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Multifunctional Orthogonally-Frequency-Coded Saw Strain Sensor

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MULTIFUNCTIONAL ORTHOGONALLY-FREQUENCY-CODED

SAW STRAIN SENSOR

A Dissertation submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in Electrical Engineering at Virginia Commonwealth University.

by

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each with an aperture of 890 μm. The bus bar heights are 50 μm, and the delay between the two IDTs is 7 wavelengths.
List of Abbreviations

CCM     Composite Crew Module
EDA     Electronic Design Automation
IDT     InterDigitated Transducer
IVHM    Integrated Vehicle Health Management
LGS     Langasite
NBW     Null Bandwidth
OFC     Orthogonal Frequency Coded
RF      Radio Frequency
SAW     Surface Acoustic Wave
SHM     Structural Health Management
TTE     Triple Transit Echo
VHDL    VHSIC Hardware Description Language
VHSIC   Very High Speed Integrated Circuits
Abstract

MULTIFUNCTIONAL ORTHOGONALLY-FREQUENCY-CODED

SAW STRAIN SENSOR

By William C. Wilson PhD

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at Virginia Commonwealth University.

Virginia Commonwealth University, 2013

Major Director: Gary M. Atkinson
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A multifunctional strain sensor based on Surface Acoustic Wave (SAW) Orthogonal Frequency Coding (OFC) technology on a Langasite substrate has been investigated. Second order transmission matrix models have been developed and verified. A new parameterizable library of SAW components was created to automate the layout process. Using these new tools, a SAW strain sensor with OFC reflectors was designed, fabricated and tested. The Langasite coefficients of velocity for strain ($\gamma_S = 1.699$) and Temperature ($\gamma_T = 2.562$) were experimentally determined. The strain and temperature characterization of this strain sensor, along with the coefficients of velocity, have been
used to demonstrate both the ability to sense strain and the capability for temperature compensation.

The temperature-compensated SAW OFC strain sensor has been used to detect anomalous strain conditions that are indicators of fastener failures during structural health monitoring of aircraft panels with and without noise on a NASA fastener failure test stand. The changes in strain that are associated with single fastener failures were measured up to a distance of 80 cm between the sensor and the removed fastener.

The SAW OFC strain sensor was demonstrated to act as an impact sensor with and without noise on the fastener failure test stand. The average measured signal to noise ratio (SNR) of 50, is comparable to the 29.1 SNR of an acoustic emission sensor. The simultaneous use of a high pass filter for impact detection, while a low pass filter is used for strain or fastener failure, demonstrates the multifunctional capabilities of the SAW OFC sensor to act as both as a fastener failure detector and as an impact detector.
Chapter 1 Introduction

1.1. Motivation

The Decadal Survey of Civil Aeronautics: Foundation for the Future, identified Integrated Vehicle Health Management (IVHM) as the top NASA and national priority within the area of materials and structures [1]. The survey also identified IVHM systems that warrant attention over the next decade such as “locally self-powered, wireless microelectromechanical sensors of various types tiny enough that very large numbers of sensors become practical.” An IVHM system that monitors for fastener failures in aircraft is one potential problem where SAW strain sensors can be applied. Models are being developed for detailed fastener failures modes; however, more extensive research is needed to correlate these models with test data before they can accurately capture the physical behavior of the fasteners [2]. Fastener failures of bolted composite components are being investigated for composite spacecraft like the NASA’s Composite Crew Module (CCM) [3]. While others are attempting to detect aircraft fastener failures using fiber optics [4].

However, the environment of aerospace vehicles is typically harsh, with temperature extremes ranging from cryogenic to very high temperatures. For example, the
hypersonic X-43 vehicle will fly at Mach 10 and will therefore will require sensors that must be able to withstand temperatures up to 1282°C [5], as well as cryogenic sensors for monitoring fuel tanks (Fig. 1.1).

![X-43A Hypersonic Experimental Vehicle](image)

Fig. 1.1. X-43A Hypersonic Experimental Vehicle. (a) Artist Conception, (b) X-43A prototype deployed from B-52 Aircraft

Of these issues, power is the most critical for aerospace applications which require extremely low power components for all sensing devices. Sensors are typically located in internal structures with limited access, making the periodic changing of batteries costly and time consuming. Furthermore, batteries do not work well in extreme temperatures. In contrast to current systems, passive surface acoustic wave (SAW) sensors operate across a large temperature range and do not require batteries. From ground tests to the operation of high altitude long duration aircraft, many applications could benefit from small, passive, radiation tolerant sensors. For these, and many other reasons, passive SAW strain sensors
are being investigated for aircraft Structural Health Monitoring (SHM) applications specifically fastener failures.

1.2. Surface Acoustic Waves for Sensing Strain and Temperature

Surface acoustic waves were first described by Lord Rayleigh in 1885 in his seminal work “On Waves Propagated along the Plane Surface of an Elastic Solid” [6]. Surface acoustic waves were difficult to generate until White and Voltmer invented the interdigital transducer (IDT) in 1965 [7]. From that point on SAW devices have been proliferating. In 2007, Triquint shipped 130 million SAW filters for GPS products only. New techniques such as Orthogonal Frequency Coding (OFC) and the introduction of high temperature piezoelectric materials have led to more research on SAW devices for uses as sensors.

In June of 1975 the first patent for a SAW strain sensor was awarded [8]. This system used two SAW devices with only one being stressed the other was used as a reference. The first temperature sensor patent was awarded in 1981 [9]. In 1989 Tilmann proposed the use of two SAW resonators arranged so that they are inversely strained to give both temperature compensated strain measurements [10]. The first wireless strain sensor implementation was developed in 1997 [11]. A wireless passive strain and temperature sensor was developed by Kalin; however, it uses two separate SAW devices, one which is strained and a separate reference device that is not strained and therefore can be used to measure temperature [12]. Other SAW strains have been developed; however, none provide temperature and strain from a single device [13, 14]. A strain sensor that
incorporates OFC reflectors has been developed [15]. The device has several difference from the embodiment presented here, it uses Lithium Niobate not Langasite as a substrate, and it does not incorporate temperature compensation or measure temperature. The strain response of Langasite in comparison to Quartz and Lithium Tantulate has been investigated; however, temperature effects were not included [16]. The temperature effects using phase measurements on Langasite have been performed [17], but strain measurements were not included.

1.3. Theory

The Impulse Response method [18] was used as the basis for the initial modeling of the SAW device. This method is valid only for transducers where at least one of the two IDTs has a constant aperture or finger overlap [19]. This modeling technique captures both the mechanical and electrical behavior of a SAW device and is sufficient for use as a first order model. The model calculates the frequency response, the loss of the system, the admittance, and the electrical parameters for circuit simulators. This model assumes a constant metallization ratio of 0.5 (equal spacing and finger widths).

A simple SAW delay line is shown in Fig. 1.2. The circuit model for the delay line (Fig. 1.3) can be used to convey the basic elements of the Impulse Response Model. The figure shows the source voltage and both the source and load impedances (which are not part of the model). In the circuit model, $C_T$ is the total capacitance of the fingers, $B_a(f)$ is
the acoustic susceptance (inverse of the reactance), and $G_a(f)$ is the radiation conductance (inverse of the resistance).

From the Impulse Response model one can calculate the wavelength ($\lambda$) and the number of finger pairs ($N_p$) using the following equations:
\[ \lambda = \frac{v}{f_0}, \quad (1) \]

\[ N_p = \text{round}\left( \frac{2}{NBW} f_0 \right), \quad (2) \]

where \( v \) is the acoustic velocity in the media, \( f_0 \) is the center or synchronous frequency, and \( NBW \) is the Null BandWidth or fractional frequency.

### 1.3.1. Radiation Conductance

To begin the discussion on the Impulse Response model, first the variable \( X \) is defined as [18]:

\[ X = N_p \pi \frac{(f - f_0)}{f_0}, \quad (3) \]

where \( f \) is the frequency. The real part of the input admittance is called the radiation conductance. The radiation conductance is shaped by the sinc function and is found by [18]:

\[ G_a(f) = 8k^2 C_s H_a f_0 N_p^2 |\text{sinc} (X)|^2, \quad (4) \]

where \( k \) is the piezoelectric coupling coefficient, \( C_s \) is the capacitance of the finger pair per unit length, and \( H_a \) is the aperture or overlap height of the fingers. The results of equation (4) are normalized by dividing by the radiation conductance at the synchronous frequency.
1.3.2. Acoustic Susceptance

The second element of the model is the imaginary part of the input admittance which is called the acoustic susceptance. The acoustic susceptance is the acoustic wave modeled as an electrical parameter. The acoustic susceptance is found by taking the Hilbert transform of the radiation conductance and is given by [18]:

\[ B_a(f) = G_a(f_0) \frac{\sin(2X) - 2X}{2X^2}. \] (5)

Since the acoustic susceptance at the synchronous frequency is zero, the acoustic susceptance is normalized by dividing by the radiation conductance at the synchronous frequency.

1.3.3. Admittance and Impedance

The total static capacitance \( C_T \) for the IDT is found by multiplying the capacitance per unit length for a pair of fingers \( C_s \) times the finger overlap, or aperture \( H_a \) times the number of fingers pairs \( N_p \):

\[ C_T = C_s H_a N_p. \] (6)

The total admittance is found by combining the radiation conductance, the acoustic susceptance, and the total capacitance [20]. The total admittance is given by:

\[ Y = G_a + j(2\pi f C_T + B_a). \] (7)

Impedance matching is often used to reduce reflections in high frequency systems. Inverting (7) yields the impedance of the system [18]:
\[ Z(f) = \frac{1}{G_a + j(2\pi f C_r + B_a(f))} . \] (8)

1.3.4. Aperture Optimization

An optimal design must match the IDT resistance (real impedance) to the source resistance. The device aperture \((H_a)\) is adjusted so that the IDT design achieves the correct resistance and reduces the reflections caused by impedance mismatches. The following equation is used to optimize the aperture in terms of the source resistance \((R_{in})\) at the synchronous frequency:

\[ H_a = \frac{1}{R_{in}} \left[ \frac{1}{2 f_0 C_s N_p} \right] \left( \frac{4k^2 N_p}{(4k^2 N_p)^2 + \pi^2} \right) . \] (9)

1.3.5. Frequency Response

The frequency response from the model for a single IDT is approximated from the Fourier transform of the impulse response and is given by [18]:

\[ H(f) = \left| 4k^2 f_0 C_s N_p^2 \left( \frac{\sin(x)}{x} \right)^2 e^{-jN_F f_0} \right| . \] (10)

To find the frequency response of a SAW transducer that is composed of two IDTs, use the following equation:
where \( H_1 \) and \( H_2 \) are the frequency responses of the two IDTs, \( e^{-j(2\pi f \tau)} \) is the broadband delay between the center of the two IDTs, and \( H_T \) is the overall frequency response for the device.

**1.3.6. SAW Delay Line Example**

To illustrate the capability of the impulse response model, a simple example of a SAW delay line transducer that consists of two identical IDTs will be presented (Fig 1.3). Both IDTs are un-apodized, which means the finger overlap length is constant. The synchronous frequency is 65.79 MHz. The substrate is ST cut Quartz which was selected for its low thermal expansion coefficient at room temperature. The NBW is 1.367 MHz. The delay length between the two IDTs is 12 wavelengths.

Once a substrate material is selected, in this case quartz, the capacitance per finger pair \( C_s = 0.5 \text{pF/cm} \), the piezoelectric coupling coefficient \( k=0.04 \), and the acoustic velocity \( v=3158 \text{ m/s} \) for SAW waves are known [21]. From the impulse response model one can calculate the wavelength \( \lambda \), the delay time \( \tau \), and the number of finger pairs \( Np \) using the equations given earlier. For this example, the wavelength is 48 \( \mu \text{m} \), the delay time is 15.2 ns, and the number of finger pairs is 96.

