‘Strain Measurement With Surface Acoustic Wave (SAW) Resonators’

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ABSTRACT

The subject of strain measurement has previously been addressed extensively. Most of the existing transducers either rely on low voltage analogue systems (e.g. conventional resistive strain gauge), complicated mechanical assemblies by physically assessing the specimen displacement, optical systems, acoustic systems or pneumatic systems.

This paper identifies a new, potentially low cost, non-contact, frequency domain strain sensor utilising SAW (Surface Acoustic Wave) Technology for surface strain measurement. The sensor has a short axial length making it flexible in terms of integration into a variety of applications, encompassing both static and dynamic strain measurement. The paper presents a technical description of the resulting strain transducer, regarding its operation, construction and in particularly, application to areas requiring strain measurement. Demonstration of the transducer performance will be addressed utilising test results from existing developed transducers.

1.0 Background

The stress-strain relationship is fundamental to the study of the mechanics of materials and is used to measure many physical quantities such as axial force, bending moment, torque, pressure, acceleration and temperature. In order to practically assess the stress state in a specimen it is imperative to measure the strain. Simple computation[1] of the strain, along with material properties, provides a method for determining the stress state. Effective practical measurement of strain has long been a problem. The following is a summary of the existing methodologies for strain assessment.

Mechanical devices evolved as the first type of strain gauge e.g. extensometer, which relies on the displacement of levers to indicate the strain. Another example is that of the photoelectric strain sensor, which utilises the displacement of light passing through gratings separated at a set distance; sensing of variation in light intensity by photocells provides a signal indicative of the strain. On the whole, such methods are bulky, difficult to use and mostly limited to static strain analysis.

Optical techniques, such as photo-elasticity, holography or Moire’ methods for strain analysis prove to be both accurate and sensitive. However, the apparatus and intricacy of the optical processes generally restricts the practise of such methods to specially prepared laboratories.

Existing electrical devices for measuring strain can utilise any of the following methods; capacitive, inductive, piezoelectric, resistive and piezo-resistive techniques can be identified as the main contributors to the solution of practical strain measurement. However, all rely on the interrogation of low power density analogue signals, highly susceptible to amplitude modulated noise.

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Of all the techniques described, resistive strain-gauges[2] have emerged as the dominating technique for strain measurement. The gauge is generally bonded onto the specimen and provides a low cost solution with the following characteristics: short gauge length, small physical size, small mass, moderate signal error resulting from temperature fluctuations and capability of measuring both static and dynamic strain. However translation to non-stationary applications e.g. a rotating shaft, demands expensive slip rings or large low frequency transformers.

It is apparent, therefore, that there is great demand for a low-cost, unobtrusive, high performance, non-contact strain sensor. This paper will identify a new, potentially low cost, non-contact, frequency domain strain sensor utilising SAW (Surface Acoustic Wave) Technology[3] for surface strain measurement. The fundamental behaviour of the device will be discussed along with brief attention to its construction. Following this, sensor performance with respect to particular application areas will be highlighted.

2.0 Non-Contact Strain Measurement Utilising Rayleigh Waves

2.1 Surface Acoustic Waves (SAW) - Rayleigh Waves

In 1885, the English scientist, Lord Rayleigh, theoretically demonstrated[4] that waves could be propagated over the plane boundary between a linearly elastic half-space and a vacuum (or a sufficiently rarefied medium e.g. air), where the amplitude of the waves decays exponentially with depth. Rayleigh, predicted such waves to be a major component of earthquakes, a fact to be confirmed much later in the 1920's due to the advent of seismographic recordings.

Some forty five years later, Voltmer and White, of the University of California, generated such waves[5] , which are more commonly referred to as Surface Acoustic Waves (SAW) or Rayleigh Waves, on the free surface of an isotropic, elastic substrate, namely, quartz.

