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Improving the Bandwidth of Air Coupled Capacitive Ultrasonic Transducers Using Selective Networks

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Abstract— **One of the key limitations on using CUT (Capacitive Ultrasonic Transducers) and cMUTs (Capacitive Micromachined Ultrasonic Transducers) in air is their relatively narrow bandwidth which although superior to that of current piezoceramic devices could be improved. Most air coupled capacitive devices could benefit hugely through the use of selective networks for bandwidth expansion, resonance reinforcing, or a combination of both. This work has investigated the application of pole/zero manipulation techniques to modify and enhance the transmission characteristics of capacitive transducers through front end mounted components. The main objective was to positively enhance the performance characteristics of capacitive transducers.**

A modified electrical equivalent circuit for CUTs to include the selective networks used was developed. The work assessed the effects of a tuned amplifier on the passband of the devices studied and then focused on more complicated network designs for enhancement. Simulations of the effects of the networks on the devices using equivalent circuit models were carried out and the response curves to pulsed operation were calculated and compared to experimental measurements from a pair of fixed CUTs with a combined centre frequency of 280kHz and 3dB bandwidth of 160kHz.

Increases in centre frequency of 25% and 3dB bandwidth of 77% using a single tuned amplifier were obtained. Resonance reinforcing, resonance shifting and ripple suppression were also studied through the manipulation of the q factor and pole location of such an amplifier. Performance enhancements were studied for a number of CUT aperture sizes and membrane thicknesses and a comparative study of the theoretical and experimental effect of these variations was conducted. With the appropriately designed network, enhancement of peak resonance with a simultaneous bandwidth expansion was obtained at the expense of other operating parameters such as stopband ripple. Simulations of more complicated circuit designs using equivalent circuit models of capacitive devices showed that the maximum level of passband ripple observed for the bandwidth expansion method using a single tuned amplifier was reduced while achieving simultaneously the same 3dB results.

The implication for bandwidth expansion of a capacitive transducer through selective network design is significant, allowing increased resolution in imaging systems, ultrasonic ranging and non destructive evaluation. Significant improvements have been observed without additional signal manipulation, through digital means or otherwise, in certain transmission properties of the devices. Future work will expand on the enhancement of capacitive transducers through the use of hybrid resonator circuits and other related methods.

Keywords-Air Coupled Ultrasound, Resonator Circuits, Bandwidth Expansion, CUT

I. INTRODUCTION

Capacitive ultrasonic transducers (CUTs) [1-3] and capacitive micromachined ultrasonic transducers (cMUTs) [4-7] are well established technologies and are finding increasing application in medical and industrial measurement. Whilst their performance in air is generally superior to that of most piezoelectric devices, many CUT and cMUT designs are still highly resonant to increase their sensitivity. Hence, both air-coupled and immersion devices could benefit significantly by bandwidth and resonance modification through the use of selective networks. By manipulating the poles/zeroes of a resonator circuit consisting of front-end mounted components, the transmission characteristics can be modified to enhance transducer performance. One of the advantages for CUTs and cMUTs is that variations in transducer performance produced by any lack of repeatability in their manufacture may be reduced or even eliminated. For cMUTs, an additional advantage is that the selective network may be incorporated with the transducer on a suitable CMOS-compatible IC.

As such the use of front end mounted components in CUTs and cMUTs is not a new concept, filter networks have been tightly integrated into capacitive sensing and transmission devices by a number of groups. Among other methods flip chip bonding has been used to integrate cMUT arrays with ASIC designs. Resonator circuits are widely employed in EMRF (Electromagnetic Radio Frequency) transmission and receive systems including among others passive, cascode active and cascade active selective designs. Selective networks allow for maximising the excitation signal of a sensor off resonance [8], assuming that a physical limit of the sensor is not exceeded (dielectric strength, membrane stress, collapse force etc.). The frequency response of the sensor when viewed from outside the network is modified. Such conditioning comes at the expense of power consumption, phase distortion, non linearity and reduced SNR (signal to noise ratio) or some combination of these effects.

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The bandwidth of an ultrasonic system can most practically be defined as the transmission envelope of a transmitter/receiver pair. In air, a transmitter will typically be made highly resonant by design in order to maximise range or sensitivity, however a receiver should inherently have a wider bandwidth as the thinner membrane dominates the oscillations to a lesser extent. At close range, the additional transmit power afforded it by a resonant design is unnecessary and any extra bandwidth on the transmission end of such a system can have significant impact on the overall sensor resolution. The aim of this work is to demonstrate the use of selective networks in manipulating ultrasonic transducer resonant behaviour. Section II outlines the design procedure for front mounted components to facilitate such modification, Section III will describe the simulation data, Section IV will outline the experimental method, Section V will present the results from this preliminary work and Section VI will give conclusions from this work.