Next, the impulse response model was used to calculate the radiation conductance using equation (4), and the acoustic susceptance (5).
The results are plotted in Fig. 1.4. The results have been normalized by using the following equations:

\[ G_n(f) = \frac{G_a(f)}{G_a(f_0)}, \quad B_n(f) = \frac{B_a(f)}{G_a(f_0)}. \] (12)

Notice that the acoustic susceptance is normalized using the radiation conductance since the acoustic susceptance at the synchronous frequency is zero.

Also, note that for this example the aperture height is optimized to give us 50Ω real impedance at the synchronous frequency. This will reduce the impedance mismatching between the input source and our SAW device. The value of 50Ω was chosen to match the impedance found in most standard test equipment.
Figure 1.5 is a plot of the frequency response of a SAW delay line.

Fig. 1.5. Frequency response of the SAW delay line.

Note that the values are normalized by using the log equation:

\[
H_n(f) = -20 \cdot \log \left( \frac{H_1(f) \cdot H_2(f)}{H_1(f_0) \cdot H_2(f_0)} \right),
\]

(13)
Chapter 2 SAW Modeling

To facilitate rapid design and analysis of SAW sensors Electronic Design Automation (EDA) tools are required. However, since commercial automated design tools for SAW devices are not available; EDA tools had to be developed. These tools raise the level of abstraction and reduce the amount of time it takes to create a design, perform simulations, and analyze the results thus, improving productivity.

2.1. Extended First Order Modeling

First order models presented in the theory section are good for approximations but often second order effects are important. Because IDTs act as reflectors and transducers, spurious effects such as Triple Transit Echoes (TTE) are detected on the signals (Fig. 2.1). The effects of TTE have been included in an extended model. The model generates plots for analysis and a text file of parameters, which are used for automatic layout generation. The model allows quick design and analysis of SAW delay line devices, followed by automatic layout generation and fabrication.
2.1.1. Second Order Effects

The model has been extended to include the second order effect from triple transit echoes. This effect occurs when a small amount of signal is reflected from the receiver back to the transmitter and then reflected back again to the receiver. The frequency of the signal is $\frac{1}{2}f_0$ and the amplitude is 1/64 of the power of the original [22]. The signal is large enough to cause discernible ripples in the frequency response. The modified frequency response is given by

$$
H(f) = 20 \log \left( 4k^2C_0f_0N_p^2 \left( \frac{\sin(X)}{X} \right)^2 e^{-\left( \frac{N_p+D}{f_0} \right)} + \frac{1}{64} \sin \left( \frac{f}{0.5} \left( \frac{\sin(X)}{X} \right)^2 \right) \right). \quad (14)
$$
2.1.2. SAW Delay Line Prototype

To demonstrate the extended model, a simple SAW delay line that consists of two identical IDTs was chosen. The synchronous frequency is 78.95 MHz. The NBW or fractional frequency is 1.5 MHz. The delay length between the two IDTs is 5 wavelengths. Both the source and load resistances are assumed to be 50 Ω, which is the impedance of the test instrumentation. The substrate is ST cut Quartz, selected for its low thermal expansion coefficient at room temperature. The selection of a substrate material determines the capacitance per finger pair $C_s = 0.503385$ pf/cm, the piezoelectric coupling coefficient $k = 0.04$, and the acoustic velocity $v = 3158$ m/s for the SAW device [21]. Using these values in equation (9) yields an optimized aperture of 1571.0 μm. For this example, the wavelength ($\lambda$) is 40 μm and the finger widths and spaces between the fingers are both 10 μm. The optimal number of finger pairs (105) is calculated using equations (1 and 2).

The model generates frequency response plots of the normalized radiation conductance and normalized acoustic susceptance (Fig. 2.2), using the values for the prototype device. The plots are used for analysis of the device design before the device layout is performed.
Parameterizable library of components was developed and used to automatically generate layouts of prototype SAW devices [23]. See Appendix A for more information on the automatic layout generation. The prototype device was then fabricated from the layout (Fig. 2.3). Note that the salient parameters of the design are annotated on the layout using the same metal as the fingers. On the layout, H is the height of the fingers (1671 μm), W is the width of the fingers (10 μm), N is the number of finger pairs (105), A is the aperture height or length of the overlap between the fingers (1571 μm), B is the height of the buss bars (500 μm), and T is the delay between the two IDTs which is measured in wavelengths (5 for this device). Note that the finger length at 1671 μm is 100 μm greater than the aperture height. This is the non-overlap length of the fingers, and the space between the fingers and the bus bars.
2.1.3. Prototype SAW Delay Line Results

The frequency response of the system is calculated using equation (14) and is plotted in (Fig. 2.4), along with the measured frequency response from a fabricated device. This figure shows that the minimum insertion loss for the system naturally occurs at the synchronous frequency. A comparison between the calculated frequency response and the measured frequency response demonstrates that the first order model captures the main characteristics of the central lobe and the first side lobes. The addition of the triple transit echo signal to the model makes the response more accurate and can be seen as the small ripple on the top of each lobe.
Noise in the measured results has distorted the second and subsequent side lobes. The ripples and peaks on the top of the main lobe are caused by second order effects such as internal reflections. Although the modeling fits the example well, the measured shape of the main lobe is not symmetrical. It was believed that the distortion of the main lobe was caused by bulk waves which interfered with the SAW waves. To rectify the situation, a second prototype wafer was designed and fabricated using single side polish wafers to remove the bulk wave interference. The results from the devices on the second wafer are presented in the Transmission Line Modeling section.
2.2. Transmission Line Modeling

First order models of SAW devices are based upon the Impulse Response [24] [25]. These models do not take into account second order effects such as internal reflections, frequency shifts, or allow for any physical arrangement other than equal electrode widths and spaces. For more accurate results, a matrix based approach was developed [26]. This approach has been further refined and modified to include internal finger reflections [27]. The reflections occur when the thickness of the metallization is sizeable enough to result in significant reflections. The extensions are based upon matrices that were originally developed for analyzing microwave circuits using transmission line theory. The modifications are accomplished by breaking up the SAW device into zones, where the area under a metalized region is treated as one zone, and the area without metallization is treated as another zone. The impedance discontinuities that occur at the edges of the metal fingers enable the simulation of the internal reflections of the mechanical acoustic wave. The modifications also enable incorporation of the different velocities for each region, which produces a more accurate characterization of the frequency response of the device.

2.2.1. Conventional Matrix Method

The methodology utilizing transmission matrices was based on the approach given by Campbell [26]. This method is based upon the Mason equivalent circuit using the
crossed field technique (Fig. 2.5). Where for modeling purposes, an IDT can be modeled as a single entity with one electrical port, and two acoustic ports.

![Transmission matrix model of an IDT.](image)

This allows the acoustic waves ($W_i$) and electrical parameters ($a_i$ and $b_i$) to be related through the use of transmission matrix $T$ in:

$$
\begin{pmatrix}
W_{i-1}^+ \\
W_{i-1}^-
\end{pmatrix}
= T
\begin{pmatrix}
W_i^+ \\
W_i^-
\end{pmatrix}.
$$

(15)

The transmission matrix is in turn broken up into sub-elements, given by

$$
T = \begin{pmatrix}
t_{11} & t_{12} & t_{13} \\
-t_{12} & t_{22} & t_{23} \\
st_{13} & -st_{23} & t_{33}
\end{pmatrix}.
$$

(16)

The sub-elements for the $T$ matrix are given by Campbell [26]. Given the $T$ matrix for an IDT, calculations for a SAW delay line or filter can be performed. The matrix for a
SAW delay line is simply the multiplication of a 2x2 sub-matrix (elements $t_{11}$, $t_{12}$, $t_{21}$, and $t_{22}$) for the two IDTs and a matrix for the delay in between (Fig. 2.6).

Fig. 2.6. Transmission matrix model of a complete SAW delay line comprising of two IDTs and the delay between.

The delay matrix is modeled after an acoustic transmission line as well. The delay matrix is given by:

$$
\begin{bmatrix}
\frac{2\pi d}{\lambda} & 0 \\
0 & \frac{2\pi d}{\lambda}
\end{bmatrix},
$$

(17)

where $\lambda$ is the wavelength at the synchronous frequency and $d$ is the distance between the reference planes or in this case the center of the two IDTs. Therefore, complete SAW device matrix is given by:

$$
[S\text{AW}(f)]=\begin{bmatrix}
T_1(f)D(f)T_2(f)
\end{bmatrix}.
$$

(18)
2.2.2. Modified Matrix Method

For more accurate results, the conventional matrix approach was extended to include internal finger reflections [26, 27]. The model divides an IDT into $\frac{1}{2}$ wavelength sections. These sections are further divided into zones. Two of the zones are un-metalized areas (1/8 of a wavelength) around one zone that is comprised of a metal finger (1/4 of a wavelength). Each zone is modeled by a transmission line matrix equivalent circuit (Fig. 2.7). Two identical circuits model the un-metalized areas while the middle circuit models the area under the metal finger. The transmission matrix relates the voltages $V_1$ and $V_2$ to the currents $I_1$ to $I_2$. The acoustic wave is assumed to have entered from the left and travels through the element towards the right. In this model $Z_m$ and $Z_u$ are the acoustic impedances for the metalized and un-metalized areas, $C_0$ is the capacitance for a single finger, $\theta_u$ and $\theta_m$ are the transit angles of the substrate. The turns ratio of the transformer is assumed to be 1:1 for this example.
The transmission matrix that represents the middle circuit of Fig. 2.7 for a metalized region that is assumed to be lossless, and is given by:

\[
[R_m(f)] = \begin{bmatrix}
\cosh(j\theta_m(f)) & Z_m \sinh(j\theta_m(f)) \\
\frac{1}{Z_m} \sinh(j\theta_m(f)) & \cosh(j\theta_m(f))
\end{bmatrix}.
\]  

(19)

The transmission matrix (19) is determined by the acoustic transit angle \( \theta_m \) and the metalized region’s acoustic impedance \( Z_m \). The acoustic impedance \( Z_m \) is calculated by:

\[
Z_m(f) = \frac{1}{k^2 C_s H_d f_m},
\]  

(20)
where $f_m$ is the frequency of the acoustic wave under the metalized area. The acoustic transit angle of the substrate $\theta_m$, is given by

$$\theta_m(f) = \frac{\pi f}{2 f_m}.$$  \hfill (21)

The frequency of the acoustic wave under the metalized area $f_m$ is given by:

$$f_m = \frac{v_m}{\lambda},$$ \hfill (22)

where $v_m$ is the acoustic wave velocity under the metalized area and is 3134 m/s for ST cut Quartz.

The matrix (19) calculates the parameters for the metalized area, but cannot be used for the un-metalized sections. This leads to the transmission matrix ($R_u(f)$) for the un-metalized region as is given by:

$$[R_u(f)] = \begin{bmatrix} \cosh(j\theta_u(f)) & Z_u \sinh(j\theta_u(f)) \\ \frac{1}{Z_u} \sinh(j\theta_u(f)) & \cosh(j\theta_u(f)) \end{bmatrix}. \hfill (23)$$

The un-metalized region’s transmission matrix (23) is determined by the acoustic transit angle $\theta_u$ and the un-metalized region’s acoustic impedance $Z_u$. The acoustic impedance $Z_u$ is calculated with:

$$Z_u(f) = \frac{1}{k^2 C_s H_u f_0}.$$ \hfill (24)

The acoustic transit angle of the substrate $\theta_u$, is given by

$$\theta_u(f) = \frac{\pi f}{4 f_0}.$$ \hfill (25)
To find the transmission matrix for the \( \frac{1}{2} \) wavelength periodic element \((R_t(f))\) one must multiply the three matrices together for both metalized region and the un-metalized regions adjacent to it:

\[
[R_t(f)] = [R_u(f)][R_u(f)][R_u(f)] .
\]  

(26)

To find the transmission matrix \((IDT_1(f))\) for an entire IDT one simply raises the \((R_t(f))\) matrix to the power of \(2N_p\):

\[
[IDT_1(f)] = [R_t(f)]^{2N_p} ,
\]  

(27)

where \(N_p\) is the number of electrode pairs, so \(2N_p\) is the total number of electrodes in the IDT.

