Electromagnetic Excitation of Acoustic Biosensors

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***Abstract*—One of the problems associated with the acoustic biosensor format, is the isolation of the electrical connections, from the liquid test sample. In this paper, we describe our search for an electromagnetic coupling solution, how we modified it for acoustic biosensors, and some of the physical characteristics that we did not anticipate: We began by reviewing the formal descriptions of electromagnetically induced acoustic produced by solid-state physicists of the 1960s, to help understand electronic properties. Over the past decade, our group has modified this electromagnetic geometry to increase signal levels, operating frequency and resolution. Our focus was to prepare a simple non-contact acoustic device that could emulate the functionality of traditional Surface Acoustic Wave and Quartz Crystal Microbalance sensors. The result was a simple non-contact acoustic device with high signal performance, and low cost. It also supported superior bandwidth, so interfacial acoustic spectroscopy could be performed, and enhanced coherence obtained for broken chips of quartz. We conclude that non-contact approaches increase the value of acoustic biosensors.**

I. INTRODUCTION

There are two types of acoustic biosensor that are already established: The first, quartz crystal resonators, appeared when Cady constructed a stable quartz oscillator in the 1930s [1]. It was fabricated by depositing metal electrodes onto a single crystal plate and applying an RF potential to instigate acoustic standing waves in the crystal. Since then, many QCM systems allied to different biological recognition layers have been evaluated. For example, protein A was used capture IgG antibodies at concentrations in the range of 1-10,000 µg/ml onto the QCM [2]. Similarly, S. Typhimurium cells could be captured onto a device and detected at concentrations between 10^5 to 10^9 cells/ml. Also, the detection of HIV detection via a 20 MHz AT crystal has been ob obtained by Koblinger et al., 1991 [3]. There are many recent examples that continue this theme.

The second, acoustic waveguides, depend on interdigitated transducers attached to a piezoelectric plate to couple sound efficiently into the waveguide. Martin and Ricco introduced one of the first acoustic plate mode viscosity sensor using this format [4]. Similarly, White was experimenting with thin SiN waveguides that could carry Lamb wave radiation [5]. As both waves could propagate in contact with liquids, they were potentially useful for biosensor applications. Since then, these waveguide structures have been used widely, including Andle [6] for the APM detection of DNA, and by Gizeli as a Love wave IgG, and protein A immunosensor [8].

Clearly contact transducers are needed for these acoustic biosensor devices to function correctly. If piezoelectric substrates are used, which is likely to be the case, then wires must be attached to metal electrodes, that contact the acoustic element. For the quartz crystal resonator, simple electrodes form the contact transducer. These bulk wave transducers, as they are also known, are used widely. Although there are many shapes and dimensions of electrode, it is likely to comprise a solid metal pattern on discs 10-15 millimetres in diameter, with a range of thickness from 100 µm to 500 µm. Normally opposite sides of the disc are metallized, crystal and wired to a voltage source of radio frequency energy, to stimulate acoustic resonances. The benefit of this form is its simplicity. In contrast, acoustic waveguides need micron sized electrode features in its contact transducer. It was conceived by White and Voltmer [9] to process electrical signals, rather than make acoustic sensors. This interdigitated electrode form has fingers that are spaced several microns apart, to control the operation frequency. Two of these electrode forms are needed to transmit and receive the acoustic wave. In conclusion, their main attributes are an extremely high operating frequency, transduction efficiency, and facility to tailor the acoustic spectrum. White has written a comprehensive text on the subject [10]. In summary, contact electrode forms are used to make acoustic devices that function in the dry conditions of radios, mobile phone and TV sets.

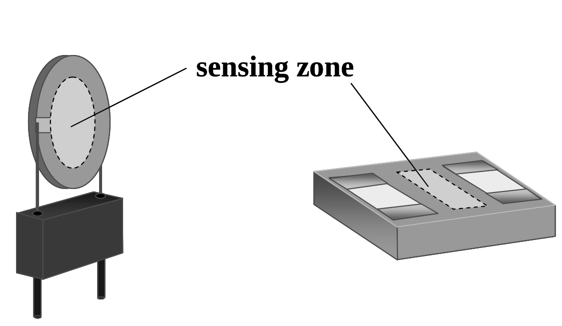

Figure 1. Biosensors based on (1) quartz resonators and (2) waveguides respectively.

When acoustic biosensors are made from these contact transducers, several practical problems arise. The primary problem is that biosensors work in a liquid environment. And contact transducers work in an air environment. So they can easily short out and fail. In response, considerable engineering is needed to work around this problem, involving o-rings and other plastic and metal components. Figure 2 shows how complex the maintenance systems need to be, so that wet chemistry can be located on dry electronic components. This problem motivated us to search for non – contact transducers, where the electrode is swapped for an antenna, isolated from the problems of the chemisty.

