Three-Phase Unidirectional Surface Acoustic Wave Transducer Model and Computer Aided Design Implementation

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THREE-PHASE UNIDIRECTIONAL SURFACE ACOUSTIC WAVE TRANSDUCER MODEL
AND
COMPUTER AIDED DESIGN IMPLEMENTATION

BY

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ABSTRACT

This thesis presents an introduction into surface acoustic wave (SAW) unidirectional transducer (UDT) technologies and identifies advantages and disadvantages of various approaches. A complete model of the three-phase unidirectional structure is presented for the purpose of design analysis. This model incorporates the effects of the electrodes and transducer pattern along with the equivalent circuit model of the transducer structure. The model, when included with the appropriate peripheral components for transducer phasing and matching, can be used to determine accurately the frequency response of a given transducer structure. Such a model is well suited for implementation on a digital computer. With this in mind, the necessary FORTRAN 77 software was developed and is presented which is an addition part of the SAW computer aided design (CAD) facilities at UCF-COE. An analysis example is given and the results are compared to published data.
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CHAPTER I
BACKGROUND OF PREVIOUS WORK

SAW Fundamentals

Acoustic waves in crystalline materials propagate at a velocity approximately five orders of magnitude less than electromagnetic waves and with very low attenuation for frequencies well into the UHF region. Acoustic waves propagating on a crystalline surface, called Rayleigh waves or surface acoustic waves (SAW), are non-dispersive and have displacements which decay exponentially away from the surface. Typically, more than 95% of the energy is confined to a depth of less than one wavelength [1]. The attractiveness of SAW devices is associated with the confinement of acoustic energy near the surface, which implies that the wave can be tapped or otherwise modified while it is propagating. This allows for the simultaneous sampling of the wave at many points in the propagating path and results in an important flexibility which cannot be easily duplicated by bulk wave devices.

Surface acoustic waves can be excited on a piezoelectric crystal using an interdigital transducer (IDT). The IDT consists of metal electrodes which are deposited by evaporation or other means on a polished substrate. The
transducer generates a spatially periodic electric field with a periodicity determined by the spacing of adjacent electrodes. This field generates surface waves through the piezoelectric effect with maximum efficiency typically at the frequency, called the synchronous frequency, \( f_0 \), where the acoustic wavelength equals the period of transducer electrode symmetry. Other frequencies have reduced generation efficiency due to the cancellation of waves generated at one end of the transducer with those at the opposite end. By reciprocity, a receiving IDT will convert an incoming acoustic wave to an electrical potential at its electrodes via the piezoelectric effect [2]. The filtering properties of SAW devices are completely determined by the processes for conversion of the electrical signal power to acoustic power and vice versa. The transducer transfer function can be calculated from the transducer impulse response. This impulse response is a waveform which has a particularly simple relationship to the transducer electrode configuration since each electrode pair constitutes a tap on the acoustic delay line whose relative time delay is given by the position of the electrode pair on the substrate. From filter theory, the impulse response and the frequency response are known to be Fourier transform pairs. There are, though, two fundamental restrictions on the impulse response and therefore the frequency response. First, only bandpass filters can be realized since acoustic
energy can not be generated at DC; secondly, since the impulse response must be of finite length, filter shapes are restricted [1].

Introduction to UDT Technologies

SAW interdigital bidirectional transducers (BDT) have been widely used as generators and detectors for transversal filter operation. But BDT's have an inherent 3 dB power loss in conversion of acoustic power to and from electric power. This yields a minimum theoretical insertion loss of 6 dB for a bidirectional SAW device. Also acoustic wave reflections generate multiple transit effects which detract from device performance. These limitations have led to the development of several unidirectional transducer (UDT) technologies. A UDT launches acoustic waves in only one direction at synchronous frequency and by reciprocity the same transducer can convert an incoming wave entirely to electrical power, thus suppressing multiple transits and achieving a theoretical minimum insertion loss of 0 dB per device.

Three-Phase UDT

A three-phase unidirectional SAW transducer consists of a periodic electrode structure with three tap electrodes per section. The length of each section is equal to the synchronous frequency wavelength, $\lambda_o$, for the transducer. Each electrode is equally spaced at lengths of $\lambda_o/3$ and is
separately excited. The interconnection of the electrodes requires multi-layer fabrication techniques. Two different structural embodiments of the three-phase UDT are shown in Figure 1 and Figure 2 [3-4].

Figure 1. Three-phase UDT structure of period $\lambda_o$. 
When each electrode is driven with a $120^\circ$ phase difference from each adjacent electrode, unidirectional power flow is achieved at synchronous frequency, $f_0$. This is illustrated as follows. Using phasor representation, let $V_1 = V \angle 0^\circ$, the phase reference signal, $V_2 = V \angle -120^\circ$ and $V_3 = V \angle -240^\circ$, where the phasor $V \angle 0^\circ$ represents a time varying sinusoidal voltage of frequency $f_0$ with a phase
angle of $0^\circ$. When the wave peak ($0^\circ$ phase point) travelling in the "A" direction of Figure 1 generated due to the electrode of $V_2$ reaches the $V_1$ electrode, it has travelled a distance of $\lambda_0/3$, which corresponds to a phase delay of $120^\circ$. Therefore $V_2$ is now at $V \angle -240^\circ$. Likewise when the wave peak travelling in the "A" direction generated due to the electrode of $V_3$ reaches the $V_1$ electrode it has travelled a distance of $2(\lambda_0/3)$, which corresponds to a phase delay of $240^\circ$. Therefore $V_3$ is now at $V \angle -120^\circ$. The sum of the waves from these three electrodes is $| V \angle 0^\circ + V \angle 120^\circ + V \angle -120^\circ | = 0$. Figure 3 shows the spacial and voltage vector representations of the wave travelling in the "A" direction.