The matrix for a SAW delay line is simply the multiplication of the matrices for the two IDTs and the delay or space between the IDTs. The SAW matrix is given by:

\[
[SAW(f)] = [IDT_1(f)D(f)IDT_2(f)] .
\]  

(28)

2.2.3. Extended Matrix Design

A simple SAW delay line that consists of two identical un-apodized IDTs was chosen as a prototype to illustrate the validity of the extended matrix model. Each IDT has 63 fingers that are 17 \(\mu\)m wide. The spacing between the fingers is 17 \(\mu\)m also. The center or synchronous frequency is 46.44 MHz, or a wavelength of 68 \(\mu\)m. The aperture height is 2730 \(\mu\)m. The delay length between the IDTs is 10 wavelengths or 680 \(\mu\)m. The design was fabricated on two different quartz wafers. One with a single side polished and one
wafer with both sides polished. The aluminum thickness is 58 nm for the wafer with a single side polished and 250 nm for the wafer with both sides polished.

2.2.4. Experimental Validation of the Extended Matrix Model

The prototype wafer has four copies of 12 designs. The devices were fabricated on a single crystal Quartz ST-cut substrate, with single side polish that is 0.5 mm thick (Fig. 2.8).

Fig. 2.8. Prototype devices on a Quartz ST cut wafer.
The salient parameters for the 12 devices are summarized in Table 2.1. The device frequencies range from 46.4 MHz to 112.8 MHz. Both single and double finger devices were fabricated for each frequency. Most of the devices have a NBW of 2.5 MHz, except for devices 5 and 12, which have NBW of 1.5 MHz. The NBW determines the width of the main lobe. Devices number 5 and 12 have a smaller NBW to allow for comparison of main lobe widths. The number of finger pairs is denoted by NP. The device aperture (Ha) was calculated to match the device’s impedance to 50 Ω. The device’s aperture height is given in the column labeled Ha. The Delay parameter denotes the number of wavelengths between the IDTs. The device style refers to the number of fingers per wavelength, where S denotes single finger pair per wavelength and D denotes two finger pairs per wavelength. Double fingers reduce internal reflections; however, the internal reflections can also be eliminated by reducing the height of the finger’s metal. The last column is the device frequency. Note that there are four copies of each device on the wafer. The wafer also contains calibration structures that allow open, through, and short calibrations to be performed on the wafer. These simple structures can be seen at the bottom of each device column in Fig. 2.8.
### Table 2.1. Prototype device parameters.

<table>
<thead>
<tr>
<th>Device</th>
<th>NBW</th>
<th>NP</th>
<th>w/λ (µm)</th>
<th>Delay</th>
<th>Ha(µm)</th>
<th>Style</th>
<th>f (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.5</td>
<td>90</td>
<td>7.0/28</td>
<td>104</td>
<td>1105</td>
<td>S</td>
<td>112.786</td>
</tr>
<tr>
<td>2</td>
<td>2.5</td>
<td>90</td>
<td>3.5/28</td>
<td>104</td>
<td>781</td>
<td>D</td>
<td>112.786</td>
</tr>
<tr>
<td>3</td>
<td>2.5</td>
<td>63</td>
<td>10/40</td>
<td>73</td>
<td>1605</td>
<td>S</td>
<td>78.95</td>
</tr>
<tr>
<td>4</td>
<td>2.5</td>
<td>63</td>
<td>5/40</td>
<td>73</td>
<td>1135</td>
<td>D</td>
<td>78.95</td>
</tr>
<tr>
<td>5</td>
<td>1.5</td>
<td>105</td>
<td>10/40</td>
<td>10</td>
<td>1560</td>
<td>S</td>
<td>78.95</td>
</tr>
<tr>
<td>6</td>
<td>2.5</td>
<td>53</td>
<td>12/48</td>
<td>61</td>
<td>1935</td>
<td>S</td>
<td>65.792</td>
</tr>
<tr>
<td>7</td>
<td>2.5</td>
<td>53</td>
<td>5/48</td>
<td>61</td>
<td>1369</td>
<td>D</td>
<td>65.792</td>
</tr>
<tr>
<td>8</td>
<td>2.5</td>
<td>42</td>
<td>15/60</td>
<td>49</td>
<td>2430</td>
<td>S</td>
<td>52.63</td>
</tr>
<tr>
<td>9</td>
<td>2.5</td>
<td>42</td>
<td>7.5/60</td>
<td>49</td>
<td>1718</td>
<td>D</td>
<td>52.63</td>
</tr>
<tr>
<td>10</td>
<td>2.5</td>
<td>37</td>
<td>17/68</td>
<td>43</td>
<td>2758</td>
<td>S</td>
<td>46.441</td>
</tr>
<tr>
<td>11</td>
<td>2.5</td>
<td>37</td>
<td>8.5/68</td>
<td>43</td>
<td>1950</td>
<td>D</td>
<td>46.441</td>
</tr>
<tr>
<td>12</td>
<td>1.5</td>
<td>63</td>
<td>17/68</td>
<td>10</td>
<td>2730</td>
<td>S</td>
<td>46.441</td>
</tr>
</tbody>
</table>

#### 2.2.5. Comparison of Matrix Modeling and Delay Line Prototype Results

The results for both simulated and measured devices are given for each of the 12 designs in figures 2.9 through 2.15. The simulation results presented here take into account the delay length, aperture, device wavelength, and whether there are single or double electrodes per wavelength. The measured data has also been normalized in frequency. In general, the higher the frequency, the better the results. None of the results have the characteristic shape indicative of bulk wave interference. The double finger pair devices (devices 2, 4, 7, 9, and 11) have higher capacitance and therefore have higher losses than the single finger pair devices. Because the metal was only 58 nm, it does not generate large internal reflections that would have made a difference in the response of the single finger pair devices.
In addition to the changes in substrate, the new prototype wafers were tested using RF probes instead of DC probes. This change made the results repeatable not only for the 78.95 MHz device from the first prototype wafer, but for all of the devices. The 112 MHz devices (Fig. 2.9) match the simulations for the main and first side lobes better than the rest of the devices.

![Graphs showing insertion loss versus frequency for 112 MHz prototype devices](a) and (b).

**Fig. 2.9. 112 MHz prototype devices 1 (a) and 2 (b).**

The 78.95 MHz devices are the next best devices when compared to the simulations (Fig. 2.10).
At 65.79 MHz the second and subsequent side lobes become very hard to distinguish from noise (Fig. 2.11).

Fig. 2.10. 78.95 MHz prototype devices 3 (a) and 4 (b).

Fig. 2.11. 65.79 MHz prototype devices 6 (a) and 7 (b).
For the 52.63 MHz devices, there appears to be a slope in amplitude away from the main lobe and first side lobes. In this case, the lower frequencies have too low of an amplitude while the higher frequencies have too high of an amplitude (Fig. 2.12).

![Graphs showing frequency response](image)

Fig. 2.12. 52.63 prototype devices 8 (a) and 9 (b).

The lowest frequency devices (46.44 MHz) exhibit both more noise and slope in the frequency response. However, the main lobe continues to match the model reasonably well (Fig. 2.13).
Device numbers 5 and 12 have a NBW of 1.5 MHz, while the other devices have a bandwidth of 2.5 MHz. The major difference in the designs is the number of finger pairs. Devices 3 and 4 have 63 finger pairs while device 5 has 105. Likewise devices 10 and 11 have 37 finger pairs, and device 12 has 63. The difference in bandwidths is clearly evident in part b of Figure 2.14 and Figure 2.15. The number of finger pairs is not the only difference; the delay length is greater for the 2.5 MHz devices. Greater delay means larger losses. This accounts for about 10% of the loss as seen in the plots. However, the rest of the difference in amplitudes is due to the higher efficiency associated with the greater number of finger pairs.
All three methods adequately model the frequency response amplitude for the main lobe and the first and second side lobes for cases without any mass loading due to the metal fingers (Fig. 2.16). The modified matrix more accurately captures the frequency
shift due to the mass loading of the metal fingers. The ideal first order model and the conventional matrix results are both centered about the synchronous frequency. The measured results and the modified matrix results are both shifted down in frequency due to velocity changes from mass loading effects.

![Graph of Insertion Loss vs Frequency](image)

**Fig. 2.16.** Comparison of model results with data from a double side polish wafer, with 250 nm of aluminum.

The main lobe peak of figure 2.17 does not have the same artifacts as are seen on the peak of the main lobe in figure 2.16. These artifacts are due in part from bulk waves that are reflected from the polished bottom surface of the wafer. The roughness of the non-
polished surface disperses the bulk waves which results in diminished artifacts in the main lobe peak (Fig. 2.16). Also note that the peak is not shifted as far in figure 2.17 as it is in figure 2.16.

![Graph showing impulse response comparison]

**Fig. 2.17.** Comparison of model results with data from a single side polish wafer, with 58 nm of aluminum.
2.3. Orthogonal Frequency Coding

OFC devices were developed by Dr. Malocha in 1998 [28]. A simple SAW sensor that employs four OFC reflectors in two banks is shown in Fig. 2.18. The radio frequency (RF) energy is transformed from electrical energy into mechanical waves in the surface of the material by the interdigital transducer (IDT). The IDT is bidirectional and therefore generates waves in two directions. The waves travel down to a depth of one wavelength of the surface. The waves travel across the substrate and encounter the four reflector gratings that comprise each identical reflector bank. The waves are reflected back to the IDT where they are transformed back into electrical energy.

Fig. 2.18. SAW sensor that employs four orthogonal frequency coded (OFC) reflectors in two banks.
In a common SAW reflector device each reflector grating is broad band and reflects back a portion of all of the frequencies from each reflector grating. This reduces the amount of energy that the subsequent reflectors receive and reduces the response from each subsequent reflector grating. To meet the constraints of orthogonality in an OFC coded device, the reflector gratings are narrow band and are designed so that the peak frequency of each reflector occurs at a minimum for all of the other reflectors (Fig. 2.19). This will allow the mechanical wave energy to pass through reflectors that do not match the reflector Bragg frequency criteria and be reflected only by a corresponding reflector. This aspect of OFC reflectors allows for more consistent amplitude and maximum efficiency of returned energy from each of the reflector gratings that comprise a reflector bank. Each OFC device can be uniquely coded for identification by modifying the frequency of the gratings, the spatial location of the gratings, order of the gratings, and the phase of the gratings. This code diversity enables large numbers of sensors to be interrogated simultaneously. The response from an OFC device is considered to be spread spectrum because each reflector grating responds to stimuli in the same way [29]. Spread spectrum devices tolerate multipath reflections and are easier for interrogation systems to discriminate because the information is carried in multiple frequencies.
A prototype design has been developed that has two reflector banks. Each reflector bank is comprised of four sets of gratings. The four grating sets have frequencies of 303.71, 304.85, 305.98, and 307.11 MHz. The reflectors banks are positioned on either side of an interdigitated transducer with spacing such that the reflections do not overlap in time. The prototype design will be used as an example for the strain model. The four separate frequencies used in both reflectors banks and the IDT responses are shown in Fig. 2.19.
2.4. Strain Coefficient of Velocity

Strain is defined as the change in length of an object divided by the original length
therefore; strain (\( \varepsilon \)) is given by:

\[
\varepsilon = \frac{\Delta L}{L},
\]  

(29)

where \( \varepsilon \) is the strain, \( L \) is the original length and \( \Delta L \) is the change in length. Under tension
(below the elastic limit) the device elongates and there is a change in the height of the
metal finger. Both the SAW finger widths and spaces increase in length (Fig. 2.20). Similarly, under compression the finger widths and spacing are reduced resulting in an
increase of operating frequency and a change in the height of the metal finger. These
changes in frequency are proportional to strain.