Figure 2. A typical operating environment for an acoustic wave biosensor.

II. ELECTROMAGNETIC INDUCTION OF SOUND

A. *Theory*

The method we used to support this non-contact transducer function is based on the magnetic direct generation (MDG) principle. This can be traced back to the first evidence of interactions between electromagnetic and acoustic waves arose in 1939 when Randal was studying the internal friction of rods at sound frequencies [11]. He found unusual results that he explained qualitatively as a reaction of the magnetic field on the eddy current induced by the electromagnetic field.

In the 1960's, the theory of the low temperature of the behaviour of the electron gas in metal plates was developed, to form a better understanding of the phenomena. At the time, the theoretical behaviour of free electrons was of great interest: Solid state physics suggested that the free electron gas of a conductive material could collide impart momentum to a uniform background of positively charged ions. At the time there was strong evidence for electrons making classical ball like collisions with the ions of the lattice. On this basis Alpher and Rubin [12]and later Harrison [13], began to predict the main features of this phenomenon, however they prepared simplified models that ignored the collisions of the conduction electrons with lattice imperfections, such as thermal phonons, impurity atoms and others. The main turning point arose when Sergio Rodriguez began work on a new microscopic model [14]. The purpose of this theoretical work was to predict the change in the velocity of sound in relation to the intensity of an applied DC magnetic field. In reality this prediction was found to be very successful, however there were other unrecognised results that had significant implications for electromagnetic and acoustic interactions. These were connected with electrons moving the lattice.

Rodriguez began his microscopic analysis by expressing the relationship between the motion of an individual ion and the elastic restoring forces applied to this ion. This is popularly known as the collision drag model. This is given by Equation 1.

$$\ddot{u} = -\gamma\dot{u} - s_t^2 \nabla x\left(\nabla x u\right) + s_1^2 \nabla\left(\nabla \cdot u\right) + F/\rho \qquad (1)$$

where $\ddot{u}$ is the acceleration of particle motion, γ is the phenomenological damping factor, $\ddot{u}$ is the velocity of particle motion, s_t is the transverse wave velocity, s_l is the longitudinal wave velocity and F is the force density on the lattice. F is the interesting feature of this equation as it expresses the force imparted on the lattice due to the collision of electrons.. Rodriguez had to be able to express this microscopic force in a fully expanded form, introducing what is known as the phenomenological time constant; the average time between two successive collisions of one electron. This is denoted by Equation 2.

$$F = n_0 e\left(E + \frac{1}{c}\dot{u} x B_0\right) + \frac{n_0 m}{\tau}\left(< v > - \dot{u}\right) \qquad (2)$$

where n_0 is the electron density, e is the electron charge, E is the electric field of the electromagnetic wave, c is the speed of light, B_0 is the applied DC magnetic field, m is the mass of an electron, τ is the single electron-lattice collision time, $< v >$ is the average velocity before collision of the electron in the lab frame of reference and $\dot{u}$ is the velocity of the electron after collision. The left-hand side of the expression indicates that the electron imparts a force on the lattice due to the local electric and magnetic field. The right hand side of the expression indicates the force which is a direct consequence of repeated electron collisions over period τ. To produce a complete set of coupled equations relating the electrons and the lattice, Rodriguez had to connect the electron current density to the local electric field. After applying transport theory he was able to produce the desired expression, Equation 3.

$$j_{el} = \sigma \cdot \left(E + \frac{mu}{e\tau}\right) - e\sigma \cdot \frac{n_0 qq \cdot u}{e^2 g(\zeta_0)\,(1 + i\omega\tau)} \qquad (3)$$

where σ is the electrical conductivity, q is the acoustic wave vector, j_{el} is the electron current. $g(\zeta_0) = (3n_0/2\zeta_0)$g is the density of electron states per unit volume, per unit energy range while ζ_0 is the equilibrium value of the chemical potential. This expression for the first time demonstrated that the electron current is derived from three different causes: The first is simply the electric field acting directly on the electron motion, the second is more intriguing and results from the scattered residual drift of the electrons, while the final contributor is the modulation of the electron Fermi level due to the dilation and contraction of the lattice. This covers all relevant interactions. Rodriguez then goes on to describe how the variation of sound velocity with the applied magnetic field, can be accurately predicted with his theory. Overall his paper merely reflects the link between the free electrons and the ions of the lattice; both are intimately coupled.