Figure 3. Phase relationships in the "A" direction
When each voltage phase is delayed by its associated spacial phase shift, the vector sum is zero which represents no power flow. Thus the "A" direction is called the reverse direction.

In a similar manner, the phase representations of Figure 4 show the "B" direction phase relationships. The waves from all electrodes add together constructively resulting in unidirectional power flow. As seen when the voltage phase relationships are delayed by the spacial phase shifts, the results are that all three waves cross the electrode of $V_1$ at phase points of zero degrees. The "B" direction is called the forward direction.

Figure 4. Phase relationships in the "B" direction
Since the phase voltages as defined have an arbitrary reference point, this arbitrary reference can be selected as one of the phase voltages. Let \( V_2 \) be the reference phase voltage for illustration. Therefore we can subtract \( V_2 \) from each of the phase voltages as follows:

\[
\begin{align*}
V_1' &= V_1 - V_2 = V \angle 0^\circ - V \angle -120^\circ = 1.73*V \angle 30^\circ \\
V_2' &= V_2 - V_2 = 0 \quad \text{(reference point)} \\
V_3' &= V_3 - V_2 = V \angle -240^\circ - V \angle -120^\circ = 1.73*V \angle 90^\circ.
\end{align*}
\]

Therefore \( V_2 \) represents a ground potential. Now normalizing \( V_1' \) yields

\[
\begin{align*}
V_1' &= V' \angle 30^\circ \\
V_2' &= 0 \\
V_3' &= V' \angle 90^\circ.
\end{align*}
\]

Let \( V_1' \) be the phase reference point, then

\[
\begin{align*}
V_1' &= V' \angle 0^\circ \\
V_2' &= 0 \\
V_3' &= V' \angle 60^\circ.
\end{align*}
\]

Therefore, the necessary transformation from a single phase source to three-phase excitation is a 60° phase shifter in the appropriate electrode excitation. Figure 5 shows a three-phase UDT with appropriate drive for unidirectional operation.
The previous analysis is for center frequency excitation only. At off-center frequencies the spatial phase shift does not yield completely unidirectional power flow. Increasingly bidirectional power flow occurs with increased deviation from center frequency.

**Group-Type UDT**

A group-type unidirectional transducer is formed by placing an even number of bidirectional transducers collinearly and exciting alternate transducers with a phase angle of $\Theta$ and $\Theta - 90^\circ$. A spacing between adjacent transducers of $n\lambda_0 + (\lambda_0/4)$ is required which corresponds to a spatial phase shift of $90^\circ$ at center frequency. This
structure is illustrated in Figure 6 using two unweighted bidirectional transducers to form a single unweighted unidirectional transducer [5].

Figure 6. Group-type UDT section electrode pattern

When each bidirectional transducer section is excited with equal power at synchronous frequency, the acoustic wave adds in phase in the forward direction and adds $180^\circ$ out of phase in the reverse direction. No power is radiated in the reverse direction and the total power flow is in the forward direction. This represents a theoretical insertion loss of 0 dB due to the transducer.
Many sections can be placed collinearly and appropriately weighted to yield a desired transducer frequency response. The ground port of a many section transducer consists of a meandering ground line which interconnects the transducer sections. This meandering line adds resistive loss to the transducer. Alternatively, a multi-level structure can be used to interconnect the ground port but this increases the fabrication complexity over the single level meandering ground line. When many bidirectional transducer section pairs are used, the length of each section is determined by the number of tap pairs in each section. This length represents the spacing between sections with the same phase. Using superposition, this arrangement can be viewed as two bidirectional transducers each having a gap between sections as shown in Figure 7. This yields a sampling of period equal to the section length which generates harmonic passbands that require special consideration during the design stage. This multiband response represents a major disadvantage of the group-type UDT. The group-type UDT requires phasing components which, if chosen appropriately, can be used as matching components also [6].
Figure 7. Decomposition of group-type UDT structure

Multi-Strip Coupler UDT

The multi-strip coupler (MSC) unidirectional transducer consists of a conventional bidirectional interdigital transducer placed in between a U-shaped 3 dB coupler [7]. The U-shaped coupler is used to combine the two oppositely directed output signals into a single signal thus achieving unidirectional behavior. As shown in Figure 8, a bidirectional transducer with an odd number of fingers is placed within the coupler so that the center of the BDT is offset from the center of the coupler by 1/8 of the
synchronous frequency wavelength towards the desired output port.

\[ T_J \]

Figure 8. Multi-strip coupler UDT structure

The two waves arrive at opposite ends of the coupler differing in phase by 90° and are then recombined by the coupler to produce unidirectional power flow [8]. This is a very narrowband approach and is not often used.

**Four-Phase UDT**

A four phase unidirectional SAW transducer consists of a periodic electrode structure with four electrode taps per section. The length of each section is equal to the wavelength at synchronous frequency for the transducer. Each
electrode is equally spaced at $\lambda_0/4$ and separately excited. Figure 9 shows a portion of an unweighted four-phase UDT [9].

This structure requires a multi-layer fabrication technique to interconnect two of the four phases. When each adjacent electrode is electrically driven with a $90^\circ$ phase difference and each alternate electrode is driven with a $180^\circ$ phase difference, unidirectional power flow is obtained at synchronous frequency. This is illustrated as follows. Let $V_1 = V \angle 0^\circ$, the phase reference signal and

- $V_2 = V \angle -90^\circ$
- $V_3 = V \angle -180^\circ$
- $V_4 = V \angle -270^\circ$
using phasor representation. Figure 10 shows the electrode voltage phase and the spacial phase relationships for both the "A" and "B" directions of Figure 10.

