ELECTRONICS FOR HIGH IMPEDANCE ULTRASOUND TRANSDUCERS

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Abstract

Whilst linear arrays of PZT composite materials are in common clinical use today, PVdF arrays have had limited commercial success. The prime reason for this lies in PVdF's lower d33 response and high output impedance. However, PVdF does have advantages in the broadband nature of its response and, potentially its ease of manufacturability into arrays due to its low inter-element cross-talk.

In this paper, the design of a 20MHz linear array using PVdF is considered, with respect to optimum elemental size and electronics for array excitation and echo reception. Measurements on transducers of various sizes are made and the system response when connected to real receivers is considered. It is shown that while little can be done to improve the low response, with appropriate system design, problems associated with high output impedance can be circumvented.

Introduction

In the commercial field, PVdF has been successfully deployed for many hydrophone applications [1]. The use of PVdF in array applications has been more limited and has not reached widespread clinical use [2]. Part of the reason for this is the lower transmit/receive sensitivity relative to PZT based transducers [3], which can compromise the signal to noise of a reconstructed image [4]. However, PVdF does potentially offer a route for the use of straightforward manufacturing techniques to define and interconnect the array elements [5]. Additionally, use of PVdF easily realises transducers of wide operating bandwidth that could potentially yield images with enhanced resolution. Finally, PVdF can be used to couple effectively to human tissue without the need for matching layers, since its acoustic impedance is reasonably close to that of tissue.

However, a feature of small PVdF transducers is their high electrical impedance. Connection to a standard 50Ω receiver may not offer the best solution. Impedance matching networks can transform a high impedance to match to a 50Ω receiver, but these can be problematic. With transmission line matching [6] for example, a previously wideband transducer is transformed successfully to 50Ω but with a much poorer impulse response. The clear solution is to employ an amplifier with a high impedance input. Whilst this is effective to a point, diminishing returns on signal strength are obtained when transducer impedance becomes too high [7].

Transducer optimisation

When subjected to a pressure wave, the equivalent circuit of a PVdF transducer can be approximated as shown in Figure 1 [8].

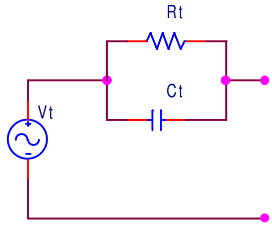

Figure 1. Basic equivalent circuit of PVdF transducer modified

The voltage source V_t is proportional to the force on the sensor arising from a pressure wave.

The equivalent circuit of an ideal operational amplifier receiving the signal is shown in Figure 2. This shows the transducer as before with a unity gain amplifier (for impedance transformation), a voltage noise source V_n, capacitance C_a and input resistance R_a. In real implementations of this amplifier, C_a will include all the interconnect capacitance and additional capacitance added by protection circuitry.

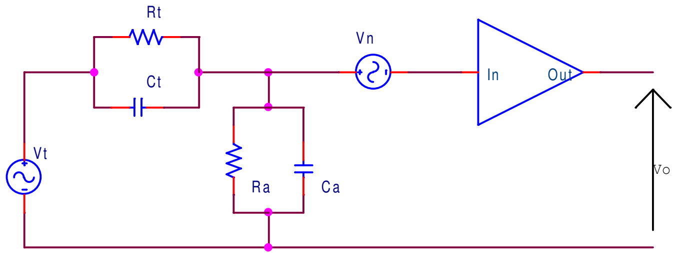

Figure 2. Equivalent circuit of front-end receiver

The signal response is given by equation 1:

$$V_{out} = V_t \cdot \frac{j \cdot \omega \cdot C_t \cdot R_t + 1}{j \cdot \omega \cdot \frac{R_t \cdot R_a}{R_a + R_t} \cdot (C_a + C_t) + 1} \cdot \frac{R_a}{R_a + R_t} \quad (1)$$

The PVdF array layout considered is shown in Figure 3.

