection coefficient with soft-tissue is very large \( R \approx -0.92 \), and they require an aspect-ratio of 20 (diameter/thickness) to show a clear thickness resonance [2], which is crucial to accurately predict the optimal electric loads. As seen in [3, 4], the optimal loads at the resonances are purely ohmic when the transmission medium is water or human tissue, and therefore, their values can be easily determined by experiments. By contrast, the optimal loads are inductive for the full frequency range when the transmission medium is steel. In this case, finding the loads experimentally is not trivial any more, and consequently, a good prediction is needed.

An alternative to pure PZT transducers are the so-called 1-3 composite transducers that consist of small piezoelectric pillars embedded in a polymer. These composite transducers offer a clear thickness resonance with low aspect-ratios, which makes them ideal for miniaturization, and therefore have no spurious modes (see figure 1)[5], which could compromise the receiver performance and should be avoided for a good optimal load prediction [6]. Furthermore, their acoustic impedance can be tuned with their PZT-polymer ratio and their electromechanical coupling factor \( k_t \) is higher than that of PZT plates [7]. These properties make them ideal as acoustic power receivers, but the advantages come at the cost of higher dielectric losses \( \delta_{tn} \) and a lower mechanical quality factor \( Q_m \) [5].
Exploring these properties, we will perform acoustic power transfer experiments with composite transducers that will allow us to view the influence of the acoustic and piezoelectric parameters on the efficiency of acoustic power receivers. As we will see from the measurements in water, less piezoelectric material in the receiver may lead to higher efficiencies and improved acoustic power transfer, contrary to intuition.

2. Experimental set-up

To prove that less piezoelectric material can give a higher efficiency, we tested three 1-3 composite transducers with different PZT-polymer fillings in water as a transmission medium at the front side and air at the back side. The properties of the transducers can be found in Table 1, which we extracted by fitting the measured electric impedance to the emitter model in [8]. As we can see, the acoustic impedance mismatch with water decreases as the piezoelectric content in the transducer becomes smaller. Furthermore, the three transducers show low mechanical quality factors $Q_m$ and high dielectric losses $\delta_{tn}$, but their electromechanical coupling $k_t$ is approximately 25% higher than that of pure PZT plates [9].

In figure 2, we can see a schematic drawing of the experimental set-up. We performed frequency sweeps between 0.70 MHz and 1.05 MHz with wave bursts of 50 cycles sent from a distant emitter to avoid standing waves, and obtained from the measured voltage $V$ the power

| Transducer | 80% | 60% | 40% |
|------------|-----|-----|-----|
| $r_p$ (mm) | 7.95 | 7.95 | 7.95 |
| Aspect-ratio | 7.6 | 8.1 | 8.1 |
| $\rho$ (kg/mm$^3$) | 6472 | 5144 | 3816 |
| $f_s$ (kHz) | 789 | 761 | 737 |
| $k_t$ | 0.58 | 0.68 | 0.64 |
| $Z_p$ (MRayl.) | 25.6 | 19.9 | 13.5 |
| $\varepsilon_{33}$ | 554 | 434 | 293 |
| $R_{\text{water}}^\text{trans}$ | -0.89 | -0.86 | -0.80 |
| $\delta_{tn}$ | 0.026 | 0.029 | 0.030 |
| $Q_m$ | 27 | 51 | 42 |
\( W_{\text{load}} = \frac{V^2}{Z_{\text{el}}} \) dissipated at the attached electric loads \( Z_{\text{el}} \) as explained in [8]. For simplicity, we only considered ohmic loads between 12 \( \Omega \) and 5.6 k\( \Omega \), but we saw in [8] that the optimal power maximization loads are complex away from the resonances. Finally, we measured the pressure \( P \) of the incoming wave bursts with a needle hydrophone at the same position without the receivers of surface area \( A \) to obtain the incoming acoustic power \( W_{\text{in}} = \frac{(AP)^2}{Z_{\text{water}}} \), and hence the efficiency of the receivers \( \eta = \frac{W_{\text{load}}}{W_{\text{in}}} \). Due to the non-planar shape of the incoming waves, we corrected the efficiency to account for the actual force on the receiver as explained in [8].

3. Measurement results

In figure 3, we see on the one hand that the 40% transducer achieves the highest efficiency (0.67) at the resonance despite having less piezoelectric material and higher dielectric losses than the 60% (0.59) and 80% (0.48) composite receivers. Furthermore, it has a lower \( Q_m \) and electromechanical coupling \( k_t \) than the 60% composite, but its performance is still better.

On the other hand, the 40% receiver should also have a local maximum at the anti-resonance with a higher efficiency than the other receivers, but this is attenuated, probably due to leakage of water vapour into the brass casing. This leakage modified the electric impedance at the anti-resonance (see figure 1), which also lead to a decrease of the efficiency at this frequency.

The better performance of the 40% transducer is due to its lower acoustic reflection with water, which we can also see in figure 4. There we show the numerical prediction of the maximum efficiency at the resonance of the transducers with the optimal load according to the model in [3, 4]. The predictions suggest that the transducer with the closest acoustic impedance to the transmission medium will have the best performance for a set of receivers with equal losses and electromechanical coupling. Furthermore, a lower acoustic impedance mismatch can compensate the efficiency decrease caused by a slightly lower \( Q_m \), as it is the case of our 40% transducer compared to the 60% composite. However, a receiver with a much lower \( Q_m \), such as our 80% composite, will perform worse for the whole front reflection spectrum. Additionally, simulations of the 60% and 40% composites suggest that higher \( Q_m \) values will increase the front reflection.
coefficient range, at which the efficiency shows high values ($\eta \geq 0.7$).

In the figure, we have also plotted the reflection coefficient (gray line; $R=0.92$) of pure PZT with water, which initially suggests that pure PZT transducers would achieve a lower efficiency than the composites with a lower acoustic impedance mismatch. However, we must stress that their mechanical quality factor can be higher than that of our test-composites ranging from $Q_m \approx 80$ for soft to $Q_m \approx 2000$ for hard PZT materials [9]. A higher $Q_m$ will lead to higher efficiencies as we can conclude by comparing the predicted efficiency curve of the 80% composite to the other two transducers.

Finally, we have seen a mismatch between the measured and the predicted efficiency of the 40% and 60% composites, which we believe is due to the influence of the brass casing to which the composites are clamped. Furthermore, the power transfer is also very sensitive to the positioning of the receiver inside the narrow central beam of the acoustic field as we already saw in [8], which can also reduce the measured efficiency if there is a slight misalignment.

4. Conclusions
In this paper, we have investigated the influence of the filling fraction of 1-3 composite acoustic power receivers on the maximum efficiency. In our acoustic power transfer experiments, the 40% composite receiver performed best due to its low reflection coefficient with water, despite having less PZT content and higher dielectric losses $\delta_{\text{tn}}$ than the 60% and 80% receivers, and a lower $Q_m$ and electromechanical coupling $k_t$ than the 60% composite. Finally, we conclude that 1-3 composite transducers with a low acoustic impedance mismatch with the transmission medium and despite their low $Q_m$ are very capable acoustic power receivers due to their high efficiency ($\eta \geq 70\%$).

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