![Voltage Phase and Spacial Phase Relationships](image)

Figure 10. Four-phase UDT phase relationships

When for each direction the electrical phase relationships and the spacial phase relationships are combined, the net phasor diagrams of Figure 11 result.

![Resultant Phase Relationships](image)

Figure 11. Resultant phase relationships
This represents total power flow in the "B" or forward direction and no power flow in the "A" or reverse direction at synchronous frequency.

**Quadrature Three-Phase UDT**

Using the electrode structure of Figure 9, an alternate UDT implementation can be obtained if the electrodes are driven with only three phases. This transducer, called the quadrature three-phase transducer [10], is obtained by the following excitation. Let

\[
\begin{align*}
V_1 &= V \angle 0^\circ \\
V_2 &= V \angle -90^\circ \\
V_3 &= 0 \\
V_4 &= 0
\end{align*}
\]

Figure 12 shows the voltage and spacial phase representations for the given excitations.

![Figure 12. Phase relationships for quadrature three-phase UDT](image-url)
When the voltage phase diagram is combined with the spacial phase diagram for each direction, the resultant phase representation is shown in Figure 13.

Figure 13. Resultant phase relationships

This indicates total power flow in the "B" direction, which is the forward direction, and no power flow in the "A" or reverse direction. Recall, this analysis is valid at only the synchronous frequency. The greater the deviation from synchronous frequency, the greater the bidirectional power flow becomes.

**Single Phase UDT**

Single phase unidirectional transducers use internal reflections within the transducer to achieve unidirectional power flow [11]. A section from an unweighted single-phase UDT is shown in Figure 14.
This structure has $\lambda_0/8$ electrodes and electrode gaps with pairs of adjacent electrodes electrically equipotential. Therefore every four electrodes represents a single wavelength. The shaded regions represent areas of acoustic reflecting medium which are $\lambda_0/4$ in width. When a single periodic section of the structure is considered, as shown in Figure 14 between points "3" and "5", there are two reflecting surfaces contained. Due to the different propagation properties of the substrate and the reflecting surface, when a wave travelling on the substrate reflects off the boundary of the reflecting surface, a phase shift of
180° occurs, but when a wave travelling through the reflector reflects off the boundary of the surface and the substrate, no phase change occurs. For both cases, the reflection coefficient for the returning wave is "R". It is assumed that the electroacoustic transduction and the reflecting areas act independently of one another. In analyzing the propagating waves, let point "1" be the phase reference point which is referred to as the center of transduction. From the transduction process two waves are launched, one in the "A" direction of wave amplitude $A_a$ and one in the "B" direction of wave amplitude $A_b$. Now considering the effects of the reflecting surfaces, also propagating in the "A" direction are portions of the wave excited at point "1" which propagate in the "B" direction which have been reflected at four boundary points in the transducer section. The reflected "B" wave due to point "4" has a round trip spacial delay of 180° in returning to point "1" with no phase change at point "4." Therefore the wave is

$$ R A_b \angle -180°. $$

At point "5", which by transducer symmetry may be viewed as point "3", the reflected "B" wave has a round trip spacial delay of -360° with a phase reversal of 180° at point "5." The wave returns to point "1" as

$$ (1-R) R A_b \angle -180°. $$

Likewise the reflected "B" waves from points "2" and "1"
are

\[(1-(1-R)R)R_{A\theta} \angle -180^\circ\]

Assuming that the reflection coefficient is small, the total wave in the "A" direction is

\[A_a - (4R)A_b\]

With a similar argument the wave propagating in the "B" direction has reflected components of the wave excited in the "A" direction which add in phase with the transduced "B" wave resulting in a wave given by

\[A_b + (4R)A_a\]

Notice that if the reflection coefficients can be fabricated such that \(R=1/4\) then there would be almost no wave propagating in the "A" direction, thus unidirectional behavior would result. More realistically, many more reflecting surfaces would be needed extending periodically past the last transducer electrode in order to reduce the "A" wave such that little power is propagated. Again, unidirectional transducer behavior occurs only at synchronous frequency with increasingly bidirectional behavior resulting from increased deviation from synchronous frequency.

**Tradeoffs of the Various Approaches**

The low-loss unidirectional transducer technologies which have been introduced each have advantages and
disadvantages inherent in their structure and operation. In application, each transducer type must be evaluated against a set of design specifications to obtain a satisfactory device implementation. A consideration of weighting techniques, fabrication complexity, insertion loss limits, maximum frequency, multiple transit suppression and fractional bandwidth limits are some of the device performance characteristics which affect the utility of the different UDT technologies.

The group-type UDT structure can be completely defined with only a single level fabrication, but this forces one port, usually the ground port, to be implemented as a meandering line which increases resistive losses in the transducer. This can be overcome with multi-level air gap cross-over structures, but the fabrication complexity is compromised [12]. The multiple pass bands are the highest side lobes of the group-type and require special consideration during the device design. Matching and phasing components are required which can be realized using only two components [6]. Insertion losses of under 5 dB have been realized with triple-transit suppression of greater than 40 dB [13].

The four phase device structures require complex fabrication technologies due to the cross-overs required for electrode interconnection and due to the finer line widths which are required by having four electrodes per
synchronous frequency wavelength. This does have the advantage of giving a weight sample every $\lambda_0/4$ as opposed to $\lambda_0/3$ for three-phase and $\lambda_0/2$ for bidirectional devices [9]. The four phase has broader unidirectional bandwidths than three-phase or group-type UDTs and use of third harmonics can extend the SAW usable frequency range [10,14]. Devices with 2 dB of insertion loss including matching and phasing have been fabricated using four-phase UDTs [9].