II. Network Design and Simulation

A. Masons Electrical Equivalent Model

A detailed explanation of the basic electrical equivalent model used can be found in [9]. In the electrical equivalent circuit the electroacoustic transformation factor (T), radiation impedance (R_r), dissipation impedance (R_d), mechanical inductance (L) and mechanical capacitance (C) are modeled as lumped element parameters. The transducer capacitance is modeled by C_0. In this work the circuit diagrams are shown with only the transmit equivalent circuit for simplicity however for the simulation and experimental results a combined system circuit was used for comparative analysis of the data.

B. Passive Amplifier

The first frequency selective network design explored was that of a simple LC tuned amplifier, this device operates reasonably within the kHz and MHz regions. This design of amplifier, although not highly selective in passive designs, facilitates both wide and small signal amplification, as it does not require any transistors, which must be conducting at all times. The voltage across the equivalent radiation resistance for the case of the LCR oscillator design chosen is governed by (1) where relevant symbols represent their counterparts in Fig. 1, the input voltage is denoted by V_i, the subscript x refers to the LCR oscillator values, and the subscript extension $_E$ denotes transformation across the electroacoustic equivalent transformer using the usual methods. The basic structure of the LCR resonator circuit is shown below in Fig. 1, for simplicity line matching and delay compensation circuitry are omitted:

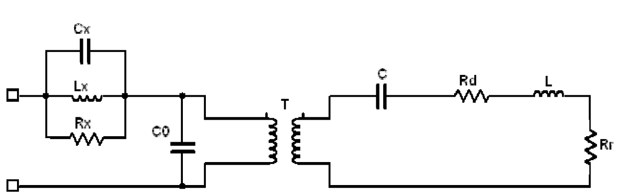

Figure 1: Basic LCR Equivalent Circuit

$$
\begin{aligned}
V_{R_{rE}} &= \frac{Z_R R_{rE}}{Z_R Z_M + Z_M S_{C_0} + 1} V_i \\
Z_R &= \frac{s/C_x}{s^2 + \frac{s}{C_x R_x} + \frac{1}{L_x C_x}} \\
Z_M &= sL_E + \frac{1}{sC_E} + R_{dE} + R_{rE} \\
S_{C_0} &= sC_0
\end{aligned}
\tag{1}
$$

As is evident from analysis of (1) appropriately choosing the selective network components will have an effect on the transfer function all the way up to the fifth order. The voltage across the electroacoustically transformed equivalent radiation resistance (V_{rE}) can then be related to pressure along the acoustic axis $p(r)$ at a distance r within air of density ρ_0 from a circular membrane of area S vibrating at a frequency f by

$$
p(r) = \frac{j\rho_0 f S V_{rE}}{r R_r} T , \tag{2}
$$

where $j = \sqrt{-1}$.

C. BJT Differential Design

To advance on the concept of a LCR resonator design a more sophisticated BJT (Bipolar Junction Transistor) common collector common base cascade tuned amplifier design was developed. This amplifier design has a number of advantages such as immunity to the Miller effect [10] as well as being suitable for implementation in BiCMOS wafer as the differential structure is suitable to common biasing techniques. The basic structure of this design including the Wilson current mirror used for biasing is shown in Fig. 2. Although this design is not suited to wide signal amplification due to the dependence of the active elements on the upper rail it provides advantages in terms of skirt selectivity and source isolation.

The voltage across the equivalent radiation resistance transferred to the electrical domain through the electroacoustic

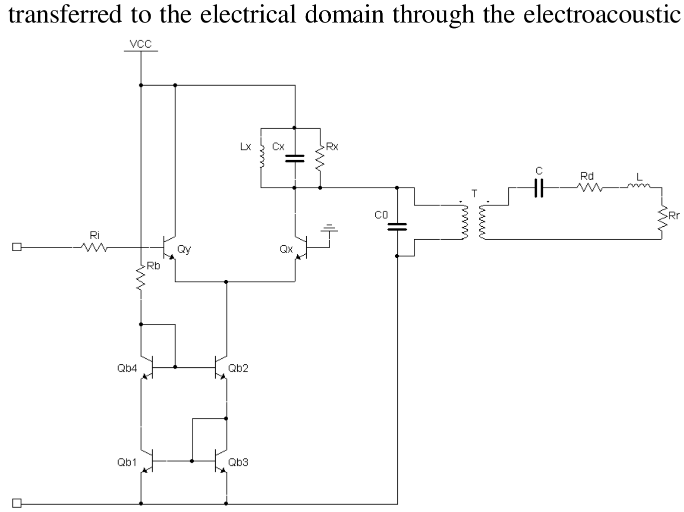

Figure 2: BJT Differential Amplifier

transformation as described in [9] for may be given by

$$V_{R_{rE}} = G_{CUT}\left(V_{CC} - \frac{s/C_x}{s^2 + s\ 1/R_xC_x + 1/L_xC_x}\left(I - \frac{g_m \upsilon_i r_\pi}{R_i - r_\pi}\right)\right), \qquad (3)$$