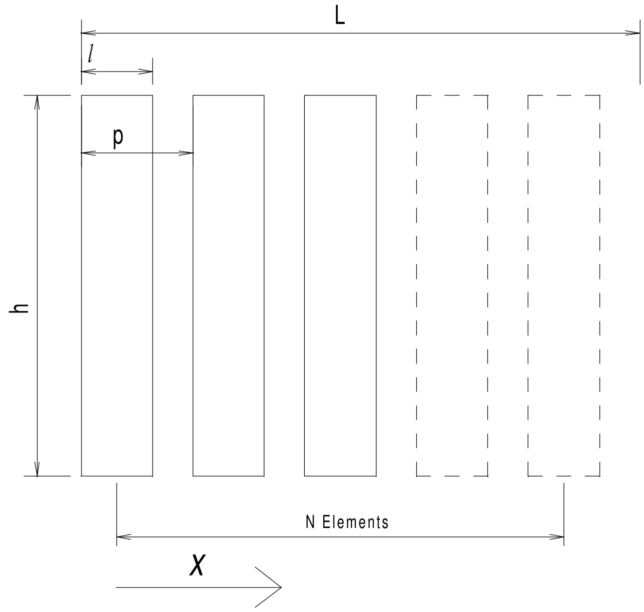

Figure 3. Layout of PVdF array

With typical PVdF and circuit parameters (ε_r=5.84 [9], Tan delta =0.25 [9], PVdF thickness, t=28µm, C_a=1.5pF, R_a=1MΩ, PVdF element height, h=7mm, element width, l=0.22mm and pitch, p=0.25mm), it is clear that at frequencies around 20MHz (the expected centre frequency of the array), typical values of C_t (=$\varepsilon_r\varepsilon_0 hl/t$) and R_t are 3pF and 10kΩ respectively, and hence the receive circuit will operate above the pole and zero frequencies of equation (1). Hence equation (1) reduces to (if R_a>>R_t):

$$V_{out} = \frac{V_t}{1 + \frac{C_a}{C_t}} \quad (2)$$

C_t can alternatively be expressed as C_x.r.p (ignoring capacitive edge effects) where C_x is the capacitance per unit width (in the x direction), r is the fill factor(=l/p), the ratio of element width to element pitch, p. Hence, with an array of N elements forming an A-line, the total signal (given that the relevant delays are applied), V_T is given by

$$V_T = \frac{N \cdot V_t}{1 + \frac{C_a}{C_x \cdot r \cdot p}} \quad (3)$$

And assuming that the noise is uncorrelated between transducer elements, the total noise, N_T is given by

$$N_T = \sqrt{N} \cdot V_n \quad (4)$$

Now assuming that a particular length, L, of PVdF is divided up into an array, the ideal number of elements to divide the array into can be determined. Rewriting N=L/p, the signal to noise of a reconstructed A-line, S_T (from equations (3) and (4)), is given by V_T/N_T:

$$S_T = \frac{V_t \cdot \sqrt{\frac{L}{p}}}{V_n} \cdot \frac{1}{1 + \frac{C_a}{C_x \cdot r \cdot p}} \quad (5)$$

Maximising S_T with respect to p, yields after differentiation:

$$p = \frac{C_a}{C_x \cdot r} \quad (6)$$

This simply says that the optimum signal to noise ratio is attained when transducer element capacitance is equal to that of the amplifier capacitance. A good operational amplifier will have an input capacitance of 1.5pF. For PVDF film as detailed above, C_x=13pF.mm^{-1}. Taking the transducer fill factor at r=0.8, the ideal element pitch is then 145µm.

The function in equation (5) is plotted in Figure 4 with op-amp and PVdF parameters as before, with pitch as a variable.

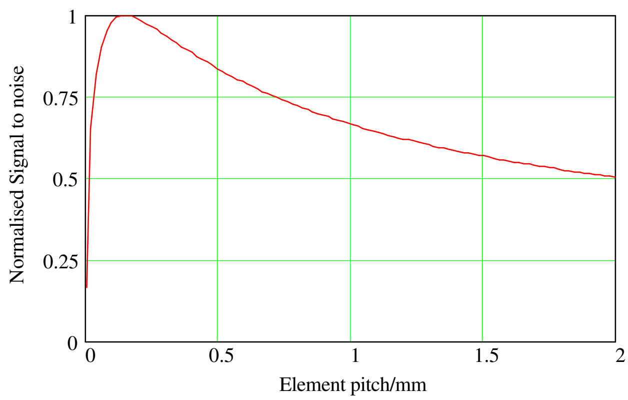

Figure 4. Signal to noise variation with element pitch (from equation (5)).