The multi-strip coupler UDT has the advantage that no phasing components are required and only single level fabrication is needed. But there are high parasitic losses due to the multi-strip coupler which increases with narrower band devices. Another disadvantage is the large substrate area which is required for the multi-strip coupler UDT. Also it is not practical for application with materials of low piezoelectric coupling coefficients such as quartz [15]. Devices have been fabricated with less than 3 dB of insertion loss.

The three-phase UDT structure is capable of implementing very wideband SAW devices in the UHF/VHF regimes. Like the four phase, air-gap cross-overs are required for electrode interconnection. Matching and phasing can be done in as few as four components and with only three components in some cases. Transducer weighting can be performed with withdrawal techniques for narrowband
devices and with apodization techniques for wider bandwidth devices. Devices with less than 0.65 dB of insertion loss, 2 dB including all components, with passband ripple of 0.1 dB have been realized. Also directivity of 20 dB over a 20% fractional bandwidth has been demonstrated [15]. Three-phase devices have promising second harmonic operation for extending the upper frequency limits of the devices.
CHAPTER II

OBJECTIVE OF PROPOSED WORK

The advantages of the three-phase UDT makes this technology useful in a variety of applications requiring low-loss with little passband ripple. The objective is to understand the basic structure and operation of the three-phase interdigital transducer and to analyze the piezoelectric transduction process using the theory of superposition. This requires the determination of the array factor and element factor for the three-phase UDT [16-17]. Once determined, equivalent circuit models can be formulated to predict the behavior of the device. Such analysis is well suited towards implementation on a digital computer. With this in mind, a Computer Aided Design (CAD) system architecture is proposed and generated for the numerical analysis of the identified transducer model. The CAD system will provide the designer with transducer electrical characteristics, necessary phasing and matching components, and numerically determine the transducer frequency response of specific transducer designs. The results will be examined in light of published device performance for the purpose of evaluation of the model's accuracy.
CHAPTER III
THREE-PHASE UDT ANALYSIS TECHNIQUE

Development of Accurate Model

In order to predict the frequency response of a three-phase UDT, an accurate model must exist which will account for the dominant electro-mechanical effects of the piezoelectric transduction process. The modeling of the transducer can be segmented into two interactive processes, which link the electrical excitation of the electrodes with the electrode pattern effects, to predict the resulting surface wave propagation. The first segment of the model uses the electrode pattern and the electrode charge distribution to identify the frequency response of the transducer using the theory of superposition [16]. The second segment of the modeling identifies an electrical equivalent circuit model of the entire transducer for prediction of the electrical interactions of the transducer and the source excitation [3]. The resulting complete model thus can be used for the design and analysis processes of impedance matching, electrode phasing, and accurate frequency response determination.
Superposition Principle for Periodic Transducers with Arbitrary Voltages

This section briefly reviews the superposition analysis technique for determining the charge distribution of a periodic electrode pattern with arbitrary voltages. For a full discussion of the analysis refer to the references cited.

Associated with each three-phase transducer section is a weighting constant which identifies the interaction between the transducer electrode excitation and the propagating surface wave. Depending upon the weighting technique, the resulting electrode pattern modifies the propagation waveform in various manners, but regardless there remains a proportional relationship between the section weight and the power induced in the surface wave. For a three-phase UDT undergoing electrical excitation, at any given instant in time, the differential amplitude of the surface wave between adjacent electrodes is proportional to the potential difference between these electrodes. This voltage, in conjunction with the electrode weight, represents an instantaneous time domain sample of the propagating wave [2]. For each three electrode section of the transducer (Figure 5), the equivalent voltage excitation appears at subsequent electrodes within the section at a phase delay of 120°. This represents the identical sample delayed in time with the same section weight. At
this point, consider only one time sample per transducer section with the effects of the delayed time samples to be incorporated in the electrical equivalent circuit model. Therefore a single time domain sampling of the propagating waveform with a corresponding weight for each section exists. For an impulse input, each section thus represents a time sample of the induced surface wave of value equal to the section weight. Therefore the section weights represent the values of the time domain impulse response, \( h(nT) \), where "n" is the number of sections and "T" is the time associated with the spacing between electrodes. Defining \( W(nT) \) as the weight of each section yields

\[
h(nT) = W(nT)
\]

Therefore the frequency domain impulse response, \( H(w) \), is the discrete Fourier transform of \( h(nT) \). The transducer section weights thus represent an idealized impulse response model from which the frequency response of a given transducer can be determined. This frequency response is sufficiently described by the number of transducer sections, the spacing between sections and the weight associated with each section, and is referred to as the "array factor" [16].

In determining the array factor, \( H(w) \), an ideal impulse was assumed to be the sampling window which corresponded to an electrode in each transducer section. This model is simple but it neglects the interaction
between neighboring electrodes. An accurate sampling operator may be determined by examining the charge distribution under each electrode. As first approached, this represents a complex static electromagnetic field problem to be solved as shown in Figure 15, where $Q_n$ represents the charge distribution under each electrode. This problem, though, has been solved by using the superposition principle [16]. If all electrodes of an arbitrarily large transducer are grounded except for one electrode which is given some voltage $V_0$, then the charge distribution may be solved using field theory with results of Figure 16. This is called the basic charge distribution function (BCDF).