where G_{CUT} is the CUT equivalent circuit transfer function, υ_i is the small signal input voltage, g_m is the transconductance of the matched BJTs, r_π is the base to emitter resistance of the BJTs, L_x, C_x, R_x and V_{cc} are as shown in Fig. 2 and the biasing current I supplied by the Wilson current mirror may be given by:

$$I = \left(\frac{V_{cc} - 2V_{BE_{Qb3}}}{R_b}\right)\exp\left(\frac{V_{BE_{Qb3}} - V_{BE_{Qb4}}}{V_t}\right). \qquad (4)$$

III. SIMULATION

A. Passive Amplifier

Using the equivalent circuit as described in Section I a simulation result for bandwidth modification for the chosen samples which are a pair of roughened backplate CUTs with a transmitter capacitance of 651pF, a receiver capacitance of 250pF, and a film thickness of 5um PET can be seen in Fig. 3. The peak resonance of the combined transmission envelope of the unmodified system is 220kHz. The 3dB bandwidth is 165kHz with a centre frequency at 273kHz. The 75% modification case produces the best results which are a 3dB bandwidth of 311kHz and a centre frequency of 335kHz. One feature of note is the sharp rolloff in the high frequency cutoff region which is intended to demonstrate that such manipulation can easily be achieved. The correlation of these simulation results with the experimental data will be discussed in Section V.

B. BJT Differential Amplifier

The active results presented in this work seek to produce off resonance peaks in order to demonstrate the ability of selective networks not only to expand bandwidth through boosting off resonance signals but also to modify the properties of a CUT as seen by the transmit network from a broadband device to a highly selective device at a frequency determined by the selective network. Simulation results for the manipulation of

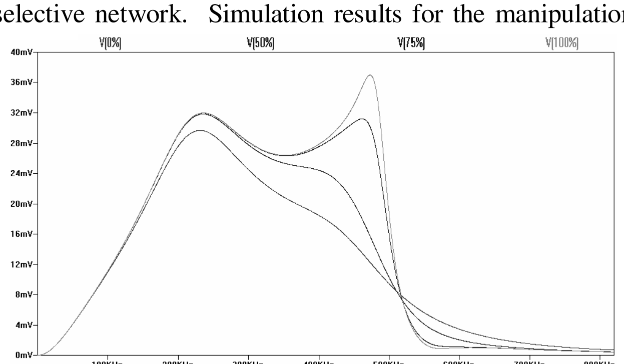

Figure 3: Simulation Results for Passive Design

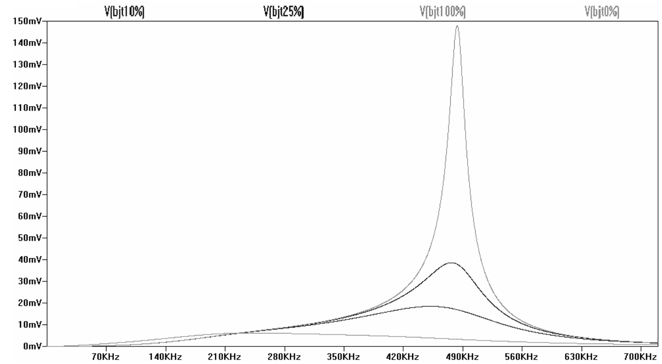

Figure 4: Simulation Results for BJT Differential Design

the envelope of the system using the BJT based differential amplifier design can be seen in Fig. 4. It should be noted that the BJT design assessed will attenuate the transmission envelope off resonance of the BJT differential amplifier which can be seen with reference to Fig. 3. This however is not a concern for this work as the objective of this design is not bandwidth expansion but amplification at a particular frequency.

Significant manipulation of the transmission envelope can be achieved including a large degree of control over the *q* factor, gain and resonance. The degree of allowable manipulation of these parameters is dependant on the physical limits of the CUT itself.

IV. EXPERIMENTAL METHOD

The experimental system constructed to test the various configurations of the selective networks designed is shown in Fig. 5. The Panametrics 500PR pulser (Panametrics, Waltham, MA) was set to pulse at an appropriately low repetition rate so as to avoid overlap of signals. Pulse height was determined by the tolerance levels of the components of the selective network and capabilities of the pulser. After passing through an air gap of 15mm the waveform detected by a capacitive ultrasonic receiver was amplified using a Cooknell CA6/C charge sensitive amplifier (Cooknell Electronics Ltd, Dorset, UK) and digitized. Both transducers were biased using 100V. The received waveform was then Fourier transformed in MATLAB® (The Mathworks Inc. Natick, MA), on the workstation PC which captured a triggered window of the digitized waveform from a Tektronix TDS210 100MHz digital oscilloscope (Tektronix Inc., Beaverton, OR) via a GPIB interface.

