Series-connected Interdigitated Surface Acoustic Wave Sensors for Structural Health Monitoring

Goutham R.Kirikera^{1,2} and Sridhar Krishnaswamy^{3,2}

Abstract: Active health monitoring using narrowband Raleigh-wave or modeselective Lamb-wave actuation and reception involves the use of a pair of matched multi-element transducer arrays. The spacing of the elements of the transducer arrays dictates the Lamb mode wavelength, and by appropriate choice of drive frequency, a specific mode can be selected. Typically, the elements of the transducer array are all connected in a parallel configuration and are used for both excitation and reception. It is shown in this paper that for reception a series connected transducer array results in better performance. Connecting multiple electrodes in a series configuration allows the summing of individual voltages generated by each piezoelectric transducer and it is shown that this results in better sensor performance.

Keywords: Continuous Sensors, Mode selective excitation/reception, series configuration transducer array, parallel configuration transducer array

1. Introduction:

Surface Acoustic Wave (SAW) devices have been used in various applications including as SAW filters and delay lines. More recently, SAW sensors have been used as acoustic wave sensors for anomaly detection in various engineering applications including: biosensing to identify damage in bones [Toda et al (2005)], chemical sensing to identify analyte changes [Dong et al (2001)], surface acoustic wave gyro sensor to detect changes in angular velocity [Kurosawa et al (1998)], health monitoring of structures [Monkhouse et al (2000)], and wireless sensors [Pohl (2000)]. For many applications, the aim is to generate an acoustic wave *within* a single piezoelectric substrate, part of which has electrodes to excite the waves and part of which has electrodes to receive the propagating waves [Ryoer et al (1999)]. Any change in the material properties of the piezoelectric substrate due to an anomaly

¹ Pressent address: Geophysical Research Company LLC. Tulsa, OK 74115

² Center for Quality Engineering and Failure Prevention, Northwestern University, Evanston, IL, 60208

³ Contact author: s-krishnaswamy@northwestern.edu

results in a changed waveform (amplitude/phase/frequency) which can be correlated to the anomaly information [Dong et al (2001)]. The SAW sensors can have various configuration of electrodes. The most widely used sensors have interdigitated electrodes placed on the surface of the piezoelectric substrate.

For structural health monitoring applications, the SAW sensors are used to launch and receive surface or Lamb waves in structures which themselves are not piezoelectric. These SAW sensors typically use thin piezoelectric elements with electrodes on both faces, and the whole sensor is insulated and bonded onto the structure [Petculescu et al (2008)]. A good example of using piezoelectric elements is shown in the article by Kuhn et al [2009] where they mention monitoring safety critical aircraft components using piezoelectric materials in a pitch catch mode. Since this configuration allows access to both sides of the piezo-material, creative ways to connect the interdigitated electrodes in parallel or in series are possible. Since plate structures can support several acoustic modes that are dispersive, it is often useful to be able to generate and receive single modes at frequencies where they are least dispersive [Petulescu et al (2008)]. Such narrowband minimallydispersive wavepackets can travel large distances in the structure and be used to effectively discern anomalies such as debonds, cracks or delaminations. Various methods exist to excite and receive a specific Lamb mode in a plate structure including: (a) use of multi-element transducer arrays spaced according to the mode that requires to be excited and received [Petculescu et al (2008), Drafts (2009)]; (b) conventional piezoelectric transducers coupled to the structure via an angled wedge whose angle is chosen appropriately based on Snell's law [Rose (1999)]; and (c) use of electromagnetic acoustic transducers (EMAT) based on meander-coil design [Rose (1999), Thompson et al (1972)]. In this paper, we use the first approach but propose a new transducer configuration for the receiver transducer with improved performance. The proposed transducer configuration involves connecting multiple piezoelectric elements in a series configuration (also called continuous sensor) to receive a specific mode of interest. Series connected sensor arrays have been proposed in the past for other purposes. For instance, Sundaresan et al [2002, 2001] proposed what they call a "continuous sensor" with multiple piezoelectric elements joined in a series configuration to identify the location of acoustic emissions. Martin et al (2001) and Ghoshal et al (2005) have performed simulations of such continuous sensors and have developed wave simulation algorithms based on the continuous sensor architecture to detect the locations of acoustic emissions. Kirikera et al [2007, 2008 (1)] have developed the concept of a "structural neural system" using continuous sensors to identify in near real time the location of an acoustic emission due to crack growth in wind turbine blades [2008 (2)]. In this paper, we show that the architecture of connecting multiple elements in series is in fact better suited than a parallel sensor configuration for sensing of a single Lamb wave mode propagating in a structure.