Fig. 2.20. SAW without strain (above) and with strain due to tension (below).
For strain measurements to be repeatable the SAW devices must operate inside of the elastic portion of the stress-strain curve for the SAW material. Within the elastic region, strain will cause repeatable changes in length of the device. Stretching and compressing the device will cause the finger widths, heights, and spaces to change and will therefore change the wavelength ($\lambda$) of a SAW device. Changes in wavelength will cause a change in the frequency of operation of the SAW device. The synchronous or center frequency ($f$) of a SAW device is related to the velocity of the acoustic wave ($v$) and the wavelength ($\lambda$) and is given by:

$$f = \frac{v}{\lambda}.$$  \hspace{1cm} (30)

Wavelength is not the only parameter that changes within the SAW device. Strain will also cause the elastic coefficients and the density to change [30]. Both of these parameters affect the acoustic wave propagation and are manifest in changes in the velocity ($v$) of the SAW device. Since both the velocity and wavelength affect the frequency, both will have to be considered when examining the changes due to strain. To do this, each of the changes is divided by its original value to yield a fractional value. The fractional change in frequency ($\Delta f_3$) due to the fractional change in the velocity ($\Delta v_3$) from strain and the fractional change in length ($\Delta L_3$) from strain are given by [31]:

$$\Delta f_3 = \frac{\Delta v_3}{v} \quad \text{and} \quad \Delta L_3 = \frac{\Delta \lambda}{\lambda}.$$
\[ \frac{\Delta f_s}{f} = \frac{\Delta v_s}{v} - \frac{\Delta L_s}{L} = \frac{\Delta v_s}{v} - \varepsilon. \] (31)

The strain coefficient \( (\gamma_S) \) of velocity for uniaxial strain is defined as [31]:

\[ \frac{\Delta v}{v} = \gamma_S \varepsilon. \] (32)

The strain coefficient is highly dependent on the anisotropic material parameters and therefore it is dependent on the crystallographic orientation of the substrate as well as the propagation direction on the substrate. The strain coefficient will yield an equation that relates the fractional frequency to the strain and is given by [31]:

\[ \frac{\Delta f_s}{f} = (\gamma_s - 1)\varepsilon. \] (33)

### 2.5. Strain Results

The SAW sensor measurements were obtained by exciting the SAW device with the vector analyzer while simultaneously measuring the S parameters, specifically the reflection coefficient \( S_{11} \). For each desired strain measurement, the data received from the SAW sensor consists of 20005 complex data points over the range of 430.05 to 431.05 MHz. The magnitude of the signal at each frequency for four conditions is shown in Fig.
The four conditions are: room temperature (nominally 23.1°C ±0.15°C) without any loading, room temperature with a 0.500 kg load, elevated temperature (nominally 29.8°C ±0.57°C) without any loading, and elevated temperature with a 0.500 kg load.

The frequency shift is proportional to both strain and temperature changes. Increasing strain and/or temperature both cause a shift to a lower frequency. The frequency shift is measured through cross correlation of the first data set at room temperature without any strain to all subsequent data sets. To characterize the strain response of the SAW sensor, multiple experiments were performed. For the first
experiment the load was increased from 0 kg to 1.0 kg in 0.1 kg steps at room temperature (nominally 23.1°C ±0.15°C). The frequency shift results are converted to strain using a conversion factor of 0.000914 με/Hz [32]. The results are given in Fig. 2.22.

![Fig. 2.22. SAW strain sensor versus strain gauge data at room temperature.](image)

The SAW strain measurements are in good agreement with the strain gauge when the measurements are taken at room temperature. For the second experiment the load was decreased from 1.0 kg to 0 kg in 0.1 kg steps at room temperature. The results are given in Fig. 2.23.
For both experiments the SAW sensor data is comparable to the strain gauge data. The SAW sensor data from the two experiments agree very closely with each other. The average fractional frequency values versus the average strain values for both increasing and decreasing loads from Fig. 2.22 and Fig. 2.23 was plotted together in Fig. 2.24.
Fig. 2.24. The average fractional frequency values versus the average strain values for both increasing and decreasing loads shown in Fig. 2.22 and Fig. 2.23.

The lines in Fig. 2.24 are calculated using linear regression. The slopes are similar, with -306.128 Hz/με for the increasing strain and -287.379 Hz/με for the decreasing strain data. The small offset in the lines is probably due to small temperature differences between the experiments which occurred on different days. Using (32) the strain coefficient ($\gamma_S$) was calculated to be 1.746 for increasing strain and 1.652 for the decreasing strain case. The average of the two numbers ($\gamma_S = 1.699$) is used for further calculations. The strain coefficient will be different for different crystal cuts and orientations of the SAW device on the wafer. These values are for Langasite crystal with an Euler orientation of (0, 138.5, 26.6) with propagation in the X direction.
2.6. Temperature Characterization

Like strain, temperature causes both a change in length of an object and material parameter changes such as density and elastic coefficients. The linear thermal coefficient of expansion is defined as the change in length divided by the original length caused by thermal expansion; therefore, the linear thermal coefficient of expansion ($\alpha$) is given by:

$$\alpha = \frac{\Delta L_T}{L_T},$$

where $\Delta L_T$ is the change in length due to temperature and $L_T$ is the original length of the device. Again, the stretching and compressing the device will cause the finger widths and spaces to change and will therefore change the wavelength ($\lambda$) of the device resulting in changes in the frequency of operation of the SAW device. Changes to both the elastic coefficients and the density will affect the velocity ($v$) of the SAW device. These changes lead to a fractional change in frequency due to the fractional change in the velocity and the fractional change in length due to temperature which is given by [33]:

$$\Delta f_T = \frac{\Delta v_T}{v} - \frac{\Delta L_T}{L_T} = \frac{\Delta v_T}{v} - (\alpha_1 \Delta T + \alpha_2 \Delta T^2).$$
There are two temperature coefficients in (35), the first order \((\alpha_1)\), and the second order \((\alpha_2)\) [34]. For a Langasite substrate the values of \(\alpha_1 = 5.68\), and \(\alpha_2 = 5.43\) will be used [35]. The temperature coefficient of velocity \((\gamma_T)\) is defined as [33]:

\[
\frac{\Delta v_T}{v} = \gamma_T \frac{\Delta L_T}{L} = \gamma_T (\alpha_1 \Delta T + \alpha_2 \Delta T^2) .
\] (36)

Similar to the strain case, the temperature coefficient of velocity will yield an equation that relates the fractional frequency to the temperature and is given by:

\[
\frac{\Delta f_T}{f} = (\gamma_T - 1) (\alpha_1 \Delta T + \alpha_2 \Delta T^2) .
\] (37)

**2.7. Temperature Results**

To characterize the SAW sensor for temperature effects the bar was unloaded and the temperature was raised quickly using a heat gun to a peak of 44.54°C. The bar was then allowed to cool slowly while data was recorded from the SAW, strain gauge and thermocouple (Fig. 2.25). The frequency shift data from the SAW device was converted to temperature (red line). The SAW fitted data agrees closely with the thermocouple (green line) and is mostly within ±0.25 °C.
Fig. 2.25. SAW frequency and model data scaled to match thermocouple data, and SAW data fitted to match the thermocouple data.

The differences between the SAW sensor and the thermocouple are in part due to the thermal characteristics of the Langasite material and the adhesive between the SAW sensor and stainless steel bar. To adjust for these differences a 3rd order polynomial regression was performed (black line).
The following equation is used to fit the SAW values to those of the thermocouple:

\[ y = 4.866 \cdot 10^{-4} x^3 - 0.062 x^2 + 3.548 x - 30.835 \]  (38)

The SAW sensor data and (Eqn. 38) can be used as a temperature sensor as long as the device is unloaded and is not experiencing any strain changes. To determine the temperature coefficient of velocity, both the fractional frequency and temperature data are required (Fig. 2.26)

Fig. 2.26. SAW fractional frequency data versus temperature data, and a linear regression of the data.
The red line (Fig. 2.26) is the fractional frequency versus the temperature from the thermocouple. Using Eqn. 37 along with the SAW data allowed the temperature coefficient of velocity \( \gamma_T \) to be calculated to be 2.562. The blue line is a plot of Eqn. 37 using the thermocouple as an input and \( \gamma_T = 2.562 \). This value for the temperature coefficient of velocity will be used to temperature compensate the SAW strain values.

2.8. Combined Strain and Temperature Results

The combined effects from temperature and strain are found by combining equations (33 and 37) into a single equation given by:

\[
\frac{\Delta f}{f} = (\gamma_S - 1) \varepsilon + (\gamma_T - 1)(\alpha_1 \Delta T + \alpha_2 \Delta T^2).
\]  \hspace{1cm} (39)

Rearranging Eqn. 10 yields the temperature compensated strain equation:

\[
\varepsilon = \frac{\frac{\Delta f}{f} - (\gamma_T - 1)(\alpha_1 \Delta T + \alpha_2 \Delta T^2)}{(\gamma_S - 1)}.
\]  \hspace{1cm} (40)
To characterize the combined strain and temperature measurement capabilities of the SAW sensor, the cantilevered test specimen was subjected to mechanical strain (tension) from a 0.500 kg mass at room temperature (nominally 21.46°C ±0.15°C). The mass was removed after ~15 minutes, leaving the bar unloaded at room temperature. Next the temperature of the bar was raised quickly to 27.3°C and allowed to cool to close to room temperature. Then the bar temperature was raised to 36.89°C and the bar was again allowed to cool. Before the bar cooled to room temperature the 0.500 kg mass was placed on the bar and was removed after ~15 minutes while the bar was cooling. The bar was allowed to cool unloaded for an additional 40 minutes. The results from the strain gauge, the thermocouple, and the temperature compensated SAW sensor and are given in Fig. 2.27.

Fig. 2.27. Temperature compensated SAW sensor data versus strain gauge and thermocouple data.
The compensation method uses both the strain coefficient of velocity and the temperature coefficient of velocity to remove temperature effects from the SAW data. The thermal shock caused by applying a large temperature difference in a short amount of time causes small perturbations in the compensated data that need to be eliminated.

In another experiment the cantilevered test specimen was subjected to mechanical strain (tension) from a 0.500 kg mass at room temperature (nominally 21.46°C ±0.15°C). The mass was removed after ~15 minutes, leaving the bar unloaded at room temperature. Next the temperature of the bar was raised quickly to 78.4°C and allowed to cool. Before the bar cooled to room temperature the 0.500 kg mass was placed on the bar and was removed after ~15 minutes while the bar was cooling. The bar was allowed to cool unloaded for an additional 60 minutes. The results from the strain gauge, the thermocouple, and the temperature compensated SAW sensor are given in Fig. 2.28.
Fig. 2.28. Temperature compensated SAW data versus strain gauge and thermocouple data (peak 78.4°C).

In Fig. 2.28 the red line is the temperature compensated SAW strain data. The dark blue line is the compensated strain gauge data. The light blue line is the uncompensated strain gauge data. The pink line is the uncompensated SAW data. The green line is the thermocouple data. When using the compensation technique the SAW data agrees closely with that of the compensated strain gauge, even at elevated temperatures of 78.4°C. Note that the perturbations are much smaller than those of the previous experiment. This could be due to the difference in how fast the temperature was elevated compared to the previous experiment. In this case the temperature was elevated at much slower rate than in Fig. 2.27.
To further demonstrate the technique another experiment was performed where the 0.50 kg weight was added and removed while the bar was at room temperature then the bar was heated to 107°C. Temperature was allowed to vary slowly by ±2.48°C and the weight (0.50 kg) was again placed on the bar and removed (Fig. 2.29).

Fig. 2.29. Temperature compensated SAW data versus strain gauge and thermocouple data at 107°C.