Similarly, the theoretical behaviour of electrons moving in helical paths was of great interest. At superconducting temperatures within a few degrees of absolute zero, the electron gas, subject to an applied magnetic field, support this helical wave or helicon. It arises because any electrons that have a forward velocity are forced to move in helical paths around the magnetic lines of force. In the 1960's these waves were of great interest due to their effect on the metal lattice. It particular it seemed that the specific frequencies of the helicon would transfer energy to an acoustic wave, therefore supporting a mechanism for electromagnetic-acoustic interaction. In order to characterise the interaction frequencies, Quinn and Rodriguez embarked on a detailed analysis of the Eigen--frequencies of the system [15]. This related the mutual electromagnetic interactions of motive ions and electrons. The surprising aspect of this work was that the essence of the theoretical treatment also described an entirely new interaction mechanism that had nothing to do with the helicon.

B. Discovery of Magnetic Direct Generation

The first indication of a new electromagnetic-acoustic interaction mechanism was provided by Houck, who provided extremely strong evidence that acoustic waves could be produced without the propagation of Helicons [17]. This was supported by Saermark [16] who had also come to the same conclusion. The first experimental evidence that this newly discovered interaction effect also occurred at room temperature was provided firstly by Betjemann et al. [18] and then by Gaerttner et al. [20]. Later Gaerttner verified that the effect was related to excitation of surface plasmons responsible for the skin depth of the metals. He went on to describe the new interaction mechanism as a consequence of magnetic body forces acting on the skin depth of the metal and described this as "Magnetic Direct Generation" The connection with the earlier 1963 theory of Quinn was that the low temperature helicon system could be labelled by the product of the electron mean free path l and the acoustic shear vector q. Likewise magnetic direct generation could also be labelled by ql product. Gaerttner and Quinn went further than mere association by labelling the helicon system as ql>>1 (non local) and the magnetic direct system as ql<<1 (local), indicating the two mechanisms were essentially part of the same physical construct.

Abeles (1967) performed experiments with helicons. He used a thin 2500Å film of indium on the end of a germanium rod. The operating frequency was 9.3 GHz where the electron mean free path is larger than the microwave penetration depth and the phonon wave number. Applying a 10 Watt 1 µs pulse to the film produced a signal at a conversion efficiency of 3 10-12, which corresponded to a shear thickness resonance of the film. The low efficiency and extreme conditions of excitation removed any likelihood of practical application arising from this electromagnetic-acoustic coupling phenomenon. In the same year, Saermark and Larsen [16] used disc-shaped samples of monocrystalline aluminium to generate higher efficiency helicons; however, at certain frequencies he observed complicated traces of RF amplitude versus magnetic field strength. The reasons he suggested for the effect were unrelated to helicons. The enigma, therefore, remained: The helicon phase velocity did not coincide with the acoustic velocity and yet there was conclusive evidence of shear wave generation. Houck [17] confirmed a new electromagnetic-acoustic coupling mechanism had been discovered. He provided conclusive experimental evidence for this new electromagnetic-acoustic coupling mechanism - magnetic direct generation - by designing an experiment around a coil driven by a 10-40MHz electromagnetic source, a 3 cm quartz delay rod and an AC cut quartz transducer. The coil was used to excite the shear waves while the quartz transducer was used to detect the same waves, all at 4.2K.

Operation at room temperature was the surprising discovery of Betjemann [18]. However, independently Russian researchers Mikhailov and Shutilov, had already verfied room temperature electromagnetic generation and had begun measurements of acoustic velocity [19]. Back in the West, significant contributions from a number of theorists; Rodriguez, Quinn, and Merideth established a solid foundation to electromagnetic-acoustic coupling via magnetic direct generation in metals, semi-metals and semiconductors, based on the scattering between the electron gas and the ions of the metal lattice.

Practical work on magnetic direct generation appeared when Gaerttner et al. [20] used flat-sided coils to generate waves over a wide range of temperatures and frequencies. Using a pulse-echo technique and frequencies up to 100MHz, he was able to generate acoustic waves and measure transmission variations due to temperature and frequency. This validated the theoretical model. The most useful aspect of this data was the treatment of the efficiency of low and high temperature coupling mechanisms, which were treated separately, and in great detail. Finally, the elucidation of the acoustic body forces appearing in the skin depth of the metal allowed a more confident prediction of the performance of the electromagnetic system, particularly at high operating frequencies. The second major contributor of this decade was Gordon and Seidal [21] who studied the standing wave resonances that can occur in metal plates. In summary, electromagnetic waves could be used to create acoustic waves without piezoelectricity, and without contact to the resonator..