Cross-Coupling

A facet of using very high impedance sources (such as small PVdF transducers), is that they can be very susceptible to cross-coupling. The impedance from between transducer elements can easily, with inappropriate design, become of the same order as the impedance of a transducer element relative to the measurement reference (ground). This effect can be modelled using the same theory as applied to microstrip lines [10]. A measure of cross-talk can be discerned by plotting the ratio of inter-element capacitance cross-talk to that of element capacitance as shown in Figure 5. The parameters used are as above, with again a fill factor of 0.8.

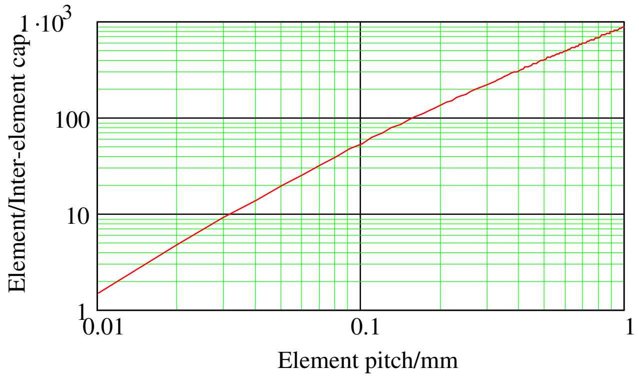

Figure 5. Ratio of transducer element capacitance to that of inter-element capacitance

A low level of cross-coupling, where coupling is less than –40dB between elements, requires an elemental pitch of greater than 150µm.

However, a greater degree of cross-coupling potentially exists away from the sensing area. With pre-poled PVdF film, the active area is constrained by the overlap of the top and bottom electrodes. In this region, electrical cross-coupling is minimal due to the effect of the ground plane. Where there is no overlap, the electric field around an active electrode is much more unconstrained, and cross-coupling can occur. To reduce this effect for a prototype array, ground lines have been placed between conductors on non-active areas of the film as shown in Figure 6. Transducer elements have been made larger than the required 150µm for the prototype since additional capacitance is added by protection diodes and interconnects.

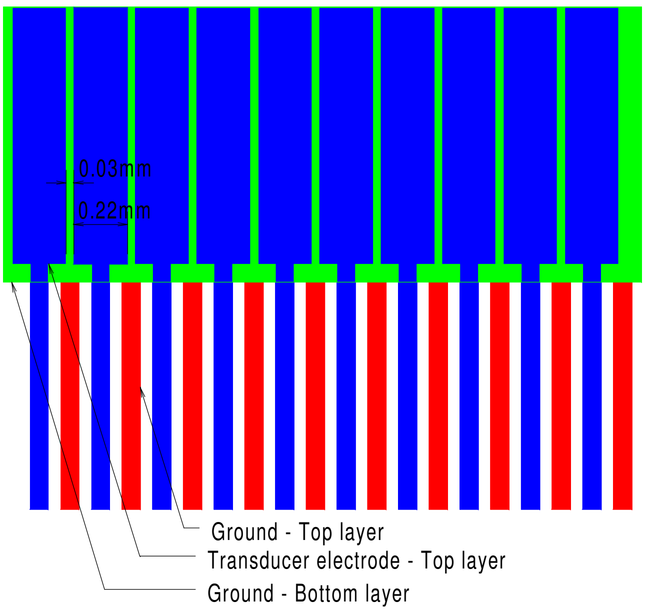

Figure 6. Prototype electrode pattern

Conclusions

An optimum element size has been determined for a PVdF transducer given parameters for the amplifier to which the element is connected. Below a certain element size, the signal-to-noise ratio of a reconstructed A-line is shown to decrease when transducer capacitance is less than that of the amplifier to which it is connected. This in turn places restrictions on the protection schemes that can reasonably be employed. For the reasons of optimisation of signal to noise ratio, and the minimisation of inter-array element cross-talk, it is proposed that close-coupled amplification of ultrasound signals near to the transducer will be a requirement for successful system operation. As such, a customised high-density buffer array integrated circuit is being designed which can be wire bonded directly to the array elements.

Acknowledgments

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