In Fig. 2.29 the red line is the temperature compensated SAW strain data, the dark blue line is the compensated strain gauge data, the light blue line is the uncompensated strain gauge data, the pink line is the uncompensated SAW data, and the green line is the thermocouple data. When using this compensation technique and a moderate rate of
change of temperature, the SAW data agrees closely with that of the compensated strain
gauge even at elevated temperatures of 107°C.

2.9. Strain Modeling of an OFC Device

As discussed earlier, the change in width of the metal fingers will cause a change in
the height of the metal finger. The changes in the height of the metal fingers will change
the mass loading and the average propagation velocity of the surface acoustic wave. To
understand the effects of strain on the SAW sensor, wavelength changes and metal height
changes were incorporated into the strain model along with velocity changes.

Strain models have been previously included in the coupling of modes approach for
devices on ST-Cut Quartz [36]. Here, the technique was applied to the transmission line
models for devices on Langasite substrates. The technique changes the average wave
velocity by inclusion of strain effects on the wavelength and metal height through the self-
coupling coefficient. The change in metal height is related through the use of the
Poisson’s ratio of the metal. The new wavelength and metal height are given by:

\[ \lambda' = \lambda (1 + \varepsilon) \]

\[ h' = h (1 - \varepsilon V) \]
where \( \lambda' \) is the new wavelength, \( \lambda \) is the original wavelength, \( h' \) is the new metal height, \( h \) is the original metal height, and \( V \) is the Poisson’s ratio of the metal. The new values are used to modify the self-coupling coefficient \((k'_{11})\) which is given by [37]:

\[
k'_{11} = A + B \left( \frac{h'}{\lambda'} \right) + C \left( \frac{h'}{\lambda'} \right)^2.
\]  

(43)

The constants \( A, B, \) and \( C \) are equal to \( A=0.0004, B= -0.02, \) and \( C= 7.9 \) for ST cut Quartz. The constants \( A, B, \) and \( C \) had to be experimentally determined for Langasite and are equal to \( A=2.0, B= -0.3776 \text{ e-6}, \) and \( C= -0.01913\text{e-6}. \) The self-coupling coefficient is used to adjust the metalized velocity for each element. The new average velocity \((v_{a'n})\) is given by:

\[
v_{a'n} = \left( v_0 \left( 1 - k'_{11} \right) \right) \left( (\gamma_s - 1)\varepsilon + 1 \right),
\]  

(44)

where \( v_0 \) is the velocity of surface acoustic waves in an un-metalized, unloaded region of a substrate, and \( n \) is the grating number (in this case \( n=1 \text{ through } 4 \)). The new velocity under the metal fingers of the IDT is called \( v_{m'n} \) and is given by:

\[
v_{m'n} = -\frac{v_0}{2v_0 - \frac{v_0}{v_{a'n} - 1}},
\]  

(45)
The new metallized velocity is also used to calculate the new metallized frequency of each grating \( (f_{m'}^n) \) and is given by:

\[
f_{m'}^n = \frac{v_{m'}^n}{\lambda_n}, \tag{46}
\]

where \( \lambda_n \) is the wavelength of each grating. To calculate the reflector response the radiation conductance must be determined. Since the radiation conductance is frequency dependent, the new conductance must use the new frequency variable. The equation for calculating the conductance \( (G_{a_n}) \) of each grating has been modified to use the new frequency variable \( f_{m'}^n \) from eqn. (46) and is given by:

\[
G_{a'}^n = 8k^2C_s f_{m'}^n (N_t - 1) \left( \frac{\sin \left( \frac{\theta_t}{2} \right)}{\theta_t} \right)^2, \tag{47}
\]

where \( k^2 \) is the piezoelectric coefficient, \( C_s \) is the capacitance per unit length for a pair of fingers, the number of fingers is \( N_t \), and \( \theta_t \) is the transit angle. The susceptance \( (B_{a_n}) \) has been modified as well and is given by:
The new frequency dependent transit angle $\theta'_n(f)$ is calculated by using the new susceptance and is given by:

$$\theta'_n(f) = (2\pi f C_s N_n + Ba'_n)(R_s + Z_e), \quad (49)$$

where $f$ is the frequency, $N_n$ is the number of fingers, $R_s$ is the total lead and metal resistance, and $Z_e$ is the load or source resistance. The new conductance variable is used for computing the transmission matrix elements for a grating. The base element $t_0(f)$ uses the new conductance and the new transit angle variables and is given by:

$$t_0'(f) = \frac{Ga'_n(f)(R_s - Z_e)}{1 + j\theta_e(f)}. \quad (50)$$

Although the frequency change cascades through the other elements by the use of the new conductance ($Ga'_n$) and new transit angle ($\theta'_n$), the equations for the other elements of the transmission matrix do not change. The response for a single grating is found using the same techniques as the transmission line matrix for an IDT and is explained in the modified matrix method [26]. The grating transmission matrix for a
shorted reflector grating is a sub-matrix of the IDT transmission line matrix and is given by: [27]

\[ G(f) = \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} \tag{51} \]

where \( G \) is the grating transmission matrix, and \( g \) is sub-element for the grating matrix, \( t \) is the sub-elements from the modified IDT transmission matrix.

The reflection coefficient (S parameter) \( S_{11} \) is given by

\[ S_{11}(f) = \frac{g_{21}}{g_{11}} \tag{52} \]

For the earlier SAW OFC example, the time delay of each of the four reflectors \( (\tau_i) \) is 0.8601, 0.8634, 0.8635, and 0.87 \( \mu \)s. The metallization thickness used in the model is 0.15 \( \mu \)m. The four gratings have frequencies of 303.71, 304.85, 305.98, and 307.11 MHz arranged in order \( f_1, f_2, f_3, \) and \( f_4 \), with \( f_1 \) closest to the IDT. More diverse arrangements of the frequencies that make up a reflector bank would allow for more code diversity when uniquely identifying the sensor in a multisensory environment [38]. Langasite (La₃Ga₅SiO₁₄) was chosen for the substrate because it has the potential for high temperature operation. Langasite does not have any phase transitions up to its melting point, it is not pyroelectric and therefore, does not lose its piezoelectric properties before it
melts at 1470 °C [39, 40]. This property makes it applicable for harsh environments such as those found in aerospace vehicles. Langasite crystal with an Euler orientation of (0, 138.5, 26.6) was used for modeling. For this orientation and material, the Rayleigh velocity is 2741 m/s.

The reflector banks are positioned on either side of an interdigitated transducer with spacing such that the reflections do not overlap in time. The reflectors are shorted, meaning that for each grating the fingers are connected on the top and bottom through metal bus bars. The reflector gratings for each frequency are electrically isolated from each other. It takes time for the mechanical wave to travel to the reflector banks to be reflected and then travel back to the IDT. The delay to the beginning of the closest reflector bank is \(0.860122 \mu s\) or \(\tau_0\). The time delay of the reflector bank (\(\tau_B\)) is just the sum of the individual time delays for each frequency grating, and is given by

\[
\tau_B = \tau_0 + \tau_1 + \tau_2 + \tau_3. \tag{53}
\]

The time delay of the reflector banks are \(\tau_B = 3.4571 \mu s\) long. The second reflector bank is farther away from the IDT than the first bank. The second reflector bank time delay (\(\tau_{D2}\)) is 5.177 \(\mu s\). The first reflector bank is delayed by \(\tau_0\) from the IDT. The second bank is delayed by the round trip time of two times \(\tau_0\) and twice the time delay of the first reflector bank to insure that none of the reflected signals overlap in time. The delay time for the second reflector bank (\(\tau_{D2}\)) is given by:
\[ \tau_{D2} = 2\tau_0 + 2\tau_B . \]  

The reflection coefficient response of all eight gratings are combined together taking into account the time delay for each grating to give the total frequency response of the device. The total \( S_{11} \) response is given by:

\[
S_{11}(f)_{total} = \sum_{i=1}^{N} S_{11}(f)_i e^{-j2\pi f d_i \tau_i},
\]

where \( S_{11} \) is the single port reflection S parameter, \( f \) is the frequency, \( d_i \) is the delay for each reflector with respect to the IDT, \( \tau_i \) is the time delay of each reflector, and \( N \) is the number of reflectors (eight for this example). Note that the time delay (\( \tau_i \)) of the reflectors is not unique since there are four different reflector designs each with the same time delay. The time delay (\( d_i \)); however, is unique because it spatially locates each of the eight reflectors in reference to the IDT.

The insertion loss of the frequency response is usually converted into decibels and is given by:

\[
IL(f) = -20 \log(|S_{11}(f)_{total}|),
\]
where $IL(f)$ is the frequency dependent insertion loss from the $S_{11}(f)_{total}$ parameter. Using the prototype parameters given earlier, the complete insertion loss for a SAW device with two sets of gratings that correspond to those in figure 2.19 can be calculated. The results are shown in figure 2.30.

![Figure 2.30](image-url)

**Fig. 2.30.** Frequency response of all eight OFC gratings combined, with the subsection used for cross correlation highlighted in blue.
2.9.1. Frequency Detection

The SAW device is interrogated with a network analyzer. Each measurement (strain or temperature) is comprised of many points of $S_{11}$ amplitude data for a range of frequencies. Strain and temperature changes are evident as a shift in frequency of the $S_{11}$ response. The time and frequency response of a SAW sensor with and without a strain is presented in Fig. 2.31.

Fig. 2.31. The time and frequency response of a SAW sensor with and without strain.

The surface plot contains 600 frequency spectrum measurements. Each measurement is 20001 points of $S_{11}$ data ranging in frequency from 304.45 to 304.62 MHz. The data was taken for 25 minutes without any strain. Next, the SAW device was
strained (7.6 µε) for 25 minutes and then the strain was removed. Underneath the surface plot is a contour plot of the same SAW data. Here the step function of strain application and removal is clearly observable. Note that the strain causes a shift to lower frequencies.

There are multiple ways to detect a change of frequency, one way is to use cross correlation to compare a baseline frequency spectrum to the current spectrum. Correlation is often used in communication systems and SAW sensors systems [41]. It can be performed in either the time or frequency domain [42]. The discrete cross correlation function used on the frequency data in the model is given by:

\[
R_{xx}(\tau) = \sum_n x_n x'_n \tau ,
\]

where \( R_{xx} \) is the discrete cross correlation, \( x_n \) is the original signal, \( x'_n \) is the complex conjugate of \( x \), and \( \tau \) is the lag for each signal point.

The measurement system requires a baseline to be taken in a calibration procedure. A subset of the baseline acquired data is gated to capture the main response of the reflector banks and then cross correlated against subsequent data. The subset baseline measurement is used instead of the model response because it includes higher order effects found in real-world systems. The improved correlation is due in part to higher order effects that are captured in the baseline data that are absent from the ideal model response. The model uses a similar gating technique. The model baseline data is gated and used in a cross correlation on subsequent model data sets. The model gated subset response is shown in
blue in figure 2.23. The results of cross correlation that correspond to three cases are shown in figure 2.32. The maximum peaks in figure occur at 303.00 MHz, 302.55 MHz, and 302.10 MHz for 0 με, 700 με, 1400 με respectively.

Fig. 2.32. Correlation peaks for three strain conditions.
2.9.2. Strain Model Results

The final results from the model are in the form of micro strain. These values come from taking the maximum peak of each correlation and referencing the frequency value that corresponds to that peak. The peak frequency for no elongation (zero strain) is used as the baseline. The other values are subtracted from the baseline to yield the frequency shift. The frequency shifts are multiplied by a conversion factor to change them from Hertz (Hz) into micro strain (\( \mu \varepsilon \)). The conversion factor was determined empirically and the value used for the model is 0.000914 \( \mu \varepsilon \) s. The units for the conversion factor are micro strain seconds. The final results are micro strain. Prototype devices have been fabricated (Fig. 2.33). The device was clamped down in a cantilever fashion for initial testing. Weights from 0 kg to 1.0 kg were used for force to apply strain to the device.