C. Single wire MDG

To better quantify the magnetic direct mechanism, an idealised system consisting of a metal surface, a magnet and a single wire electrode has been widely analysed by Gaerttner; Gordon and Seidal; Dobbs and others. Their analysis begins with a consideration of eddy currents in the metal surface due to the radiated electromagnetic field from the electrode. This is relatively straightforward to derive and in essence gives an exponentially decaying eddy current, from the metal surface closest to the electrode to the interior of the metal. This depth distribution of the eddy current is given by Equation 4:

$$J(z) = \hat{x}\frac{(1+i)}{\delta}\frac{ch_0}{4\pi}\exp\left(\frac{(1+i)z}{\delta} + i\omega\tau\right) \quad (4)$$

where $J(z)$ is the variation of current density in the metal as a function of the normal separation from the metal surface, $\hat{x}$ is the unit vector parallel to $J(z)$, δ is the classical skin depth $(2/\omega\mu\sigma)^{1/2}$, c is the speed of light, h_0 is the amplitude of the ac magnetic field (from the electromagnetic wave) while z is the surface normal. This equation is particularly important, as it defines the region of the metal surface that feels the magnetic body forces and consequently excites acoustic waves. The thickness of this region at a point of the surface maximum depends on the frequency of the source, which is around 25 µm for a silver surface, excited by a 10MHz electromagnetic wave. To progress further it is necessary to calculate the magnitude of the sideways force felt by the electrons in this region. This force is known as the Lorentz force, which is proportional to the current in the electrode and the applied magnetic field and is given by Equation 5:

$$F(z) = \frac{J(z)}{c} \times \left(B_0 + \hat{y}h_0 e^{i\omega\tau}\right) \quad (5)$$

where F(z) is the Lorentz force perpendicular to $J(z)$ and B_0, and y is the unit vector perpendicular to $J(z)$. Figure 3 illustrates the directions of these components. The magnetic component of the electromagnetic field is normally far smaller than B_0, therefore the right hand term can be neglected.. At this point Rodriguez's collision drag model is able to provide an essential perspective to understanding the excitation problem. The fact that the electrons feels a sideways force is not unusual, according to the Lorentz force mechanism, however what is remarkable is the transference of all of the free electronic force to the ions on the lattice. Therefore assuming the background magnetic field is present, the lattice becomes effectively driven by the electrodes electromagnetic field. From this point the remainder of the problem is straightforward. It consists of solving the equation of motion for the ions of the metal surface, under the driving force of the electromagnetically derived Lorentz force. This is shown to be

$$\rho\frac{\delta^2 u}{\delta t^2} - C\frac{\delta^2 u}{\delta z^2} = F(z) \quad (6)$$

where ρ is the metal density, u is the lattice ion displacement, C is the elastic modulus, z is the surface normal and $F(z)$ is the variation of the surface force with depth z, where this is a shear horizontal force derived from a surface perpendicular magnetic field. To obtain a solution the mechanical conditions of the boundary must be incorporated. Based on the assumption that the surface of the metal is free to vibrate, the solution can be determined to be

$$u(z) = i\frac{K_{sd} \times B_0}{c\rho s\omega}\frac{1}{(1-i\beta)}\left(e^{iqz} + (i\beta)^{1/2}\exp\left(\frac{(1+i)}{\delta}z\right)\right) \quad (7)$$

where $u(z)$ is the lattice ion displacement as a function of depth into the metal surface, K_{sd} is the integrated skin depth current $= ch_0/4\pi$, B_0 is the DC magnetic field, c is the shear

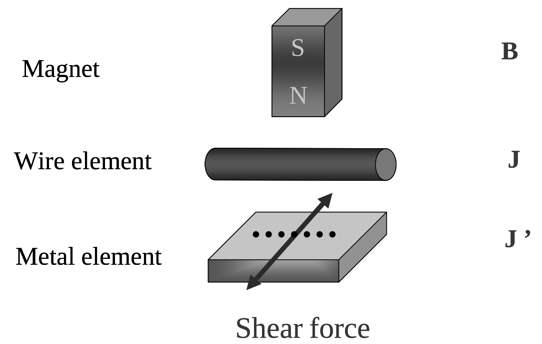

Figure 3. A typical operating environment for an acoustic wave.

elastic constant, ρ is the metal density, s is the acoustic velocity $(c/\rho)^{1/2}$, β is $0.5q^2\delta^2$ and the acoustic wave number $q = \omega/s$.. This equation relates the shear amplitude of the free surface, which is less than angstroms, to the essential variables such as the magnetic field, the excitation frequency, the current in the skin depth and the mechanical properties of the metal surface concerned. This explains why the Low density metals such as aluminium, tungsten and the anomalous, but highly toxic beryllium yield the largest amplitudes and also why large magnetic fields and currents also increase the shear amplitude. What is slightly misleading is the frequency dependency, which in terms of amplitude appears to fall off with the reciprocal of the frequency. As the frequency of operation has a considerable importance for sensor applications, it is worthwhile clarifying the nature of this frequency dependency:

In essence we are interested in the conversion efficiency, i.e. the power contained in the radiated acoustic wave relative to the power contained in the electromagnetic wave. The power contained in a plane polarised electromagnetic wave incident normally on the metal surface is denoted by Equation 8 and the power in the acoustic wave by Equation 9.

$$P_{em} = \frac{ch_0}{32\pi} \quad (8)$$

$$P_a = \frac{1}{2}\rho s\omega^2|u|^2 \quad (9)$$

Dividing these and combining with Equation 7, the conversion efficiency indicated by Equation 10 is obtained.

$$\eta = \frac{4}{\pi}\frac{B_0^2}{c\rho s}\left(\frac{1}{1+\beta^2}\right) \quad (10)$$

If β <<1 then the conversion efficiency is clearly independent of frequency, however there is an important physical condition which can limit the frequency of operation. This special condition is denoted values of β close to unity or greater. It occurs when acoustic wavelengths are similar to the eddy current penetration depth. In aluminium this occurs at 70 MHz and for tungsten at around 30 MHz. Fortunately these higher frequencies are not prohibitive to magnetic direct generation, only indicative of reduced electromagnetic efficiency.

III. ELECTROMAGNETIC ACOUSTIC TRANSDUCERS (EMATS)

Several non-contact transducer variants can be formed once single wire generation is understood:

(i) Spiral

The simplest is based on a spiral of metal wire, that can excite shear acoustic bulk waves [22]. This spiral is formed on a flat surface, so an electrical connection can be made to the centre and to the outer edge of the spiral. This configuration was evaluated by B. Maxfield who measured the displacement of a metal surface, by positioning a 2 x 2 x 1 mm rectangular coil along its edge. He claimed the shear displacement of a metal surface placed proximal to the coil was cylindrically symmetric to within a 5% accuracy, with propagation into the metal, normal to the surface. However a problem with asymmetry was noted. This was connected with the position of the magnet and the generation of unwanted longitudinal acoustic modes. He summarised the transducer as operating like a transformer providing a perfect mechanical match to the metal. Since then this transducer has been found to exhibit excellent efficiency and a substantial bandwidth.

(ii) Meander line

The meander line coil can direct shear vertical acoustic radiation along a metal surface [23]. It consists of a metal track or wire that is patterned on a rectangular substrate as a kind of compressed square wave (Figure 1.12). The ends of the square wave, form the terminals of the transducer. This serpentined coil can be used to generate Lamb waves or angle beam plate waves [24]. For wavelengths shorter than the periodicity of the pattern, both shear vertical and longitudinal waves are generated, however this depends on the direction of the magnetic field. Other modes can be generated by electronically firing the elements [25], which enhances the directionality of the radiation and its dispersion characteristics, however this is not normally applied because of the significant complexity required. In its plain form its major advantage is the generation of surface modes with a relatively simple electrode, however the main difficulty is the need for the electrode and sample, to be awkwardly close for higher operating frequencies.

(iii) Meander Line plus tape

The disadvantage often levelled at the electromagnetic transducer is the need for a metal surface in which transduction can occur. Generation on insulating materials was simply not possible. A shortcut for satisfying this need, although not wholly satisfactory involved adhering metal tape to a given insulation surface ([26]. Using the meander electrode described above, shear vertical Rayleigh waves were generated. Typical loss factors of 113 dB were found for copper metal tape stuck to glass and 101 dB for aluminium metal tape stuck to glass. This compares to losses of 90 dB for a pure aluminium block. In addition signal shaping could be performed by altering the shape of the metal tape from a diamond to a rectangle. Ultimately this line of work never progresses because of the 1 MHz frequency limitations and because of possible adhesion variability, destroying the key reason for employing such a transducer in the first place.

(iv) Periodic Permanent Magnet (PPM)

In the field of non destructive test, the most useful transducers generate shear horizontal waves, as these tend to reflect more strongly off microstructural discontinuities. With this in mind the periodic permanent magnet transducer was designed and constructed, with a very reasonable transfer impedance of 35.3μΩ [27]. It was constructed from a line of 6 samarium cobalt magnets, placed side to side with opposite polarities. Wire would then be wound along the line passing over the top surface, then back over the lower surface, until on the order of 20 to 80 windings were complete. The surface shear mode generated from this transducer was simply not possible with the piezo-transducer. It is noted for its particularly clean ultrasonic response which improves interpretation of reflected waves, plus its ability to steer the wave in any direction with the same strength.