![Figure 15. Charge distribution function](image-url)
Therefore, by superposition, the charge distribution for arbitrary electrode voltages may be determined by the summation of the BCDF scaled to the electrode voltage and displaced according to the electrode pattern as shown in Figure 17. It is the BCDF, called $S_n(nT)$ that now represents the sampling window so now

$$h(nT) = W(nT) * S_n(nT)$$

where "*" indicates convolution. Using the Fourier transform a more accurate determination of the transducer frequency response becomes

$$H(w) = W(w) \times S_n(w)$$
where $s_n(kw)$ is called the "element factor" [17]. Thus the total response is the product of the array factor and the element factor.

two arbitrary voltages

$V_1 \quad V_2$

resultant charge distribution

$Q_n$

Figure 17. Application of superposition theory
The element factor, \( S_n(w) \), can be simply approximated by the sine function as follows

\[
S_n(w) = \sin\left(\frac{wT}{W} \right)
\]

where

\[
W_s = \frac{1}{2\pi T} \text{ rad/sec}
\]

and "T" is the period of the transducer electrode structure.

For example, let the array factor, \( W(w) \), be defined from a specific electrode pattern with characteristics shown in Figure 18. Also, in Figure 18 is shown the element factor \( S_n(w) \) and the resultant transfer function formed by the product of the element factor and the array factor.
Figure 18. Example of element and array factors
Equivalent Circuit Transducer Model

For the determination of the effects of the transducer on the input source, an equivalent circuit model as shown in Figure 19 will be used. This is the transducer equivalent circuit model for one port of the three-phase UDT structure.

\[ Y_A(w) = \frac{1}{C_s} + \frac{1}{G_a(w)} + jB_a(w) + \frac{1}{G_p} \]

- Parasitic Conductance: \( G_p \)
- Static Parasitic Capacitive Susceptance: \( B_p(w) = wC_p \)
- Static Capacitive Susceptance: \( B_c(w) = wC_s \)
- Acoustic Conductance: \( G_a(w) \)
- Acoustic Susceptance: \( B_a(w) = \frac{1}{\pi} \int \frac{G_a(w')}{w' - w} \, dw' \)

- Single Port Admittance: \( Y_a(w) = G_a(w) \cdot G_p \cdot j \left( B_c(w) \cdot B_p(w) \cdot B_a(w) \right) \)

- Transducer Q: \( Q_t = \frac{B_c(w_s) \cdot B_p(w_s)}{G_a(w_s) \cdot G_p} \)

Figure 19. Single port equivalent circuit model

The elements which model the effects of the transduction process are the acoustic conductance, \( G_a(w) \), and the acoustic susceptance, \( B_a(w) \). The electrode pattern determines the static capacitance, \( C_s \), while the parasitic effects of the transducer structure are modeled as a parasitic conductance, \( G_p \), and parasitic capacitance, \( C_p \). The acoustic susceptance is the Hilbert transform of the acoustic conductance. This term goes to zero at
synchronous frequency where the acoustic conductance is at a maximum.

In order to determine the equivalent circuit component values, the knowledge of the values for the following list of device and material parameters must be obtainable. The following list identifies each parameter by name and description:

- \( k^2 \) - piezoelectric coupling coefficient
- \( v_0 \) - substrate wave velocity (m/sec)
- \( f_0 \) - synchronous frequency (Hz)
- \( f_s \) - electrode sampling frequency (Hz)
- \( n \) - electrode duty factor
- \( b_w \) - transducer width (beam width in \( \lambda_0 \)s)
- \( C_d \) - substrate capacitance (pF/cm per \( \lambda_0 \))
- \( p \) - metal resistivity of electrodes (ohms/square)

Using the parameters specified and with the knowledge of the electrode for the pattern design to be analyzed, the equivalent circuit component values may be determined from the established relationships which follow [12].

The synchronous frequency wavelength, \( \lambda_0 \), is calculated by

\[
\lambda_0 = \frac{v_0}{f_0} \text{ meters.}
\]

The single electrode capacitance, \( C_0 \), is calculated from the substrate capacitance and geometry by
\[
35
C_o = \frac{4}{\pi} \cdot b_w \cdot \lambda_o \cdot C_d \quad \text{Farads.}
\]

The vector sum of the electrode tap weights, \( \text{N}_{\text{eff}} \), the number of active electrodes, \( N \), and the sum of the squared electrode tap weights, \( \text{N}_{\text{s}} \), is calculated by

\[
\text{N}_{\text{eff}} = \left| \sum_{i=1}^{n} a_i e^{-j2\pi i} \right|
\]

\[
N = \sum_{i=1}^{n} (a_i e^{-j2\pi i})
\]

\[
\text{N}_{\text{s}} = \sum_{i=1}^{n} (a_i e^{-j2\pi i})^2
\]

where \( a_i \) is the "i"th transducer electrode section weight for "n" electrodes [12].

The acoustic wave amplitude, \( U_a \), is determined from the relationship

\[
U_a = k^2 (0.56n + 0.54) \cdot \text{N}_{\text{eff}}
\]

The linear relationship between "n" and \( U_a \) compensates for the effect of the duty factor on the wave amplitude and is valid for "n" on the order of 0.5.

The characteristic impedance, \( Z_o \), is derived using a transmission line analogy and is in units of ohms/wave-length

\[
Z_o = \frac{k^2}{2\pi C_d v_o}
\]

The synchronous frequency conductance, \( G_a(w_o) \), is given by
where the $3/4$ factor is empirically determined to compensate for the electrode sampling rate.