The first section of this paper provides analytical modeling of the parallel configuration and the series configuration arrays. The parallel configuration transducer array is hereafter referred to as PCTA and the series configuration transducer array is referred to as SCTA. Experimental results described in the second section of this paper confirm that the SCTA configuration is indeed the better choice for reception.



Figure 1: Geometric view of the electrodes on a PZT sensor (a) PCTA configuration (b) SCTA configuration.

1 Array Sensor Architecture:

Figure 1 shows the architecture of parallel and series connected piezoelectric transducer arrays fabricated on a piezoelectric substrate. The basic feature common to both configurations is that they comprise a number of equally-spaced copper electrodes on a piezoelectric material forming the individual elements of the transducer array. The spacing of the array elements is designed to be equal to the wavelength of the acoustic wave that is of interest. In the parallel configuration shown in Fig.1a, the bottomside of the piezoelectric substrate is actually just a single electrode, and the topside electrodes are all connected together in parallel. In the series configuration shown in Fig 1b, both the topside and bottomside electrodes are aligned and the individual elements remain separate. The SCTA configuration requires that each array element be connected in series, and is therefore more complex in terms of sensor fabrication. As will be shown below, the SCTA has better sensitivity in terms of reception, and the PCTA works well for actuation but for reception the amplitude (voltage) of the received signal is reduced because of the parallel configuration of the electrodes.

2 Sensor Response - analytical

The sensor response to an acoustic wave is now calculated for two cases: a toneburst signal where all the transducer elements are simultaneously strained, and a case where only one of the transducer elements is strained (the latter is essentially an acoustic toneburst with just one cycle.) In the latter case, the effect of the remaining unstrained sensors in the array is just as a capacitive load.

A one dimensional model of the linear constitutive relationships of a piezoelectric ceramic is given by [Martin (2001), Ghoshal et al (2005)]:

$$S_1 = s_{11}^E T_1 + d_{31} E_3 \tag{1}$$

$$D_3 = d_{31}T_1 + \mathcal{E}_{33}^T E_3 \tag{2}$$

Here D_3 is the dielectric displacement with units of columbs/m², E_3 is the applied electric field with units of Volts/ meter, S_1 is the mechanical strain in direction 1 parallel to the sensor with units of meter/meter, T_1 is the mechanical stress in the material with units of Pascals, Superscript (*T*) denotes a constant stress (zero stress) boundary condition established to measure the dielectric permitivity ($[\varepsilon]_{3x3}$), Superscript (*E*) denotes the measurement of the compliance (s_{11}) of the piezoelectric ceramic under short circuit (zero electric field) configuration, d_{31} piezoelectric coupling coefficient.

In terms of the current, equations (1) and (2) can be simplified to yield [Schulz et al (2003)]:

$$i = e_{31}A_e \sum_{1}^{o} + C_p V$$
(3)

where *i* is the current in the sensor with units of Amperes, e_{31} is the induced stress constant and is the ratio of piezoelectric coupling constant (d_{31}) to the compliance of the material measured under constant electric field (s_{11}^E) with units of Newton/(volt-meter), A_e is the electrode area on the piezoelectric ceramic with units of meter², \int_{1}^{o} is the strain rate in direction 1 (one of the principal axis) with units of (meter/meter/sec), C_p is the capacitance of the piezoelectric ceramic and is given by the ratio of the product between dielectric permittivity under constant stress (ε_{33}^T) and area of the electrodes (A_e) to the distance between the electrodes (thickness of the sensor) with units of Farads, and \bigvee_{V}^{o} is the voltage rate and is the

product of rate of change of applied electric field (E_3) and thickness of the sensor with units of volts/sec. For a detailed derivation of equation (3) the reader is referred to the article by Schulz et al [2003]. Eq (3) indicates that a piezoelectric ceramic can be thought of as a charge generator (Q) in parallel with a capacitor (C_p) as shown in Fig 2. Fig 2 shows three sensors for a PCTA and SCTA network whose final voltage output is obtained across a high impedance oscilloscope having a real impedance of R_o . For simplicity, only real impedance (R_o) is modeled; however in reality at high frequencies the complex impedance will play a major role in the network response.