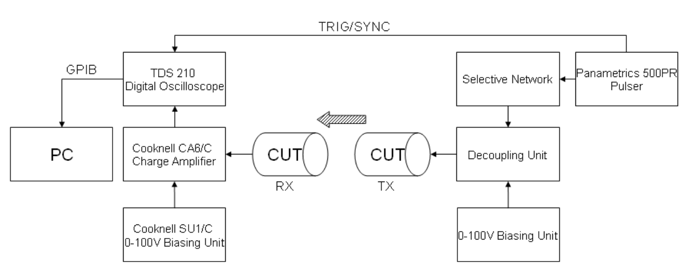

Figure 5: Experimental Layout

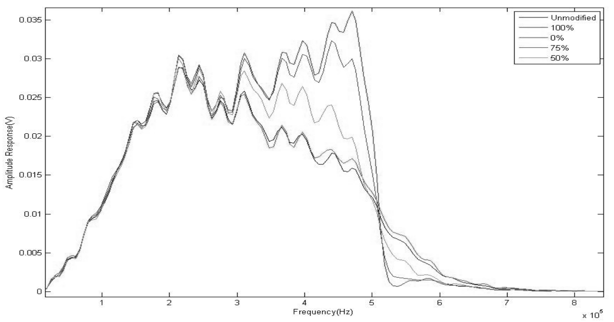

Figure 6: Passive Amplifier Experimental Data

V. Results

A. Passive Amplifier

The experimental results obtained for this configuration using the setup as described in Section III can be seen in Fig. 6 where the legend denotes the level of resistance as a percentage of total (10kΩ). These results depict the changing selective resistance (R_x) for an inductance (L_x) of 40uH and a capacitance (C_x) of 2nF. The manipulation of the transmission envelope bandwidth is clearly observable. It can be seen from Fig. 6 that the centre frequency of the transmission envelope has increased by 25% from 280kHz to 349kHz, and that the 3dB bandwidth has increased by 77% from 160kHz to 284kHz. The experimental results also closely correlate with the simulated data in that a sharp rolloff is obtained at the upper cutoff region.

It should be noted that adjustment of the resistance will primarily modify the gain and *q* factor of the selective network which may be observed from (1) and as such an amplification of the original resonance will occur at a critical balance point that is easily deducible. The inability of the equivalent circuit model to predict the local fluctuations across the passband (i.e. passband ripple) is noteworthy but does not affect the model's ability to predict the overall trend in the transmission envelope. The reason for this fluctuation is most likely a statistically non-Gaussian distribution of surface roughness.

B. BJT Differential Amplifier

Results obtained for the BJT differential amplifier design obtained using the experimental setup as described in Section IV for the values simulated in Section III can be seen in Fig. 7

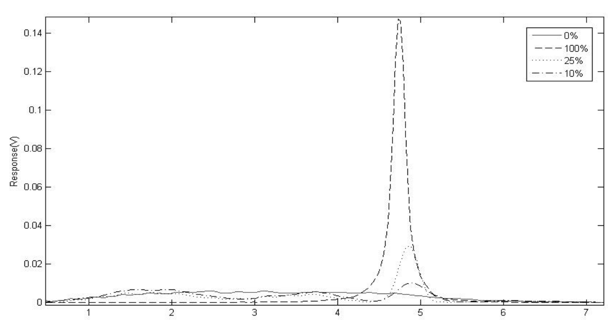

Figure 7: BJT Differential Experimental Data

below. It is evident from these results that the experimental data closely correlates with the simulated data and that selective networks can be used not only for bandwidth expansion but also to create highly resonant transmitters. Traditionally, the resonant frequency must be manufactured into the physical geometry of a CUT or cMUT; the techniques described here allow the resonant characteristics of a CUT or cMUT to be selected after the manufacture of the transducer, allowing application specific selective frequency tuning, bandwidth extension and sensitivity enhancement. As can be seen in Fig. 7, a peak response of approximately 150mV is obtained which is a response increase of 18dB in the system relative to the original envelope before the insertion of any differential amplifier as shown in Fig. 6.

VI. Conclusions

It has been shown that the bandwidth, skirt selectivity and resonant behavior of a CUT can be modified significantly through the use of selective networks placed close to the transducer in an electrical sense. Increases in centre frequency of 25% and 3dB bandwidth of 77% using a single tuned passive selective network were demonstrated and response increase of 18dB off resonance using an active selective network were demonstrated. With the appropriate use of a selective network a generic CUT mechanical design can be tailored for a large number of applications within the limits of the device.

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