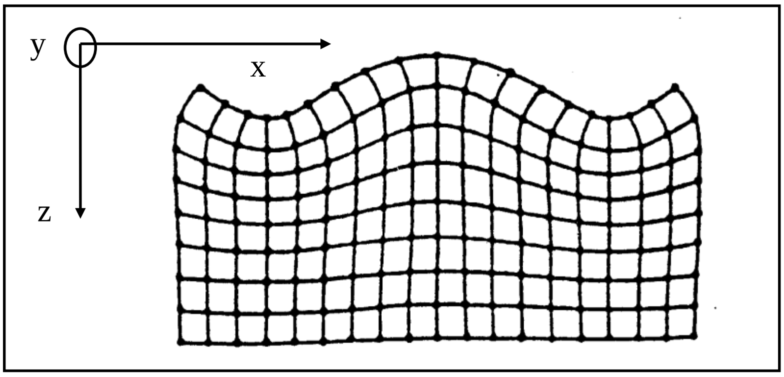

Figure 1.- Surface Acoustic Wave

The action of the wave on the solid produces a pattern of displacements as illustrated in figure1., where the dots indicate material particles, nominally equidistant both vertically and horizontally in the absence of wave motion. The components of displacement along the *x* and *z* axes are given by equations (1) and (2) respectively[6].

$$U_R = Ak_R\left[\ e^{-q_R z} - \left(\frac{2q_R s_R}{k_R^2 + S_R^2}\right) e^{-S_R z}\right]\sin(k_R x - \omega t) \tag{1}$$

$$W_R = Aq_R\left[\ e^{-q_R z} - \left(\frac{2k_R^2}{k_R^2 + S_R^2}\right) e^{-S_R z}\right]\cos(k_R x - \omega t) \tag{2}$$

where:
A is an amplitude constant,
k_R is the Rayleigh wave number,
$k_L = \omega(\rho/(\lambda+\mu))^{1/2}$ are the wave numbers for longitudinal modes,
$k_T = \omega(\rho/\mu)^{1/2}$ are the wave numbers for transverse modes,
λ and μ are the elastic Lame constants, ρ the material density and ω the circular frequency,
$q_R = (k_R\text{-}k_L)^{1/2}$, $s_R = (k_R\text{-}k_T)^{1//2}$,
t is the time, x the in-plane displacement and z the vertical displacement.

Since the displacement components U_R and W_R in the Rayleigh wave along the x and z axes, respectively, are shifted in phase by $\pi/2$, the mode of oscillation of particles supporting a Rayleigh wave is a retrograde ellipse whose normal (vertical) displacement reaches its maximum amplitude at a depth of approximately $0.2\lambda_R$ (where λ_R is the Rayleigh wavelength) and then decays to zero within two wavelengths from the surface. It also contains a component of displacement in the plane of the solid surface.

The influence of the material properties of the surface layer of a sample on the velocity and attenuation of Rayleigh waves permits the latter to be used for the assessment of residual stresses in the surface layer, as well as the thermal[7] and mechanical properties of the surface layer of the sample. Upon this is based the application of Rayleigh waves for the non-intrusive surface testing of components[8] and of particular interest strain measurement. The requirement is for a transducer design capable of measuring such phenomena.

2.2 Surface Acoustic Wave Transducer Construction

An important property of a surface acoustic wave is that its phase velocity is somewhat smaller than the phase velocity of a bulk wave in that direction. The Rayleigh wave velocity is approximately 10^5 times slower than the velocity of electromagnetic radiation in vacuo, and thus, for the same frequency, the wavelength of the elastic wave is less than the wavelength of the corresponding electromagnetic wave by a factor of 10^5. This result has immediate importance on the geometry of the resulting gauge and is the philosophy behind surface wave technology, since the devices themselves can be much smaller than their electromagnetic counterparts, with the additional advantage that the surface wave can readily be sensed anywhere along its path. Importantly, it can be shown[4] that the Rayleigh wave does not exhibit phase velocity dispersion, i.e. there is no dependence of velocity on frequency.