Fig. 2.33. Photomicrograph of a prototype OFC Strain sensor. The IDT is in the center with two banks of four reflector gratings on each side.

To demonstrate the model capabilities, data was taken from a SAW sensor and a strain gauge as the load was increased from 0 kg to 1.0 kg in 0.1 kg steps. The experimental setup will be discussed in detail later. The preliminary data from the
prototype SAW strain sensor along with the expected values and the model values are shown in figure 2.34.

![Graph](image)

**Fig. 2.34.** (a) Plot of the SAW strain values for increasing and decreasing strain cases. (b) Plot of the error between the strain gauge and SAW measurements for increasing and decreasing strain cases.

The measurement data from the SAW device for both increasing and decreasing strain agrees closely with the data from the model. The SAW error was calculated by subtracting the SAW measurement data both for increasing and decreasing strain cases from the SAW model. The error is ±400 Hz for the two cases which corresponds to ±1.2με.
2.10. Temperature Modeling of an OFC Device

In a process similar to that of the strain model, temperature effects were added to
the modified matrix by adjusting the velocity of the acoustic wave under the metalized
areas. This was accomplished by adding the thermal expansion parameters to the
wavelength and the metallization height equations, and is given by:

\[ \lambda' = \lambda (1 + (\alpha_1 \Delta T + \alpha_2 \Delta T^2)) , \]  

\[ h' = h (1 - (\alpha_1 \Delta T + \alpha_2 \Delta T^2) V') , \]

where \( \lambda' \) is the new wavelength, \( \lambda \) is the original wavelength, \( h' \) is the new metal height, \( h \)
is the original metal height, and \( V \) is the Poisson’s ratio of the metal. The new values are
used to create a new self-coupling coefficient \( k_{2'11} \) which is given by [37]:

\[ k_{2'11} = A + B \left( \frac{h'}{\lambda'} \right) + C \left( \frac{h'}{\lambda'} \right)^2 , \]

The constants \( A, B, \) and \( C \) are equal to \( A=0.0004 \), \( B= -0.02 \), and \( C= 7.9 \) for ST cut
Quartz. The constants \( A, B, \) and \( C \) had to be experimentally determined for Langasite and
are equal to \( A=353.023 \), \( B= 0.885 \), and \( C= 9.522e-7 \). The new self-coupling coefficient is
used to adjust the metalized velocity for each element. The new average velocity \((v_{a'}n)\) is given by:

\[
v_{a'}n = (v_0(1 - k2^{1/1}))(y_S - 1)e + (y_T - 1)(a_1 \Delta T + a_2 \Delta T^2 + 1),
\]

where \(v_0\) is the velocity of surface acoustic waves in an un-metalized, unloaded, region of a substrate, and \(n\) is the grating number (in this case \(n=1\) through 4).

To demonstrate the temperature models capability, the temperature of the bar mentioned earlier was raised quickly using a heat gun until it reached 45.45°C and allowed to cool while the bar was unloaded. The thermal expansion due to the temperature change is the model input. The results are given in Fig. 2.35.

![Fig. 2.35. (a) Temperature results from model and the SAW sensor. (b) Plot of the error between the SAW sensor and the model values.](image)

The temperature model values closely match the SAW temperature values. The difference is ±750Hz or is less than ±0.35°C.
Chapter 3 Fastener Failure Results

3.1. Experimental Setup

The SAW devices are fabricated on Langasite (La₃Ga₅SiO₁₄) (LGS) substrates. The sensor has two reflector banks which spread the device’s response across multiple frequencies through the use of OFC reflectors [43]. The operation of the multi-track SAW OFC sensor is explained in [44]. The device has two identical tracks where each reflector bank is comprised of four sets of gratings (Fig. 3.1.). Two tracks were required due to fabrication constraints. The gratings in each track reflect a different frequency and are arranged sequentially in ascending order as they are positioned further from the IDT. The same four frequencies are used in all four reflector banks and are mirror images of each other laterally. To avoid interference, the reflector banks in each track are positioned on either side of an interdigitated transducer with spacing such that the reflections do not overlap in time.
Fig. 3.1. SAW OFC strain sensor. The tracks are shown in yellow, the IDTs, reflector banks, and electrical contacts are all identified in black.

Placing the SAW device under tension will result in a reduction of operating frequency. While compression of the SAW device will result in an increase of operating frequency. This change in frequency is proportional to strain and is due in part to the change in the wavelength and a change in the average propagation velocity of the surface acoustic wave. Similarly, thermal expansion causes a decrease in operating frequency and thermal cooling and contraction causes an increase in operational frequency.

For this investigation a SAW strain sensor was installed on a stainless steel bar with a foil strain gauge (Fig. 3.2). The OFC SAW strain sensor was bonded to a 45.75 cm long, 5 cm wide, 0.635 cm thick bar of 304 stainless steel. Stainless steel was chosen because it has a Young’s modulus (193 GPa) that is close to that of Langasite (Young’s Modulus of 110–188 GPa depending on the orientation). A conventional foil strain gage was bonded to the stainless steel bar also. A type K thermocouple was placed in contact
with the between the SAW sensor and the strain gauge. The bar was configured for cantilever loading. Static loading using a cantilever beam is a common method for acquiring strain measurements [45-47].

![SAW Device and Strain Gauge](image)

**Fig. 3.2.** (Top) Stainless steel bar with SAW and Strain Gauge sensor. (Bottom) Close up of Strain Gauge and SAW sensors.

The instrumentation used for data acquisition is shown in Fig. 3.3. The OFC SAW sensor is connected to an Anritsu 2026B 6 GHz Network Analyzer, which is in turn connected to the host computer through a USB interface. The conventional strain gauge is a general purpose $350 \Omega$ foil strain gauge part number WK-13-125AD-350W from Vishay.
The strain gauge is connected to a NI 9236 quarter bridge analog module. The type K thermocouple is connected to a NI 9219 universal analog module. Both modules are installed in a National Instruments cDaq 9178 chassis which connects to the host computer through another USB interface. The host computer is a laptop running National Instruments Labview for synchronization and control of the network analyzer and cDaq system. The Labview program also collects and stores the data.

Fig. 3.3. Experimental Setup. The SAW sensor is connected to a network analyzer which is in turn connected to the host computer. The conventional strain gauge and thermocouple are connected to a cDaq data acquisition system which is connected to the host computer.
3.2. Fastener Failure Results

The testing was performed on a panel that was developed for evaluating technologies for use as a testbed for detecting fastener failure in aeronautical applications. The procedure for simulating fastener failure is similar to one that has been used by Rosenstengel [39]. A panel with bolted side stiffeners was used to simulate repeatable fastener failure. This panel is similar to panels suggested by Worden for Structural Health Monitoring (SHM) [48]. The aluminum panel is 63.5 cm wide and 93.98 cm long. The panel is 2.286 mm thick and is made from aluminum (6051 alloy). The side stiffeners are made of 2.54 cm “L” shaped aluminum (6051 alloy) extrusions that are 1.587 mm thick. The bolts are spaced 50.8 mm apart. The root of the panel was mounted to a steel plate using 26 bolts and a 62.865 cm x 5.08 cm x 7.62 cm base plate of aluminum on top of both the panel and side stiffeners. A 62.865 cm x 2.54 cm x 1.27 cm steel plate was attached to the end of the panel to distribute the force from hanging weights (Fig. 3.4).

In addition to previous work, the SAW cables were placed inside of a wire braid to provide added electrical shielding. The addition of the braid reduced the electrical noise considerably and enabled single fastener failures to be detected 80 cm away from the sensor. The method of using strain gauges to detect fastener failures can also be used for detection of disbonds in composite structures [49].
3.2.1. Single bolt removal results.

To determine the distance at which the SAW sensor could detect a single bolt being removed, all of the bolts were installed and tightened to the same value of 14.7 Nm ± 1 Nm. Three experiments were performed in which single bolts at three different locations were removed and then subsequently reinstalled. Data was taken for three loading conditions with all fasteners installed and then a single bolt was removed. Data was then taken for the same three loading conditions. After the data was acquired the bolt was reinstalled and tightened to the initial value. The bolts that were removed were number 8, number 12, and number 16. Both the strain gauge and the SAW sensor were measured using the same test equipment that was mentioned earlier (Fig. 3.3).
It is known that removing and re-tightening a bolt causes small changes in state of a structure, in this case the panel. Multiple changes, such as those from removing and installing multiple bolts, could add to create changes that would be large enough to cause significant errors between the experiments. However, each data set begins by taking a baseline measurement without any loading. The process of taking new baselines for each run negates any small changes in the state of the panel that may be introduced by removing and re-tightening bolts. The new baseline process allows for comparisons between the three experiments without a compounding of errors as bolts are removed and re-installed.

The error bars in the graphs (Fig. 3.5, 3.6, 3.7, 3.12, 3.13, 3.14) indicate Fisher’s Least Significant Difference (LSD). The LSD was chosen over the standard deviation and standard error because it is better suited to graphical interpretation. If the error bars do not overlap between the two points for each loading condition, then they are statistically significantly different at that alpha level (alpha =1% or $\alpha=0.01$ for this work). If the error bars do overlap then they are not significantly different at the alpha level mentioned.

To determine the LSD first the Sum of Squares for Error (SSE) is calculated using:

$$SSE = \sum_{i=1}^{N} (x_i - \bar{x})^2.$$  \hspace{1cm} (62)

Where $x_i$ is the individual measurement and $\bar{x}$ is the mean of the measurements. Next, the Mean Sum of Squares is found using:
\[ MSE = \frac{SSE}{N-k}. \quad (63) \]

Where \( N \) is the number of measurements in the data set and \( k \) is the number of data sets. For this work \( k = 2 \). The LSD is calculated by:

\[ LSD = t(\alpha, df) \sqrt{MSE \left( \frac{2}{N} \right)}. \quad (64) \]

Where \( t(\alpha, df) \) is the cumulative probability function for the t-distribution, \( \alpha \) is the level of significance or the cumulative probability and \( df \) is the degree of freedom \( (df = Nk-k) \).

For the first experiment, SAW data was acquired with loading of 0 kg, 1 kg, and 2 kg with all of the bolts tightened. Next, bolt number 8 was removed (52 cm way from the sensor) and data was acquired for all three loading cases (Fig. 3.5).
To determine if a single bolt has been removed the following criteria is proposed: if the LSD error bars from the two states do not overlap then they can be resolved as independent and therefore the condition that a single bolt has been removed can be assumed. If the LSD error bars for the two cases do overlap then they cannot be resolved as independent and the condition that a single bolt has been removed cannot be assumed. Using these criteria for the condition of one bolt being removed (#8), the SAW sensor could delineate a single bolt being removed for all three loading cases.

For the second experiment, SAW data was acquired with loading of 0kg, 1kg, and 2kg with all of the bolts re-tightened (bolt #8 re-installed). Next, bolt number 12 was removed (65.5 cm) and data was acquired (Fig. 3.6). The SAW device detected the single bolt being removed for all three loading conditions using the criteria presented earlier. But
the lines (means values) are beginning to become closer for each case. If the trend continues there is a limit to the distance at which a single bolt being removed can be detected.

For the third experiment, the SAW data was acquired with loading of 0kg, 1kg, and 2kg with all of the bolts re-tightened. Next bolt number 16 was removed (80 cm) and data was acquired for all three loading cases (Fig. 3.7). Although the lines come close to one another at the lower loading cases the error bars do not overlap and therefore the SAW device could detect the single bolt being removed for all three loading conditions using the criteria presented earlier. Again the lines are closer together for this case than they were for the two previous experiments. Assuming the trend is linear then the maximum distance

Fig. 3.6. SAW sensor strain data for three load conditions and for 6 cases of bolt removal with bars indicating the least significant difference values ($\alpha=0.01$).
at which the SAW device can detect a single fastener being removed is estimated to be 92.25 cm. At that distance it is estimated that the LSD bars will touch, making the difference between them not statistically significant.