(v) Twin Magnet

The main disadvantage of the periodic permanent magnet was the need for the awkward assembly of many magnet poles all alternating along its length. A new configuration to avoid many magnets arose by using a very novel two layer periodic electrode assembly, peculiar only to this transducer [28]. Tests of shear horizontal wave generation in a thin aluminium plate, however, revealed a significant disadvantage of this approach. The efficiency of this electrode was only one twentieth of the efficiency of the meanderline. This corresponds to transfer impedances of 0.1μΩ compared to 2.0μΩ for the meanderline. This is due to the greater number of wire windings that are possible with the PPM but are impossible with the twin magnet transducer. Finally, the shape of the acoustic radiation was found to be distorted with respect to quantitative predictions. Nonetheless, this mode does retain the advantages of clean shear wave detection plus the ability to operate at higher operating frequencies.

All of the above Non-contact transducers can excite acoustic waves in a test object without resorting to any form of mechanical contact; a considerable practical advantage for sensing. Even with a vacuum between the transducer and the test sample, acoustic waves can still be generated. The need for these non-contact transducers first became apparent when workers with contact transducers noticed th at they often got inconsistent measurements due to the difficulty in repeating exactly the same contact between the transducer and the test sample. Often coupling agents such as grease are used to minimise this problem; however, this is inadequate at frequencies above 2-3 MHz because the bond region is thick enough to scatter the acoustic wave. Any pressure change then corrupts the measurements. In addition, the surface of the test sample is rarely flat or smooth, causing further variation relative to transducer position. Furthermore, wet and damp environments were found to cause operational difficulties.

Identify applicable sponsor/s here. *(sponsors)*

This is related to the need to make electrical contact to the transducer by wires and bonds, which can interfere physically and sometimes chemically with the sensing surface. This incompatibility can make implementation of liquid phase sensors based on contact transducers very difficult. There are a number of alternative techniques for generating acoustic waves that can address the disadvantages of contact transducers. These alternatives are reviewed below. Comprehensive coverage of all non-contact transducers is given in Szilard [29].

IV. EXPERIMENTAL

A. EMAT waveguides

To make a biosensor based on a non-contact transducer, initial tests were performed with a spiral coil emat and copper bar waveguide (Figure 4). The figure shows an acoustic transmitter illustrated consists of a timing circuit, a 5 MHz signal generator, a semiconductor switch, an amplifier, an electrical matching circuit, and, finally, a spiral electromagnetic transducer. The latter has further sub-components comprising a planar spiral electrode and an adjacent NdFeB magnet; these are also known more commonly as the EMAT or Electromagnetic Acoustic Transducer. Finally, at the opposite end of the bar, a second transducer was connected to a preamplifier and a digitising scope, forming the basic acoustic receiver. In operation, bulk acoustic waves were generated by the transmitter and passed down the longitudinal axis of the copper bar, taking a finite time to traverse the medium.

In this work, a pulsed signal was used to increase the signal levels as MDG, as reported by Maxfield [30]. However in our case, the resulting signal was dominated by a resonance signal across the width of the bar, instead of the desired waveguide mode. We analysed the wave periods and found the resonance frequency to be 293 kHz, indicating the wavelength in the copper bar is 7.75 mm for shear waves and 12.96 mm for longitudinal waves. As the bar is 3 cm in diameter the best fit suggests four shear wave periods across the bar width; suggesting the bar is 30.9 mm thick. In addition, the acoustic attenuation of the bar can be determined and

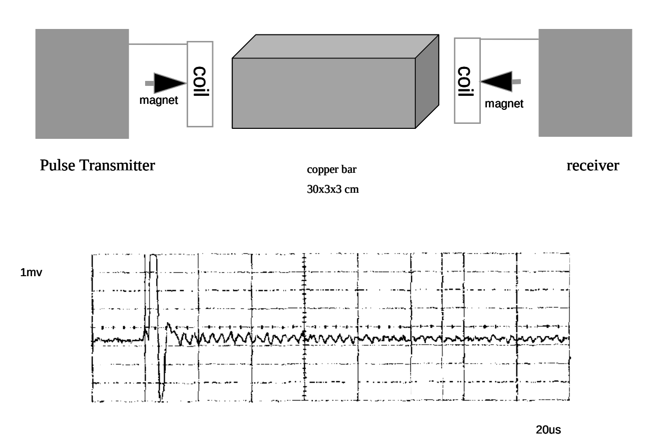

Figure 4. EMAT waveguide excitation of acoustic waves in a copper bar.