The Rayleigh waves are produced by metallic film transducers on the surface of a piezoelectric material as illustrated in figure 2. These transducers have an interdigital configuration, which is readily fabricated using standard integrated circuit technology. The period of the fingers determines the period of the wave generated. An alternating voltage applied to the transducer causes the surface of the piezoelectric material to undulate periodically, thus, producing waves. The reverse happens at the receiving transducer where the wave is converted back into an electrical signal.

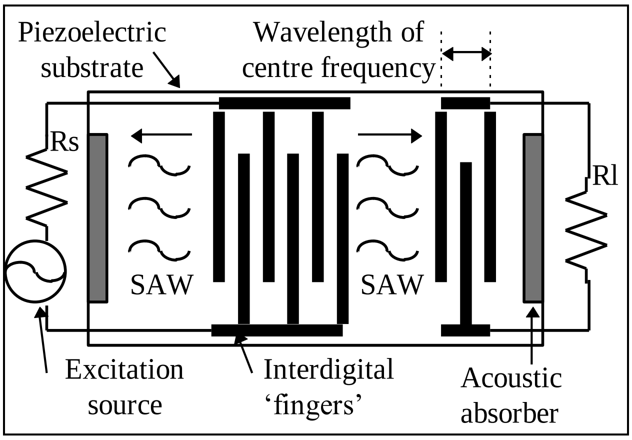

Figure 2. Outline Of A Basic SAW Transducer

The operation of a SAW transducer for strain measurement depends on the choice of a suitable piezoelectric substrate, which can be attached to the material to be stressed. The stress induces a strain, which can be in either a state of tension or compression. The sensitive axis of the transducer is longitudinal in the direction of wave propagation. Strain will change the spacing of the interdigital electrodes and hence the operating frequency. For example, for an excitation frequency of 500 MHz, 1000 $\mu\varepsilon$ of tension will decrease the frequency by 500 KHz [simply: $1000.e^{-6}.500.e^{6}$], conversely a compressive strain will increase the frequency by the same amount. To function as an oscillator the element is used as amplifier feedback. The quality factor (Q) of the transducer is high, typically 10^4, therefore, by meeting the phase and gain requirement the circuit will oscillate with very high stability, typically, one part in 10^9 is not uncommon.

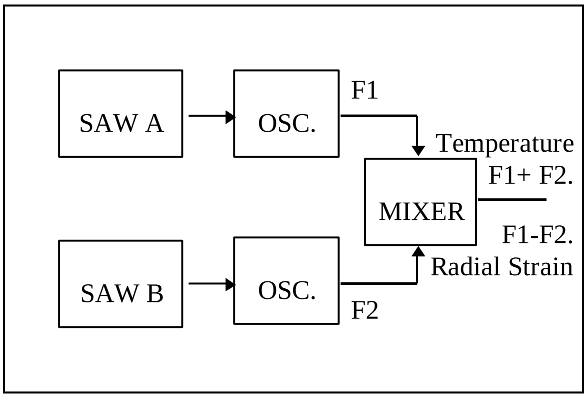

Figure 3 - Schematic Of Frequency Domain SAW Signals

From the technique described it is apparent that the output signal will be in the frequency domain as shown in figure 3. This has many advantages from an application viewpoint, particularly in variable speed electrical machines where low frequency signals can be easily contaminated by drive electronic generated noise. The SAW impedance, designed at the 50 Ω standard, means there is generally less noise than in its classical resistance gauge counterpart (resistance usually 200 - 350Ω). The maximum power of the SAW signal is in the region of 25mW, and so when compared with say a 10V half bridge resistive strain gauge system where the total power of the output strain signal is in the region of 1μW the SAW offers a more robust solution to strain measurement. Piezoelectric transducers are available for dynamic strain sensing but with the disadvantage of having a high output impedance.