![Bolt Removed](image)

![Graph](image)

**Fig. 3.7.** SAW sensor strain data for three load conditions and for 6 cases of bolt removal with bars indicating the least significant difference values (α=0.01).

It may be possible to improve the detection of fastener failure through the use of models or sensor fusion. Improved detection has been demonstrated utilizing a Bayesian sensor fusion approach [50]. Models of fastener failure have likewise demonstrated their usefulness in diagnosing damage and in giving prognosis for the rate at which the damage accumulates [51]. Mesh-independent models have also been developed to help determine the behavior of fasteners as they fail [52]. Techniques such as these could increase the coverage area of a SHM fastener detection system.
3.3.2. Fastener failure detection in the presence of structural vibrations.

Monitoring of dynamic loading during flight is important for SHM and fatigue life analysis [49]. Fastener failure detection using conventional strain sensors has been difficult during flight due to the dynamics of aircraft loading and the vibrations that are generated. The data is random and on the order of magnitude of the measurement. Strain is often measured on NASA’s research aircraft at Dryden Research Center. Typically small aircraft can experience vibrational noise in the range of \( \pm 60 \mu\varepsilon \) peak-to-peak while the aircraft experiences up to 1000 \( \mu\varepsilon \) loads during flight (Fig. 3.8). These strain measurements are similar in magnitude to those taken on other research aircraft [53, 54].

![Fig. 3.8. Strain sensor vibrational noise from four locations on the wing leading edge during takeoff.](image)

The data in Fig. 3.8 is from four strain sensors mounted on the wing leading edge during takeoff. The raw sensor data was filtered with a two point moving average. The moving average was subtracted from the original data leaving the vibrational noise only. The structural noise, which is mostly due to vibrations of the aircraft, is \(-60 \mu\varepsilon\) to \(+85 \mu\varepsilon\).
Even the bulk of the vibrational noise which is $\pm 20 \, \mu \varepsilon$ peak to peak is a large signal compared to the $\pm 2 \, \mu \varepsilon$ change due to a faster failure.

Although conventional strain gauges are not well suited for this application, SAW strain gauges are capable of achieving accurate measurements in high vibration environments. For applications such as fastener failure detection, SAW sensors are interrogated in the frequency domain with very high frequency resolution (very small frequency steps). Reducing the frequency step size for a fixed bandwidth will increase the number of samples taken by the network analyzer. For most systems, this will take longer for a full sweep to occur. For this application the aircraft vibration is considered to be high frequency random noise in the frequency domain. Conventional strain gauge measurements can be filtered but the random nature of the signal will increase the noise level in the measurement. SAW devices interrogated in the frequency domain will measure the vibration as a high frequency signal imposed upon the nominal $S_{11}$ values. When filtered this signal is almost entirely removed from the $S_{11}$ data and is further reduced by the cross correlation function. The results from SAW devices have less noise than those from conventional strain gauges and therefore are capable of detecting fastener failures during aircraft flight.

To demonstrate the SAW sensors capability for reducing the vibrational noise, a small electric motor with a flywheel and a 30g mass was used to create vibration in the panel that was used for earlier tests. The mass was located 1.43cm from the center of the flywheel attached to the shaft. For this example, a 1kg weight was hung from the panel and data was taken by both the conventional strain gauge and the SAW sensor (Fig. 3.9.).
Fig. 3.9. Strain vibrational noise from electric motor when panel has 1kg load.

The strain gauge vibrational noise from the motor increased from ±1 µε to a range of ±10 µε. At the same time the SAW strain measurements increased from ±1 µε to ±1.49 µε. The reason that the SAW measurements do not have a larger magnitude of vibrational noise is because of the way in which they are interrogated and post processed. The SAW sensors are interrogated using a network analyzer that sends out a chirp of frequencies and measures the amplitude of the response. The base data is an $S_{11}$ frequency response. Figure 3.10 compares the raw $S_{11}$ data and the same data after it has been filtered. By taking 8001 points with an intermediate frequency bandwidth setting of 1000 kHz, the vibrational noise is captured as a ripple of varying amplitudes on the frequency response. The ripple is filtered out almost entirely with a simple low pass FIR filter. Furthermore, the frequency data is cross-correlated with baseline data further reducing the vibrational
noise level in the SAW measurements during post processing. Filtering and averaging of the SAW strain frequency data reduced the vibrational noise to a usable level. It would be difficult if not impossible to filter the amplitude vibrational noise from the strain gauge and receive the same results. This is not surprising since the vibrational noise on the strain gauge is amplitude noise in the time domain while the noise on the SAW sensor is amplitude noise on frequency data where the signal information is a frequency shift. Therefore, this is similar to comparing an Amplitude Modulated (AM) radio signal to a Frequency Modulated (FM) radio signal. To further reduce the vibrational noise on the SAW signal, the centroid was taken after the cross correlation was performed. The centroid value method was used here instead of the maximum from the cross correlation, which was used previously. This reduced the vibrational noise by close to a factor of 2.

![Fig. 3.10. SAW S11 raw data (with vibrational noise) and filtered data (noise removed).](image-url)
To demonstrate the SAW sensor’s ability to detect fastener failures in the presence of vibrational noise, the previous experiment with Bolt #8 was repeated only this time the electric motor was used to create noise in the system. Data was acquired when the motor (noise source) was on and the load was changed (0kg, 1kg, 2kg, 0kg) with all of the bolts installed and, then bolt #8 was removed (52 cm way from the sensor), and the four loading conditions were repeated (Fig. 3.5). The SAW data contains minimal vibrational noise while the vibrational noise level on the conventional strain gauge makes fastener failure detection difficult (Fig. 3.11).

![Graph showing SAW and strain gauge data for three loading conditions with vibrational noise, and with and without bolt #8.](image-url)

**Fig. 3.11.** SAW and strain gauge data for three loading conditions with vibrational noise, and with and without bolt #8.
The plot in Fig. 3.12 was created using the data from Fig. 3.11 and applying the least significant difference method with $\alpha=0.01$.

Fig. 3.12. SAW sensor strain data for three load conditions and for 6 cases of bolt removal with bars indicating the least significant difference values ($\alpha=0.01$).

The plots in Fig. 3.12 are closer for the case with vibrational noise; however, since they do not overlap the values are statistically significantly different at $\alpha=0.01$ level. Therefore, it can be said that the SAW sensor can detect a fastener failure 52 cm away from the sensor in the presence of vibrational noise. It is interesting to note that the when bolt #8 was removed for the case with vibrational noise the strain is lower than with the bolt installed.

For the second experiment with vibrational noise, SAW data was acquired with loading of 0kg, 1kg, and 2kg with all of the bolts re-tightened (bolt #8 re-installed). Next, bolt number 12 was removed (65.5 cm) and data was acquired (Fig. 3.13). The lines
plotted are well separated and the error bars (LSD) do not overlap; therefore, the SAW device detected the single bolt being removed for all three loading conditions using the criteria presented earlier. With vibrational noise the plots (mean values) are farther away than for case without vibrational noise for either bolt #8 or #12. The strain patterns are very asymmetric and change for the cases with and without vibrational noise.

Fig. 3.13. SAW sensor strain data for three load conditions and for 6 cases of bolt removal with bars indicating the least significant difference values ($\alpha=0.01$).

For the third vibrational noise experiment, the SAW data was acquired with loading of 0kg, 1kg, and 2kg with all of the bolts re-tightened. Next bolt number 16 was removed (80 cm) and data was acquired for all three loading cases (Fig. 3.14).
The error bars (LSD) do not overlap and therefore the SAW device could detect the single bolt being removed at 80 cm for all three loading conditions using the criteria presented earlier. Note that the average strain values are a similar distance at 80cm than they were at 52 cm. The data for the three bolts being removed in the presence of structural vibrational noise does not have a clear trend therefore a prediction cannot be given for the maximum distance at which the SAW device can detect a single fastener being removed in the presence of vibrational noise.

Although fastener failure detection using conventional strain sensor has been extremely difficult during flight due to the dynamics of aircraft loading and the vibrations that are generated, SAW devices have been demonstrated to be capable of fastener failure
detection in a laboratory environment. Future flight testing will hopefully fully demonstrate the capability of SAW sensors for fastener failure detection.

Even if SAW devices do not work in as standalone sensors for fastener failure detection, a combination of SAW sensors and hybrid NDE and SHM could overcome these issues. The hybrid NDE/SHM would combine traditional ground NDE methods with the use of external load and/or excitation methods combined with fixed sensors and onboard SHM systems (Fig. 3.15).

Fig. 3.15. Concept for a Hybrid NDE/SHM Fastener Failure Detection System which would combine traditional NDE methods with SHM through the use of external load and/or excitation methods combined with fixed sensors and onboard SHM systems.
Load conditions, fatigue, and cracks could be monitored during flight using an SHM system and SAW OFC strain sensors. Ground testing including NDE instrumentation could be used to load the structure statically allowing for accurate measurements for detection of fastener failures. The proposed hybrid system does not have to be limited to fastener failure detection. It could incorporate an onboard fiber optic strain sensors that can be used for thermographic measurements when external heat sources are used to excite the structure. Passive ultrasonic sensors could be installed as part of the SHM system and would yield better coverage of the structure if external sources where used to excite ultrasonic waves. These techniques could be further combined with digital twin technology. The U.S. Air Force is considering the feasibility of creating a digital twin for all new aircraft. “The foundation of the digital twin will be a high fidelity structural representation of the entire aircraft. This model will be capable of taking inputs of aerodynamic loads from either actual or forecasted usage and determining the stresses, strains, temperatures, and other environmental states in the structure. This information will be used to drive damage progression models that are tightly coupled to the structural model.”[55] Allowing external systems to provide feedback to the onboard SHM system will dramatically increase the effectiveness of SHM systems. This feedback, which is necessary for a digital twin implementation, could also be used to test the effectiveness of SHM/NDE systems thereby identifying the deficiencies and generating updates that will overcome those limitations in future systems. In this manner, digital twin technology will drive improvements in successive generations of hybrid SHM/NDE systems.
Chapter 4 Impact Detection

4.1. Multifunctional SAW Strain Sensors

Early detection of events such as impacts is crucial for initiating maintenance and nondestructive evaluation of structures to capture potential damage before it has a chance to progress and cause catastrophic failure. SAW strain sensors are multifunctional and can be used for detection of impacts while monitoring strain, fatigue, and/or fastener failures. Vibrations caused by impacts create stresses upon the SAW device and are measured as strain.

Note that the vibrations are not the same as waves commonly used for acoustic emission. This is similar to the use of accelerometers for detection of impacts [56]. Acoustic emission uses waves that travel at higher velocity than simple vibrations of the structure. The vibrations caused by an impact are very high frequency events when compared to measuring strain changes or vibrational noise. A high pass filter can be used to demodulate the impact strains from the frequency response data. At the same time a low pass filter can be used to remove the vibrational noise and the impact strain from the signal. Both measurements can occur simultaneously therefore, SAW sensors are multifunctional.

4.2. Impact Detection Results
Two acoustic emission sensors were placed on the panel. The first (AE #1) is located 6.7cm away from the impact and is 44.5cm from the SAW sensor. The second acoustic emission sensor (AE #2) was placed 49.5cm from the impact and is 3.5cm from the SAW sensor. For the first set of experiments, pencil lead break tests were performed at 51cm and 2.5 cm from the SAW device but there was no response. To demonstrate the ability of SAW sensors to detect impacts, a 46g mass was dropped from a height of 46cm onto the panel 51cm away from the SAW sensor (Fig. 4.1). The impact energy is 0.208 J. This experimental setup is commonly used in impact detection studies [57].