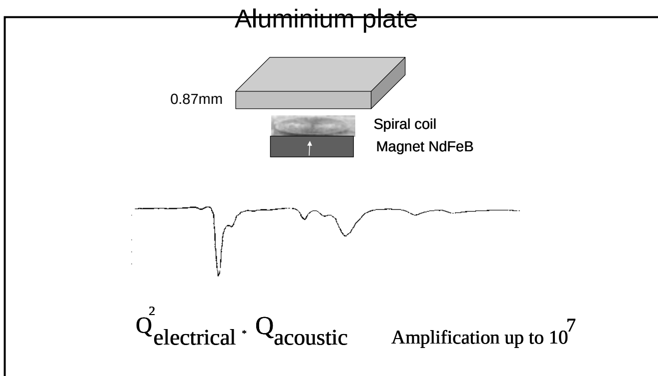

Figure 5. EMAT resonator for exciting an aluminium plate.

compared to literature values. As the time for the acoustic signal to decay to 1/e of its original amplitude is 160µS (20%) or 372 m; then the decay factor via is 1/372, corresponding to the literature value (CRC, 1977).

In summary, as the resonance signal was much greater, we proceeded to investigate EMAT resonance, based on the spiral coil..

B. EMAT resonators

To enhance the resonance signals it was decided to induce vibrations in aluminium plates with continuous waves, instead of using the conventional pulse waves approach mentioned earlier. The format of the new system that was used to excite and detect acoustic resonances in thin metal discs is illustrated in Figure 5. The components of the system are arranged as follows: First, the transmitter, which in this case is a signal generator (5-40 MHz range used), is connected to the electromagnetic transducer via some passive electrical components. The thin aluminium plate sample (0.87 x 10 x 10 mm) is positioned on top of the coil. In practise, the excitation and detection of acoustic resonances is achieved by sweeping the frequency of the signal generator around the acoustic resonance frequency, while monitoring the transducer impedance fluctuations on the oscilloscope. Under these conditions, acoustic resonance appears on the screen of the oscilloscope as as a sharp dip. A key difference of this geometry, is that the transmitter and receiver work through a single electromagnetic transducer. Also large pulse signals to compensate for EMAT losses are not used, as this requires bulky equipment and frequencies limited to the low MHz range. The key benefit of adopting this resonance approach is the storage of energy in the vibrating element, which amplifies the signal in proportion to the Q factor: This also amplifies the electromagnetic excitation, substantially. The gain is in proportion to the acoustic Q and the square of the electrical Q. This effect was discovered serendipidously with the copper and aluminium plate resonances, and is a crucial discovery for developing acoustic biosensors.

The reason for choosing the aluminium plates in this study is related to electrical and mechanical parameters. The primary electrical requirement for MDG is for the material to be a conductor ie a metal, preferably, with the highest conductivity possible.: Silver has the highest conductivity followed by copper, gold, aluminium and the rest. However when mechanical properties are included, the best materials have a low skin depth, a low acoustic impedance and a long acoustic wavelength is aluminium. More information on these parameters can be found in Kawashima's 1990 article.

As biosensors work best at the high MHz frequencies, there was interest in the upper frequency limit of the system. We tested five aluminium plate samples of different thicknesses to give acoustic resonances at 5.414 MHz, 8.544 MHz and 18.242 MHz, and found metals damp resonances and restrict operation to less than 10 MHz.:

V. MAGNETIC ACOUSTIC RESONATOR SENSOR (MARS)

A. *Pure acoustic resonator*

As effective acoustic biosensors would need higher operating frequencies than metals could provide, metal plates were exchanged for metallised silica discs. There are multiple advantages: First the amount of metal is reduced, so the vibrations are less damped, second the temperature coefficient of silica is much less than aluminium, and third silica is compatible with a wide range of chemical protocols. There is also a fortuitous partnership between silica and aluminium. The intrinsic acoustic impedance of silica from shear velocity times density, is 3764 x 2200=8.28 10^6, whilst for aluminium this product is 3040 x 2700=8.21 10^6. This similarity in acoustic impedance, means waves can traverse the silica-aluminium boundary with minimal reflection. However the main attraction is the higher Q factors that arise from low acoustic loss.

To assess the frequency response of the discs a number of silica discs 100 to 500 µm thick with coatings of 3 to 25 µm of aluminium film were prepared and tested. The measurements performed on the aluminium-coated silica discs were very similar to the resonance measurements performed with the aluminium plates, i.e. a determination of the frequency, amplitude and quality factor for the resonances were obtained. However, there was an additional variable; the thickness of the metal (aluminium) film.

The figure depicts variation in the voltage detected across the terminals of a parallel circuit comprising a transducer and a 500 µm disc. In this case the frequency varies from the left hand to the right hand by 5 kHz. The measured signal variation has many interpretable features: For example the number of peaks of verifiable amplitudes and widths suggests there is far greater sample complexity than originally envisaged. This could be explained by regions of non-uniformity in the structure of the sample and by significant fluctuations in thickness across the excitation width. In addition, a gradual variation in the height of the baseline was observed. This is linked to an impedance change associated with the electrical properties of the detection circuit and is not an acoustic effect. Also, the asymmetric nature of all of the larger amplitude signals was noted. Interestingly, it corresponds precisely to the modulation of the acoustic impedance predicted for thin film resonators (Figure 5.13). Finally the displayed amplitude of the peak was found to be an artefact of filtering the signal; the true amplitude is in fact several times larger. From this data, a single sample clearly has numerous resonance modes of differing amplitude, scattered around the predicted standing wave frequency. Overall with simple equipment it was proven that virtually all of these resonance modes could be reliably accessed, up to a limiting frequency.