2.3.0 Application of SAW Devices For Measuring Strain

2.3.1 Torque Measurement

Toque (radial strain) transducers are one of the more common devices used by development engineers. A knowledge of torque and rotational speed can be used to indicate power, from which the efficiency of gearboxes, transmissions, electrical machines and many other systems can readily be assessed. To apply the SAW element principle, two devices are used in a half bridge, analogous to the classic resistive strain gauging configuration; one positioned so as to be sensitive to the principal compressive strain and the other positioned to observe the principal tensile strain. Note that in the absence of bending moments and axial forces, the principal stress planes lie perpendicular to one another at 45° to the plane about which the torsional moment is applied. This is illustrated in figure 4.

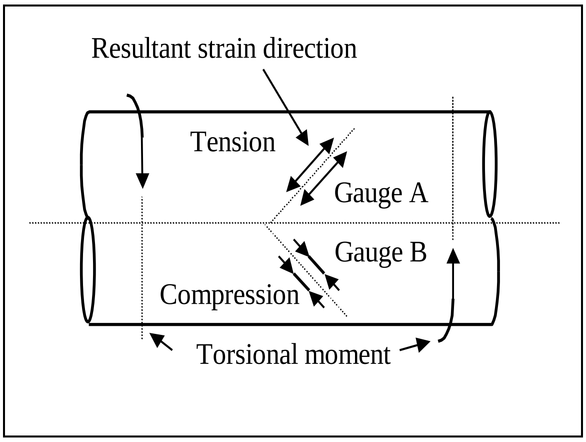

Figure 4 - SAW Gauge Arrangement For Torque Measurement

The two frequencies produced by the SAW's are mixed together to produce the difference and / or sum signals. The difference signal is a measure of induced strain due to the twisting moment and hence, from a knowledge of the material properties and the governing equations, the torque is implied. The sum signal is a measure of shaft temperature.

Coupling of the signals to and from the machine shaft is achieved via an electromagnetic coupling device comprising of two concentric hoops, separated by a suitable distance, one fixed to the shaft housing and the other fixed to the rotating shaft providing non contact interrogation which is intrinsically safe.

The primary frequency of oscillation can be chosen to lie between 100 - 1000 MHz with the difference frequency varying up to 1MHz. Such a transducer has the following specification:

Resolution: 1 part in 10^6.
Linearity: 0.1%.
Bandwidth: >1MHz.

Figure 5., shows a typical prototype torque transducer unit as designed for application in electric power steering control. Figure 5b., illustrates the mounting into a steering rack unit.