![Amplitude vs Time Graph](image)

**Fig. 4.1. Response from Acoustic Emissions sensors to ball drop tests.**

The acoustic emission sensors detected the ultrasonic waves generated by the impact. The signal-to-noise ratio (SNR) for the acoustic emission sensors is 29.3 dB for AE #1 and 41.9 dB for AE #2. The signals and SNR are both typical for acoustic emission
signals. For these sets of tests, the SAW device did respond with a measurable signal that is analogous to the acoustic emission signal although the SAW signal is not measuring ultrasonic waves but is instead measuring the slower vibrations caused by the impact (Fig 4.2).

![Fig. 4.2. (a) Unfiltered phase response from S11 of SAW sensor during impacts and (b) response filtered using a high pass filter.](image)

The impacts create a measurable phase and frequency shift of the SAW signal. The phase data from the S11 frequency response was used to make the measurements because the phase gives more consistent amplitudes from the impacts. Both the unfiltered phase and high pass filtered data are given in Fig. 4.2. Note that the SAW data looks similar to the acoustic emission sensor AE #2 which was only 6.7 cm from the impact while the SAW sensor is 51 cm from the impact. The average SNR for the SAW sensor is 50.4 dB. These SNR ratio results are similar to those published by others [58, 59]. The SAW signals are a similar shape to those from an AE sensor and have similar if not better SNR ratios and therefore can be used as an impact detector.
To demonstrate the ability of the SAW sensor to detect impacts in the presence of noise the mass was dropped twice without any vibrational noise and then the motor was turned on to create vibrational noise on the panel and then the mass was dropped three times. The raw unfiltered phase data for both with and without noise is given in Fig. 4.3.

The SAW sensor data shows the noise effects as ripples on the phase data, however, the impact is a much higher frequency event and has a larger amplitude. Although the impacts are discernible in the plot, high pass filtering of the phase data removes all of the vibrational noise and the natural shape of the phase data (Fig. 4.4).

Fig. 4.3. Unfiltered phase response from S$_{11}$ of SAW sensor during impacts (a) without vibrational noise, and (b) with vibrational noise.
Fig. 4.4. Phase response from $S_{11}$ of SAW sensor during impacts with and without vibrational noise, after high pass filter.

Although there is some variation in the amplitudes of the impacts, in general the results are fairly consistent for both cases without noise (impacts #1, and #2) and with noise (impacts #3, #4, and #5). The average SNR ratio for all five impacts is 51.03dB. These results are very encouraging for use of the SAW sensor as an impact detector in the presence of noise.

More characterization of the SAW sensor for impact detection is needed. The maximum distance from the impact location to the SAW sensor needs to be investigated. A large structure will have to be used for this effort. Since the SAW sensor detected an impact at 51 cm that was similar to the AE sensor #2 at 6.7cm then it may be possible for the SAW sensor to detect an impact 3.768m away at the same signal strength as AE sensor #1 which was 49.5cm from the impact. Impact location is another application that could be investigated using SAW sensors.
Conclusion

A SAW sensor has been developed that incorporates OFC reflectors. The sensor is capable of detecting single fastener failures under static loaded conditions (1 kg, 2 kg) for aerospace applications. The average electrical noise for the SAW sensor on the panel is ±0.389 ppm. In general terms when the loading on the panel increased, a larger response was recorded. The average value for single fastener with zero load is 0.221 με, for 1 kg it is 0.695 με, and for the 2 kg case it is 0.848 με. The larger the loading on the panel, the greater the strain change when a fastener fails. The maximum variation during bolt removal for the three loading cases is less than 2 με. The SAW devices are so sensitive that removing bolts 52 cm to 80 cm away from the SAW sensor could be detected. Extremely small strains were detected during static loading. The average strain value measured for a single bolt being removed under zero load is 0.588 με.

Due to the amplitude nature of the vibrational noise in the time domain, conventional strain gauges are not able to detect the fastener failures in the presence of vibrational noise. However, since SAW strain sensor measurements are in the frequency domain they can be filtered to remove the vibrational noise and thus able to detect fastener failures. The results show that SAW strain sensors successfully detected single fastener failures at distances up to 80 cm from the failure site under loaded conditions and with the presence of vibrational noise.
SAW sensors have demonstrated the ability to detect impacts with and without the presence of noise from a distance of 51cm. Although this method does not detect ultrasonics signals it does detect vibrations caused by impact. Because the impact signal is a high frequency event, it can be detected while measuring strain for other purposes such as loading, fatigue, or fastener failures. This ability to simultaneously detect strain and impacts makes the OFC SAW sensor a multifunctional device.

Increased sensitivity may also enable the ability to detect cracks and monitor crack growth. SAW is a multifunctional enabling technology. SAW technology offers benefits that will allow the incorporation of large numbers of SHM sensors on future aircraft.
Bibliography
Bibliography


A need has been identified for automated design tools for Surface Acoustic Wave (SAW) devices. If we develop and integrate these tools with commercial Electronic Design Automation (EDA) tools, we can take advantage of what already exists, such as 3D modeling, Electro-Magnetic solvers, Finite Element Analysis (FEA), simulation engines, and netlist generators. When designing new electronic devices it takes a considerable amount of time to create, simulate, and analyze the device. To reduce the time for this effort, EDA tools have been developed to reduce the amount of time it takes to create a design, simulate it, and analyze the results. Because the design effort is often an iterative process, the reductions have a multiplicative effect which further increases the amount of productivity. Other benefits include an increase in the level of abstraction which allows the designers to become more productive by allowing the EDA tool to keep track of design details. An increased level of abstraction thus enables an improvement in productivity.

The lack of integrated design tools for SAW devices has led us to develop tools that will address the issues raised here. Starting from the bottom up we found it necessary to develop a parameterizable library for the layout of SAW devices. This library is much like the standard cell libraries one finds in most EDA tools. We implemented the library as a layout Generator in CoventorWare’s® Designer tool. This library allows the user to input parameters which are used to generate detailed layouts of SAW components such as delay...
lines, resonators, and sensors. This library offers the highest level of abstraction by asking the user for salient parameters for the overall device and not detailed coordinates for each and every element that comprises the SAW device.

To achieve a higher level of abstraction we created first order models of the SAW devices in our parameterizable library. These models were created using a standard mixed signal system language VHDL-AMS. Along with the models we created analysis tools which graphically present the modeling results. The models increase the level of abstraction by using behavioral inputs instead of device parameters. The models generate the parameters necessary for the parametric library thus, closing the loop and eliminating any errors caused by hand transferring of data between tools.

In addition to the benefits already mentioned by integrating our tools within an existing commercial tool set, we have the added benefit of the modeling and analysis tools that are available within the Coventor tool suite. The existing tools allow us to create 3D models of the device which can be used by Coventor’s collection of solvers (electrical, mechanical, thermal, fluidic, piezoelectric, etc.) to achieve finite element modeling. When the design is finished, the tools generate a netlist from the layout for device fabrication. So instead of developing tools that already exist, we have integrated our tools into an existing framework to save development time of tools and to ultimately save development time of SAW devices.

This effort allows us to generate layouts of SAW devices with the push of a button. The simulation models in conjunction with the analysis tools allow for quick analysis of system concepts. We have even included some rudimentary automated optimization. The
inputs are high level parameters which are used to generate detailed layouts for device fabrication. These tools will enable us to prototype our designs in a fraction of time it takes without them.

Most commercial EDA tools have included a provision for the creation and execution of macros. Coventor’s Designer tools are no exception. In the Designer tool the interface is called a Generator. The Generator uses the standard Tool Control Language (Tcl) to create the macros. We utilized the Tcl language to create Generators (macros) that automatically generate layouts of SAW devices. We created several generators for basic SAW IDT structures, delay lines, and resonators. Figure A.1 is an example of the Tcl code that generates a simple IDT structure.
proc Basic_IDT { obj sname layer dfinger_L dfinger_O

    dfinger_W inum_fingers dbus_bar_h
    |
    global error_count
    set Length [expr($inum_fingers*4*dfinger_W-$dfinger_W)]
    set Gap [expr($dfinger_L-$dfinger_O)]
    # Top comb fingers
    #=======================
    # Finger origin of the first finger
    set FOx [expr 0]
    # Loops over all movable fingers
    for {set i 1} {$i <= $inum_fingers} {incr i} {
        # Draws the movable comb finger
        set finger [cat:rectangle -layer $layer $FOx
        [expr ($Gap+$dbus_bar_h)]
        [expr ($FOx+$dfinger_W)]
        [expr ($Gap+$dbus_bar_h+$dfinger_L)]]
        $obj addObject $finger
        # Next finger origin
        set FOx [expr $FOx + 4*$dfinger_W]
    }
    # Bottom comb fingers
    #=======================
    # Finger origin of the first finger
    set FOx [expr (2*$dfinger_W)]
    # Loops over all fixed fingers
    for {set i 1} {$i <= [$expr $inum_fingers]} {incr i} {
        # Draws the fixed comb finger
        set rect [cat:rectangle -layer $layer $FOx
        $dbus_bar_h
        [expr $FOx+$dfinger_W]
        [expr ($dbus_bar_h+$dfinger_L)]]
        $obj addObject $rect
        # Next finger origin
        set FOx [expr $FOx + 4*$dfinger_W]
    }
    # Top Electrode
    #------------------
    set rect [cat:rectangle -layer $layer 0
    [expr ($dbus_bar_h+$Gap+$dfinger_L)] $Length
    [expr ((2*$dbus_bar_h)+$Gap+$dfinger_L)]]
    $obj addObject $rect
    # Bottom electrode
    #------------------
    set rect [cat:rectangle -layer $layer 0 0 $Length
    $dbus_bar_h]
    $obj addObject $rect
    return
}

#---------------------------------------------------------------------------------

Fig. A.1. Example Tcl code that generates a simple IDT structure.
Using the Tcl code of figure A.1 as a starting point we created a SAW delay line layout generator by expanding the code to include both transmit and receive IDTs. We also improved the code by adding a means of annotating the layout with the design parameters. We found it necessary to increase flexibility by adding the ability to change the X and Y offset of the device. The layout generator automatically creates a dialog box for the input parameters, but it is not necessarily clear what the variables represent. To remove all ambiguity we created graphics in html and linked them to the layout generator using the help feature. These enhancements are all found in the layout generator we named Basic_SAW_Delay. The SAW delay line generator takes as inputs the length of the fingers, the amount of overlap between the fingers, the width of the fingers, number of finger pairs, the height of the bus bars, and the length of delay between the two SAW devices. Once the parameters are entered into the dialogue box figure A.2, a layout is generated (Figure A.3). This layout can be used to create 3D models of the device and netlists which can be used to create fabrication masks.
Fig. A.2. Layout Generator dialogue box. This dialogue box is where the parameters for the basic SAW delay line are input. We used the “Help” feature to include the graphic of the SAW delay device found above the parameter entry area.
To demonstrate the capability of the layout generator we used the generator and the Basic_SAW_Delay component as shown in figure A.2 to generate the layout of a SAW delay line with a wavelength of 60 μm. The fingers are 15 μm wide with 15 μm wide spacing between them. The number of finger pairs per IDT is 10, and alternate fingers are attached to bus bars that are 50 μm high. The aperture or finger overlap is 980 μm out of the 1000 μm finger height. The delay length is input in multiples of the wavelength (seven in this case), but is calculated as $7\lambda - 1/4 \lambda$ or $7 \times 60 - 60/4 = 405$ μm between the fingers of the two IDTs. The subtraction of $1/4 \lambda$ is necessary to maintain the phase relationship between the first and second IDTs. Figure A.3 is the output of the layout generator. The layout is automatically annotated with the device parameters. The text used for annotation utilizes a low flash count font. This self-documentation feature is useful when placing many different devices on a wafer.
Fig. A.3. Automated Layout result for a basic SAW delay line. The device consists of two IDTs with finger heights of 1000 μm, finger widths of 15 μm, 10 finger pairs each with an aperture of 890 μm. The bus bar heights are 50 μm, and the delay between the two IDTs is 7 wavelengths.
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