Figure 2: Different sensor configurations (only three elements are shown) (a) Parallel configuration transducer array (PCTA) (b) Series configuration transducer array (SCTA)

The response of the PCTA configuration (Fig. 2a) can be derived by applying Kirchoff's current law:

$$i_1 + i_2 + i_3 + \dots + i_n = i_{Ro} \tag{4}$$

where $i_{1...n}$ are the currents generated in each individual array element, the value of *i* is shown previously in eq (3) subscripts 1.....*n* denotes the number of elements (*n*) present in the system, and i_{Ro} represents the current through the output resistor R_o . Since the sensors are connected in a parallel configuration and assuming that the strain sensed by each sensor is identical, the voltage developed across each sensor is the same and is obtained across the output resistor R_o . Assuming that all the transducer elements are simultaneously strained harmonically by an acoustic wave of frequency ω , Eqs (3) and (4) can be combined to obtain the frequency response of the PCTA configuration as follows

$$\left|\frac{v}{s}\right| \approx \frac{e_{31}A_e}{C_p} \tag{5}$$

where $v = V/(e^{j\omega t})$, $s = S/(e^{j\omega t})$, V is a harmonic voltage function generated across the output resistor R_o with a peak amplitude of v volts. A similar explanation

holds for S. Eq (5) is obtained under the assumption that all the sensors present in the network experience the same amount of strain and indicates that the final response of the PCTA network is independent of the number of elements present in the network. For a case where only one sensor element experiences the propagating acoustic wave, the effect of the remaining unstrained sensors in the network is just a capacitive load with no charge generation in the unstrained sensors:

$$\left|\frac{v}{s}\right| \approx \frac{e_{31}A}{nC_p} \tag{6}$$

Eq (6) is obtained by eliminating charge generators Q2, Q3 etc from Fig 2a. Eq (6) indicates that the final response of the system is inversely proportional to the number of sensors present in the system. This results in a reduction in the amplitude of the response of the PCTA network. The absolute value of the frequency response given by eqs (5) and (6) are shown in Fig 3a and 3b respectively. Table 1 describes the values of the constants used to compute these figures. These values are chosen based on the experimental setup described later in this paper.

| Parameter | Value (units) |
|--|---|
| Length of the sensor | 15 (mm) |
| Width of the sensor | 2.5 (mm) |
| Area of the electrode (A_e) | $15x \ 2.5 = 37.5 \ (mm^2)$ |
| Resistance of the scope (R_o) | 10 M-Ohm |
| Piezoelectric strain coefficient (d_{31}) | -190e-12 (meters/volt) |
| Short circuit stiffness of the sensor (C_{11}) | 66e9 (Newton/meter ²) |
| Induced stress constant (e_{31}) | $(d_{31}) * (C_{11}) = -12.54 $ (Newton/(Volt-Meter)) |
| Capacitance of the sensor (<i>C</i>) | 850 (pico-Farad) |

Table 1: Values of the parameters used in the simulation

Note that Fig 3a indicates that the maximum amplitude of the PCTA configuration is the same irrespective of the number of sensors used in the network. This is true based on the assumption that all the sensors respond simultaneously to the strain at an equal rate. Fig 3b is the absolute value of the frequency response of multiple sensors connected in parallel configuration but when only one of the sensors is responding to the propagating acoustic wave. The effect of the unstrained sensor elements present in the network indicates that the maximum amplitude achieved by the PCTA configuration decreases as the number of sensors in the network increases. Fig 3 also indicates that as the number of sensors increases the frequency at which the maximum amplitude is achieved decreases. This can be explained simply by noting that in the time domain, a circuit with a larger capacitance has a

larger time constant, and the inverse of the time constant is represented in frequency domain and hence the value is smaller as seen in Fig 3.



Figure 3: Absolute value of frequency response of multiple sensors (1 through 4) connected in parallel configuration when (a) all the sensors are responding simultaneously (b) only the first sensor present in the network is responding to the propagating acoustic wave. *Sensor 1* is obtained when only one sensor is present in the network; *Sensor 2* is obtained when two sensors are connected in parallel configuration and so on.