Figure 5.- Prototype SAW Torque Transducer

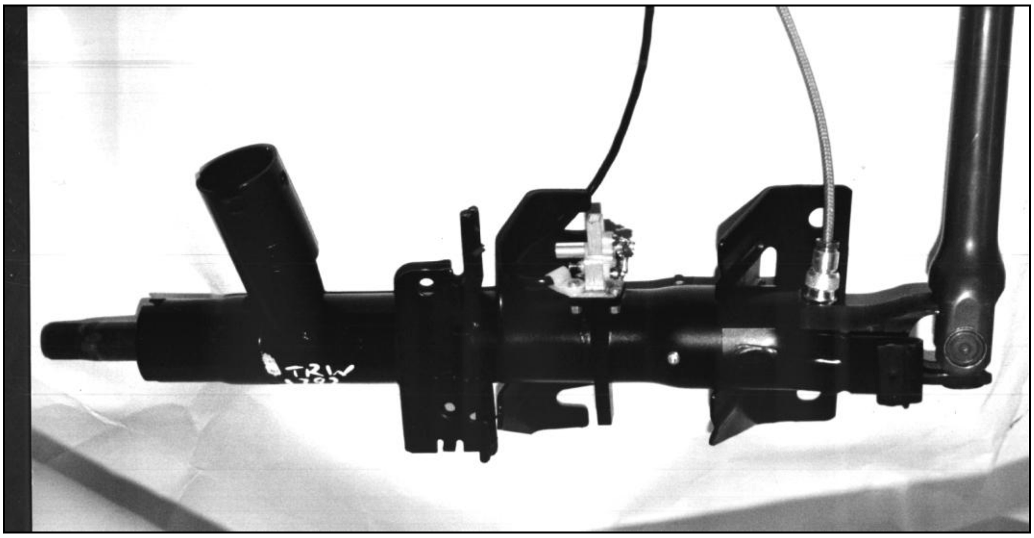

Figure 6.- Typical steering column into which torque transducer is mounted

2.3.2 Force Measurement

To incorporate the SAW element principle into a force transducer, two devices are used in a half bridge, similar to the torque measurement arrangement; one positioned so as to be sensitive to the principle compressive strain and the other positioned to observe the principle tensile strain. If the force is sensed by measuring the bending strain in a bar orientated with its length perpendicular to the axis of applied force then, from classic bending beam analysis[1] the principle stress planes are located along the top and bottom surfaces of the plane of the length of the bar as illustrated in figure 7. The fundamental reason for incorporating a half bridge is to increase sensitivity with zero temperature compensation and monitor temperature variation of the specimen material, available from the induced thermal stresses allowing correction for the variation in material properties with temperature.

Figure 7.- Bending beam arrangement

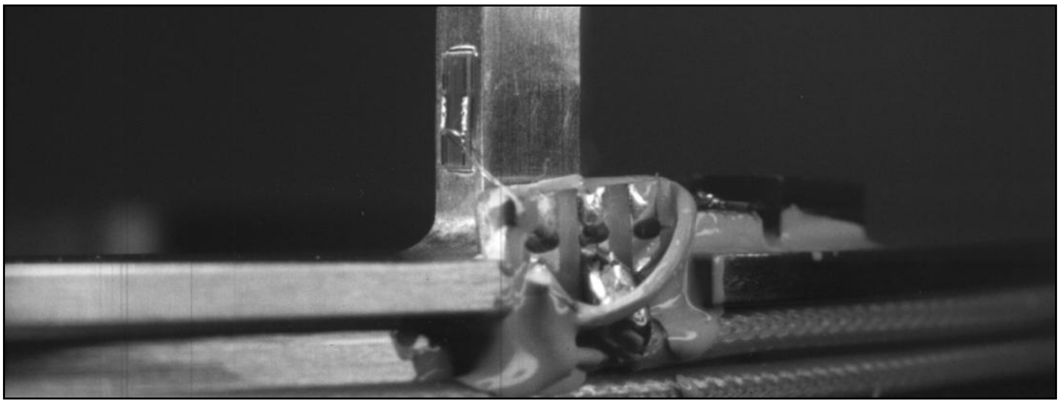

Figure 8.- SAW force transducer component

One such tested force measurement apparatus shown in figure 8., specifically designed to measure both high level static force and low level dynamic fluctuations, exhibited good linearity in SAW device response in measuring static loads of ±100N, corresponding to approximately 200με, as shown in figure 9.