The parasitic resistance, $r_e$, for all electrodes is calculated by the product of the metal resistivity and the electrode length to width ratio divided by the number of electrode lengths. This ratio can be calculated from the transducer beam width expressed in units of $\lambda_0$, which corresponds to the electrode length, and from the electrode width in units of $\lambda_0$ determined from the electrode periodicity as given by

$$r_e = p \cdot b_w \cdot f_s / (n \cdot f_o \cdot N) \text{ ohms.}$$

For the calculation of the approximate value of acoustic susceptance [2], the effective frequency is calculated by

$$f_e = N_{eff}(f - f_o)/f_o.$$  

From these intermediate calculations the equivalent circuit element values may be determined by

$$G_a(w) = |H(w)|^2 \cdot G_a(w_0) \text{ mhos}$$

$$B_a(w) = \frac{\sin(2f_e) - 2f_e}{2f_e^2} \cdot G_a(w_0) \text{ mhos}$$

$$C_s = C_o \cdot N \cdot 2 \sum_{i=1}^{10} \frac{1}{4i^2 - 1} \text{ Farads}$$
\[ G_p = (2\pi f_0 C_p)^2 \cdot r_e \text{ mhos} \]

\[ C_p = \text{device input parameter in Farads} \]

where \( H(w) \) is the product of the array factor and the element factor normalized to a peak value of 1.0 [12,17].

With the transducer admittance for a single port modeled, the necessary components for correct three-phase excitation from a single phase source can be determined. Using the excitation mentioned in Chapter I as follows,

\[ V_1 = V \angle 0^\circ \text{ volts} \]
\[ V_2 = V \angle -60^\circ \text{ volts} \]
\[ V_3 = 0 = \text{ground port} \]

then the transducer network can be phased at center frequency by either of a two element series network or a two element parallel network [3]. Figure 20 shows the parallel phasing configuration.

**Figure 20.** Parallel phasing network configuration
The values of $B_1(\omega_0)$ and $B_2(\omega_0)$ are

\[
\frac{B_1(\omega_0)}{B_c(\omega_0)} = -1 - \sqrt{3} \cdot Q_0^{-1}
\]

\[
\frac{B_2(\omega_0)}{B_c(\omega_0)} = -1 + \sqrt{3} \cdot Q_0^{-1}.
\]

Alternatively, the proper phasing may be obtained using two series elements. This series phasing configuration is shown in Figure 21.

\[Y_\omega - \text{FREQUENCY DEPENDENT ACOUSTIC ADMITTANCE}\]
\[Q_0 - \text{TRANSODUCER } Q\]
\[X_c - \text{TRANSODUCER REACTANCE BETWEEN PORTS } 1 \text{ AND } 3\]
\[X_1, X_2 - \text{REACTANCE OF SERIES PHASING ELEMENTS}\]

Figure 21. Series phasing network configuration

The values of $X_1(\omega_0)$ and $X_2(\omega_0)$ are

\[
\frac{X_1(\omega_0)}{X_c(\omega_0)} = \frac{Q_0^2 - \sqrt{3} \cdot Q_0}{3 \cdot (1 + Q_0^2)}
\]

\[
\frac{X_2(\omega_0)}{X_c(\omega_0)} = \frac{Q_0^2 + \sqrt{3} \cdot Q_0}{3 \cdot (1 + Q_0^2)}.
\]
From the values of $X_1$, $X_2$, $B_1$, and $B_2$ the corresponding values for of the necessary inductors or capacitors at center frequency are determined.

To obtain proper unidirectional operation, the three-phase transducer must be conjugately matched to the load or generator impedance. Optimally, a very wideband match is desired, but this requires many components. However, two matching configurations exist which require only two elements each. These elements are restricted to only reactive components, therefore the minimum insertion loss due to the matching components is achieved. Assuming the transducer has been properly phased for single source operation, the equivalent center frequency impedance of the transducer, $Z_{eq}$, can be obtained. Figure 22 shows a parallel/series matching configuration where the series element $X_1$ and the parallel element $X_2$ are determined by

$$X_1 = X_o + \sqrt{\frac{G_t}{R_o} - R_o^2} \text{ ohms}$$

$$X_2 = \frac{-1}{\sqrt{\frac{G_t}{R_o} - \frac{G_t^2}{R_o} - B_t}} \text{ ohms}$$

where

$$z_{eq} = R_t + jX_t \quad \text{and} \quad y_{eq} = G_t + jB_t \quad \text{for} \quad z_{eq} = y_{eq}^{-1}$$

and

$$z_o^* = R_o + jX_o \quad \text{and} \quad y_o^* = G_o + jB_o \quad \text{for} \quad z_o^* = (y_o^*)^{-1}.$$
Figure 22. Parallel/series matching configuration

Figure 23 shows the series/parallel configuration where again $X_1$ is the series element and $X_2$ is the parallel element of values

$$X_1 = \sqrt{\frac{R_t}{G_o} - R_t^2} - X_t \text{ ohms}$$

$$X_2 = \frac{-1}{B_o + \sqrt{\frac{G_o}{R_t} - G_o^2}} \text{ ohms}$$
Figure 23. Series/parallel matching configuration

Once the reactances have been determined, the inductor or capacitor values are determined using center frequency.
CHAPTER IV
COMPUTER AIDED DESIGN METHODS

Using the model identified for the three-phase SAW UDT to analyze a device design requires many calculations. Included in these, for example, are the digital Fourier transform and linear network analysis for, at times, vast amounts of data. Therefore, in order to minimize design analysis time and thus increase productivity the use of a tool such as the digital computer is a requirement.

The SAW UDT analysis has been implemented in FORTRAN 77 code as an addition to an existing SAW CAD system which is capable of both design and analysis of bidirectional SAW devices. This SAW CAD system exists within the UCF-COE EECS Department and is configured on a DEC VAX 11/780 using a Tektronix 4051 operating as a graphics display device. The SAW CAD system is supported by a group of utility routines which provide four basic functions,

1. disk file management of device data
2. digital Fourier transform operations
3. nodal analysis of a linear network
4. graphics display of device data.