The effect of reducing the film thickness is to increase the Q factor, but at a certain point electromagnetic coupling also begins to fall.. This led us to an optimum film thickness of approximtely 3µm. In summary, acoustic standing waves have been generated with high efficiency in aluminium and silica plates, although the standing wave associated with 0.5mm silica plates were found to be superior: They now had sufficient performance to be used as biosensors, but at no more than 100MHz.

B. *Multifrequency resonators*

At this point, the MARS detection method had evolved: It was possible to detect MDG without the need for high power transmitters and low frequencies of operation. However the instrumentation format developed for MDG could be used to detect magnetic or electric dipoles, and if they give rise to resonance behaviour, they could be very responsive. At this point we found quartz crystals could also be excited, without electrodes. However AT quartz could also offer the benefit temperature stability. As efficiency was very high, tuning between 6.5 to 1.1 GHz, with only one device, was possible. Other acoustic devices do not provide bandwidths of this size. The result is consistent with the very wide acoustic bandwidth of quartz, which extends to several tens of GHz. It also follows from the removal of the capacitive structure of typical acoustic devices, which tends to limit frequency response due to an electrical part. Whereas, acoustics waves can be transmitted at much higher frequencies. As a result, this approach has potential for interfacial acoustic spectroscopy.

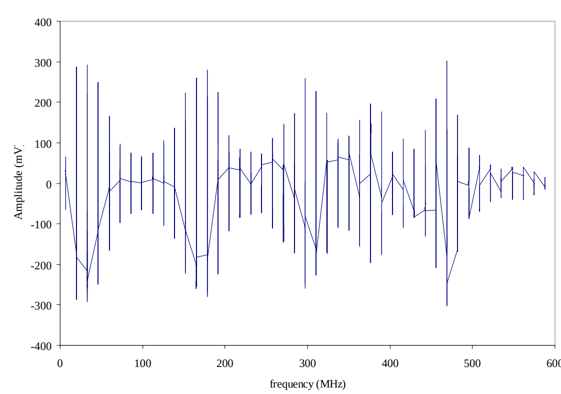

Figure 6. Quartz disc multifrequency resonance

C. Chip resonator

As the approach does not use electodes, which tend to limit the operating frequency, other practical advantages follow. It becomes easier to make smaller devices. In fact we decided to break an AT resonator into several parts. The results was several chips with irregular edges. The surprise was that these individual chips could be made to resonate. They not only resonated, but provided greater coherence than the mother disc from which they were derived. The thickness of the chips was now less variable per chip, enhancing conherence and resonance quality. Whereas the edges, as they were not regular in any lateral direction, did not store any energy and did not contribute to the resonance profile.

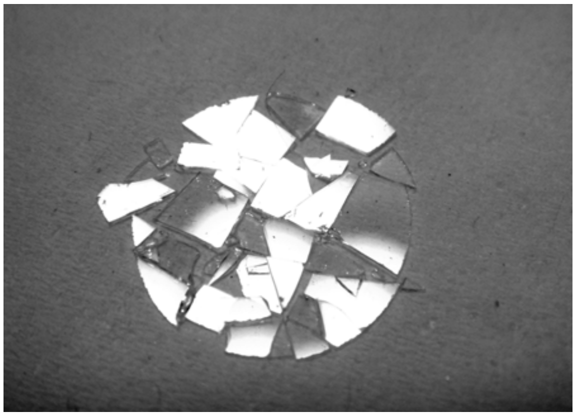

Figure 7. Quartz chip resonators

VI. CONCLUSION

To make acoustic devices work as biological sensors non contact transducer are preferred, as they separate liquid chemistry from the electronic components. We have shown how magnetic direct generation can be used instead of piezoelectricity to develop these sensors. However in the process of developing instrumentation to measure smaller MDG signals we found new opportunities when returning to piezoelectrics. Very wide acoustic bandwidths could be obtained with a single device, supporting interfacial acoustic spectroscopy. Also much smaller devices could be made more easily as there was no need to deposit electrode structures, or to add contacting wires. With this approach it is likely single lumped parameter measurements of mass and viscosity typical of many acoustic biosensors, can ultimately be extended to the recovery of spectral information. With this step it may be possible to use acoustics with the same convenience as optical probes in the life sciences.

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