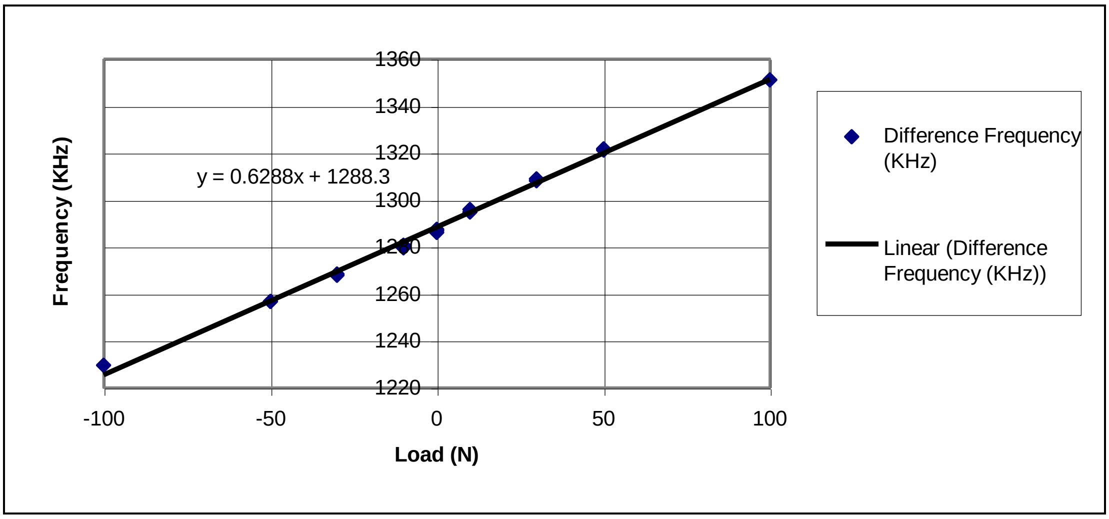

Figure 9. - Static Calibration Of Force Transducer

The dynamic performance for the same transducer for measuring low level strain fluctuations can be seen in figure 10. The noise floor of the signal processing electronics is somewhere in the region of -60dB (ignoring the effects of the induced mains harmonics due to poor screening), with a drive signal of -20dB for 100mN rms. So even at this low level drive input, the SNR is respectable 40dB.

From static analysis it is possible to evaluate a scale factor for the strain induced per unit load. For example, in this case, the SAW gauges each shifted frequency by 40KHz for 100N static loading, indicating a strain of around 200με and thus a scale factor of 2με per 1N peak loading. Combining this result with the dynamic performance it is evident that for a 40dB 100mN drive the equivalent strain is 0.2με rms. Therefore, the potential resolution for this application at voltage SNR 2:1, is an impressive 0.004με rms corresponding to 1 Hz in 200MHZ sensitivity.