The series SCTA configuration can be analyzed in a similar way. Applying Kirchoff's voltage law to Fig 2b, we obtain:

$$V_1 + V_2 + V_3 + \dots + V_n + V_{Ro} = 0 (7)$$

The frequency response of Fig 2b based on eqs (3) and (7) yields

$$\left|\frac{v}{s}\right| \approx \frac{ne_{31}A}{C_p} \tag{8}$$

Similar to the previous analysis, if only the first sensor is responding to the propagating acoustic wave then the response of SCTA network becomes:

$$\left|\frac{v}{s}\right| \approx \frac{e_{31}A}{C_p} \tag{9}$$

Eq (8) indicates that the response of the SCTA network is proportional to the number of elements present in the transducer array. Eq (9) indicates that the unstrained elements present in the SCTA network do not affect the overall response of the

network. This is advantageous when compared to the PCTA network where the maximum amplitude drops because of the capacitance of the unstrained elements. Figures 4a and 4b show plots of the response given by Eqs (8) and (9) respectively and show that the maximum amplitude of the SCTA response is independent of the number of sensor elements.

Note also that the frequency at which the maximum voltage is attained increases as the number of sensors increases because in a series network the effective capacitance decreases with increase in the number of sensors. Decrease of capacitance reduces the time constant and hence increases the frequency at which the maximum voltage is attained. For nominal values shown in Table 1, Fig 4 shows that the sensor array achieves the maximum voltage at frequencies greater than 500 Hz for a case where 4 sensor elements are used. However, for most structural health monitoring applications, the acoustic frequencies are greater than 10KHz and hence this drop in amplitude is not of concern.



Figure 4: Absolute value of frequency response of multiple sensors (1 through 4) connected in series configuration when (a) all the sensors are responding simultaneously (b) only the first sensor present in the network is responding to the propagating acoustic wave. *Sensor 1* is obtained when only one sensor is present in the network; *Sensor 2* is obtained when two sensors are connected in series configuration and so on.

3 Experimental results

A 6061 T651 aluminum block with a thickness of 64mm was used as a test block on which Rayleigh waves were generated. The surface wave velocity in this aluminum block is approximately 2888 m/sec and this was verified experimentally. Multielement surface wave generators (SWG) and surface wave receivers (SWR) were fabricated using the parallel and series configurations discussed above.

3.1 Surface wave generator transducer fabrication

Modal-selection is achieved by appropriately selecting the spacing of the elements of the transducer array in order to boost the excitation of a particular mode. Petculescu et al [2008] have previously demonstrated modally-selective SWG transducers using PVDF as the piezoelectric material. Here, we have replaced the PVDF material with a lead zirconium titanate (PZT) material. As discussed in [Petculescu et al (2008)], a PCTA configuration is well suited for generation. The electrode array necessary to fabricate a parallel SWG array were photolithographically patterned on commercially available copper sheets backed with Teflon as follows. Electrode patterns of the required dimensions were made on transparent sheets to act as a mask during the photolithography process. The copper/teflon material was cleaned with acetone before the application of AZ1518 photoresist. Photoresist was applied on the copper material and spin coated at 2750 rpm. The copper material along with the photoresist was baked on a hot plate for 2 minutes. The baked material was taken to a QE2000 mask aligner instrument to shine UV light. A custom made quartz plate was placed in between the UV light and the mask. After a 10 sec exposure to UV light, the material was developed in AZ400K to remove the exposed photoresist. The developed material was dipped in a solution consisting of 50g sodium persulphate mixed with 1 liter of water to etch away the unwanted copper. The etch bath was maintained at a temperature of 55° C. The remaining photoresist was cleaned using acetone.

Fig 1a shows the geometric setup of the SWG transducer array used for actuating. The top layer in Fig 1a is the teflon followed by the copper electrodes with a width of 2.5mm and the spacing between each of the electrodes is 5mm. This results in exciting a mode (surface wave) whose wavelength is 5mm. The PZT material was purchased from Piezo Inc which came with a thin layer of homogenous nickel electrodes deposited on the top and bottom surface of the PZT. The top electrode was removed by sanding the PZT with a sand paper. This electrode was replaced by the copper/teflon material which was bonded in place on the PZT. The bottom nickel electrode present on the PZT was bonded onto the aluminum structure using conductive epoxy.

3.2 Surface-wave receiver transducer fabrication

For SWR, the as-received nickel electrodes on both the surfaces of the PZT were removed using sandpaper. Copper/teflon electrodes were then bonded on both sides of the piezo material using conductive epoxy. Care needs to be taken in applying the conductive epoxy as any excess epoxy might change the electromechanical coupling. Also, the common connection enabling the parallel circuit configuration shown in Fig 1a is removed as shown in Fig 1b. The bottom copper/teflon electrode was then bonded to the host structure using super glue. Series connection is enabled by externally connecting the top electrode of one element to the bottom element of the next. Parallel connection of the electrodes is enabled by joining all the top electrodes together and the bottom electrodes together.