These routines give no direct engineering support of the SAW devices under analysis, but provide for the
utilization of computer resources, which is the basis of the CAD concept. The ability to store and retrieve large time and frequency models of devices is provided by the disk I/O routines. The time and frequency domain transformations used in the device analysis is given by system transform routines. The graphic display of time and frequency models, which aides in the analysis and digestion of large quantities of data, is supported by the system graphics routines.

The three-phase UDT analysis routines, which are a subset of the SAW CAD system, are implemented entirely or in part by the FORTRAN 77 subroutines listed as follows:

1. uinput
2. match
3. netan
4. forev.

These routines are contained in the program listings of the Appendix. Figure 24 depicts a function flowchart for the analysis process of a UDT design.
Figure 24. Function flowchart for UDT analysis
The following sections describe the three-phase UDT analysis programs. These subroutines are called by and call other CAD system subroutines. Subroutines which are referenced in the following discussion are listed by subroutine name and function as follows:

- **main**: CAD system main menu
- **readin**: disk file read controller
- **writeo**: disk file write controller
- **erscrn**: clear screen command
- **minp**: terminal input controller for device parameters
- **comld**: loads phasing and matching components into network arrays
- **rlcin**: permits the user to add components to the network arrays
- **admit**: determines network admittance array
- **gauss**: Gaussian elimination routine
- **norm**: general purpose normalization routine

The program listings for these CAD system routines are not in the Appendix, but their validity and function is implied.

**Subroutine "uinput"**

The transducer's equivalent center frequency circuit values are calculated by subroutine "uinput" from device parameters supplied by the user. The frequency dependent values of $B_a(w)$ and $G_a(w)$ are not determined by "uinput", but the synchronous frequency acoustic conductance value,
\( G_a(w_o) \), is calculated from which subroutine "netan" will determine these values during frequency response calculations. Subroutine "uinput" proceeds through the determination of values as directed from the derivation of equations presented in Chapter III.

The following is a list of FORTRAN 77 variables and a descriptive comment which identifies the parameters used in the calculation of the equivalent circuit

- ccsq - material coupling coefficient \((k^2)\)
- vo - substrate velocity
- bw - transducer beam width
- cs - substrate capacitance
- eta - electrode duty factor
- rho - metal resistivity
- ua - wave amplitude
- fs - electrode sampling frequency
- fo - synchronous frequency
- co - electrode pair capacitance
- flam - synchronous frequency wavelength
- gao - acoustic conductance at \(f_o\)
- ct - total static capacitance
- ge - total parasitic conductance
- re - single electrode parasitic resistance
- zo - substrate characteristic impedance
- sum - number of active electrodes
- sumsq - sum of electrode weight squared
- vsum - vector sum of electrode weights, \(N_{eff}\).

The resulting values for the synchronous frequency conductance, total static capacitance, total parasitic conductance, input admittance, and acoustic \(Q\) are displayed on the terminal. At this time the user may decide to make a hard copy of these values for later reference in the analysis process.
Subroutine "match"

The transducer phasing and matching component values are calculated by subroutine "match" from the equivalent circuit model components values using the reactance and susceptance equations defined in Chapter III. Figure 25 shows a functional flowchart for this process.

Figure 25. Function flowchart for subroutine "match"
Subroutine "match" first initializes the arrays associated with the network analysis routines and then calls subroutine "minp" in order to get the necessary transducer parameters from the user. The parameters input and their FORTRAN 77 variable names are:

- ca - electrode capacitance in micro-Farads
- qo - synchronous frequency acoustic Q
- rp - parasitic shunt resistance in ohms
- cp - total parasitic capacitance in micro-Farads

After this input session the frequency data in normalized to a peak of 1.0. The values of synchronous frequency in radians, \( w_0 \), synchronous frequency acoustic conductance, \( g_{ao} \), effective Q, \( q_e \), synchronous frequency susceptance, \( b_{cao} \), and the electrode sampling frequency are calculated by:

\[
\begin{align*}
  \omega_0 &= 2.0\pi f_0 \text{ (meg-Hz)} \\
  g_{ao} &= \omega_0 \frac{ca}{qo} \text{ (mhos)} \\
  q_e &= \omega_0 \frac{(ca+cp)}{(gao+1/\text{rp})} \\
  b_{cao} &= \omega_0 \frac{(ca+cp)}{\text{mhos}} \\
  f_s &= 3.0 \times f_0 \text{ (meg-Hz)}.
\end{align*}
\]

Using the relationships of Chapter III and the calculated parameters the phasing elements may be determined. The arrays containing these components are:

- \( pp(1) \) - parallel phasing element connected to ports 1 and 2
- \( pp(2) \) - parallel phasing element connected to ports 2 and 3
sp(1) - series phasing element connected to port 1
sp(2) - series phasing element connected to port 2

The system subroutine "comld" is then used display and to load the matching network of the users choice into the network arrays in order to calculate the matching components. The necessary network parameters are determined for the matching calculation and the user has the option of adding any components or sources to the network array before the matching calculations. The acoustic admittance is then calculated and used with the system subroutines "admit" and "gauss" to calculate the impedance at the input node. The user then enters the load or source impedance to conjugately match to the device and the matching component equations of Chapter III are used to determine the values of

pm(1) - parallel matching configuration, series element
pm(2) - parallel matching configuration, parallel element
sm(1) - series matching configuration, series element
sm(2) - series matching configuration, parallel element

These values are then displayed and the user may make a hard copy of the values at this time.