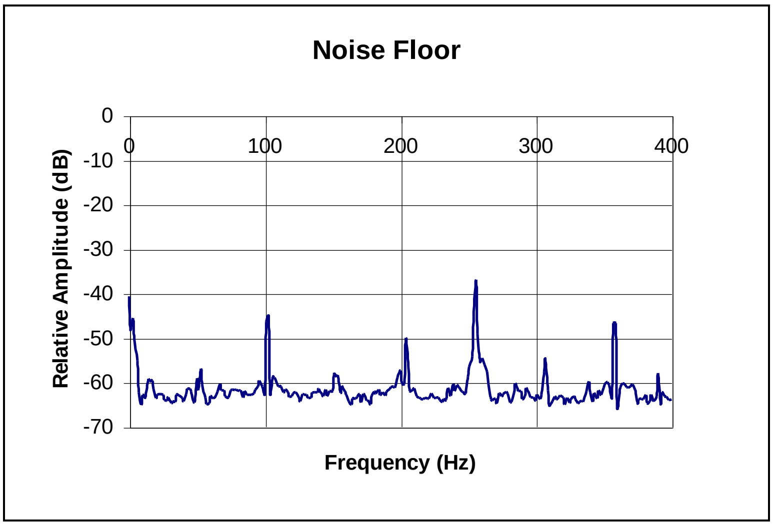

Figure 10. Dynamic Strain Measurement

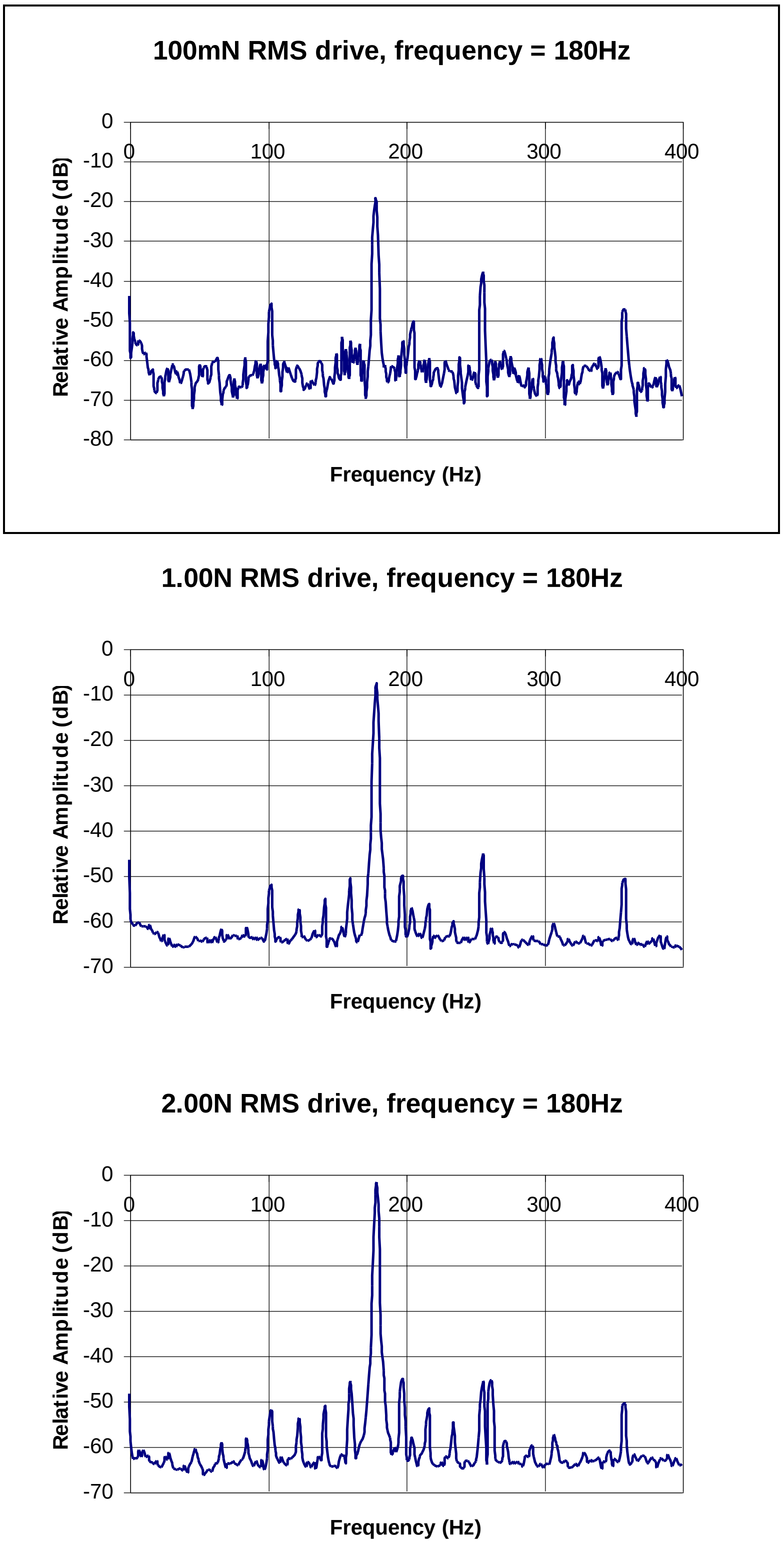

Figure 10. cont. Dynamic Strain Measurement

2.3.3 Other Applications

The fields for potential SAW strain measurement technology application are boundless. For example, pressure, level, acceleration (inc. gravity), temperature and vibration are all easily realisable, as a direct result of the demonstrated performance specification of the SAW devices.

3.0 Conclusions

It has been demonstrated that SAW devices can be used as strain gauges functioning in the frequency domain. An increase in sensitivity over prior art by two orders of magnitude is not unrealistic. The low power requirements coupled with low impedance make these devices superior to conventional resistance gauges. Due to their simplicity and ease of manufacture it is not improbable that these devices will serve well into the 21st. Century as, the resistance gauge has served in the 20th. Century.

4.0 References

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