For extremely high frequency applications where the wavelength is small, the above approach of sanding the electrodes from the surface of the sensor and bonding the copper/teflon material is not practical. The approach of selectively removing the nickel electrodes directly from the surface of the piezo material using photolithography and etching has been recently proposed and implemented by the authors [2008 - 3]. However to prove the feasibility of SCTA, low frequencies are utilized in this paper for which the copper/teflon bonding approach is acceptable.

Sensor response - results: Five elements were used for the surface wave generator and four elements were used for the surface wave receiver with a spacing of 5mm between each electrode. The width of each element was 2.5mm, and it was found that the sensor array had a maximum acoustic response at 590Khz. The distance between the generating and receiving arrays was 118mm. The structure was excited using a 10-cycle, 590KHz sinusoidal wave applied to the SWG. The SWR transducer array elements were first configured in parallel. If the first two elements of the sensor array are connected in parallel the response is denoted by *Parallel 12* in Fig 5a. Similarly if three elements of the transducer array are connected in parallel *123* etc. The portion indicated by the circle in Fig 5a is shown zoomed in Fig 5b. Plot *A* in Fig 5b is the response of *Parallel 123*. Fig 5b indicates that the maximum amplitude of the PCTA network decreases as the number of elements increases in the network. This is in accordance with that determined analytically.

Similarly Fig 6 indicates the response of connecting multiple elements of the SWR array in a series configuration. The amplitude of the SCTA network increases as the number of elements increases in the network.

For an SCTA network the maximum amplitude is proportional to the number of elements of the transducer array present in the system as shown previously in eq (8) assuming that all the transducer elements are of identical capacitance. However the experimental response does not indicate a proportional increase with number of elements. To investigate this further, the individual responses of elements 1 and 2 of the transducer array were summed mathematically and compared with the experimental response of elements 1 and 2 connected in series and is shown in Figure 7a. Similarly Figure 7b indicates the responses for elements 1 and 3. The capacitances of each of the elements in the receiving transducer array were measured to be 673pF, 252pF, 667pF, and 834pF. Element 1 (673pF) and element 2



Figure 5: Comparison of Rayleigh surface wave response in a parallel connected transducer array (PCTA) (a) Response of PCTA with varying number of elements (b) Zoomed response indicated by a circle in Fig 5a.



Figure 6: Comparison of Rayleigh surface wave response in series connected transducer array (SCTA). (a) Response of SCTA with varying number of elements (b) Zoomed response indicated by a circle in Fig 6a.

(252pF) have a large capacitance difference as compared to element 1 (673pF) and element 3 (667pF). Hence Fig 7a has a larger difference between the experimental and summed responses as compared to Fig 2b. Clearly the responses in Fig 7 suggest that the increase in the response of the signals is directly attributed to the capacitances of the piezoelectric elements in the transducer array.



Figure 7: Comparison of mathematical summation and experimental SCTA response (a) elements 1 and 2 (b) elements 1 and 3

4 Conclusions

In summary, we reiterate the following conclusions for the receiving transducer array:

- For PCTA (parallel configuration) when all the sensor elements are simultaneously actively strained, the maximum amplitude is independent of the number of sensor elements;
- For PCTA when only one sensor element is actively strained the remaining unstrained sensors reduce the amplitude. The reduction in amplitude is non-linear and is dependent on the capacitance ratio $\left[\frac{C_1}{C_1+C_{2n}}\right]$ where C_1 is the capacitance of the sensor element that is strained due to the acoustic wave and C_{2n} is the effective capacitance of the unstrained sensors 2 through n given as $(C_2 + C_3 + C_4 + \dots + C_n)$.
- For SCTA (series configuration) when all the sensor elements are simultaneously actively strained, the maximum amplitude is the summation of individual sensor elements and is linear with respect to the number of sensor elements present in the sensor array.
- For SCTA when only one sensor element is actively strained the remaining unstrained sensor elements do not affect the overall response.

At present, the series configuration is not easy to fabricate in view of the alignment of the topside and bottomside electrode patterns that is required. Further work needs to be conducted to improve the manufacturability of the continuous sensors before this type of sensor configuration plays a wider role in practical applications.

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