Subroutine "netan"

Subroutine "netan" permits the construction of an electrical network around the SAW device model and optionally including the system calculated phasing and
matching components for the purpose of determining the total UDT frequency response. This requires the system the frequency response of the transducer design which may be resident in the data arrays or may be read from a disk file. Figure 26 shows a functional flowchart for subroutine "netan".

First, the network arrays are cleared and subroutine "minp" is called to obtain the transducer parameters as identified in the discussion of subroutine "match". Subroutine "comld" is called to load the phasing and matching elements as chosen by the user. The user then has the option of adding any components to the network arrays. The forward or reverse response is then selected for calculation. After obtaining the value of \( N_{\text{eff}} \), given the FORTRAN 77 variable name "aneff," subroutine "netan" loops through all frequency values, calculates the acoustic admittance from the equivalent circuit and determines the total response. In doing so, the system subroutines "admit", "gauss", and "forev" are called for each frequency value. Upon completion the user may choose to normalize the frequency data and write the data to disk at this time.
INITIALIZE NETWORK COMPONENT ARRAYS

INPUT DEVICE ELECTRICAL PARAMETERS

CALCULATE RELATED ELECTRICAL PARAMETERS

OBTAIN ARRAY FACTOR DATA

CHOOSE AND LOAD PHASING AND MATCHING COMPONENTS INTO NETWORK ARRAYS

ADD ANY OTHER ELEMENTS TO NETWORK ARRAYS

INPUT $N_{\text{eff}}$ TO INCLUDE ACOUSTIC SUSCEPTANCE

CHOOSE TO INCLUDE ELEMENT FACTOR

CALCULATE RESPONSE BY
1. DETERMINING TRANSDUCER NODE VOLTAGES
2. INCLUDE EFFECTS OF SPACIAL PHASE
3. MULTIPLY BY TRANSFER FUNCTION FOR EACH FREQUENCY VALUE

Figure 26. Function flowchart of subroutine "netan"
Subroutine "forev"

The magnitude and phase for each value of frequency is determined by subroutine "forev" from the knowledge of the port voltages, calculated by the network routines, and the transducer transfer function, which is the product of the array factor and the element factor.

The transfer function, \( H(w) \), is held in arrays "amp" and "phase" and is used to calculate the frequency response, \( Y(w) \), as follows

\[
Y(w) = [-v_1 + (v_1-v_2)e^{j\omega t_0} + v_2e^{j\omega t_0}] \cdot H(w)
\]

where

\( v_1 \) - voltage at port 1 in volts
\( v_2 \) - voltage at port 2 in volts
\( t_0 = (\pi) \) for UDT forward response, \((-\pi)\) for reverse.

The resulting frequency data is stored in data arrays "amp" and "phase", thus replacing the transfer function data.

Example

This section presents an example of the typical analysis procedure using the software implementation of the transducer model presented in this thesis. The design to be analyzed is a bandpass filter which was synthesized using the following list of transducer specifications
center frequency \( f_0 = 273 \text{ MHz} \)

bandwidth to -1.5 dB \( B_{-1.5} > 3.0 \text{ MHz} \)

null bandwidth \( B_{\text{null}} < 10 \text{ MHz} \)

sidelobe rejection \( > 35 \text{ dB} \).

A proposed solution to these specifications is a three-phase UDT with transducer weighting as shown in Figure 27. This sampled function represents the time impulse response model of the transducer, or by previous definition the array factor, from which the corresponding frequency response is obtained using the digital Fourier transform CAD routines. Figure 28 and Figure 29 show the broadband and passband array factor's response for the design to be analyzed. The next analysis step is to determine the transducer electrical parameters using subroutine "uinput". The output is shown in Figure 30. With these parameters known and the knowledge of the substrate and package characteristics, the CAD software determines the necessary phasing components. For the specific example given, the matching configurations are calculated by subroutine "match" to be

parallel phasing element values -

element #1 : .18327 micro-Henrys
element #2 : .23282 micro-Henrys

series phasing element values -

element #1 : .059942 micro-Henrys
element #2 : .076147 micro-Henrys.
Figure 27. Transducer array factor

Figure 28. Broadband array factor response
Figure 29. Passband array factor response

***THREE-PHASE UDT***

**DESIGN INFORMATION**

Vector tap sum - $H_{eff} = 52.04$

Total tap weight sum - $H = 61.69$

Total tap weight square sum - $H_s = 42.78$

Acoustic conductance = 158.962 microhms.
Electrode capacitance = 1.457 pf.
Thin film conductance = 36.457 microhms.
Parasitic resistance = 0.02743 Meg-ohms

Input admittance: conductance = 0.195 mhos.
Susceptance = 2.499 mhos.
Input impedance: resistance = 31.092 ohms.
Reactance = -397.664 ohms.

Transducer $Q_0 = 12.79$

<<< ENTER return to continue >>>

Figure 30. Output from subroutine "uinput"
After choosing a specific phasing configuration, subroutine "match" determines the matching components. For the choice of the series phasing configuration, the matching elements are

series/parallel matching:

matching element #1 : .082609 micro-Henrys
matching element #2 : .121004 pico-Farads

parallel/series matching:

matching element #1 : .095792 micro-Henrys
matching element #2 : .220163 micro-Henrys

where for both configurations element #1 is the series element and element #2 is the parallel element.

Now the complete electrical network is built around the transducer model and the forward and reverse responses are determined by subroutine "netan". Choosing the parallel/series matching configuration yields broadband and passband forward responses depicted in Figure 31 and Figure 32, respectively. Figure 32 also shows the array factor as a dotted line for comparison from which is seen the resulting broadening of the passband due to the electrical effects of the transducer equivalent circuit. The reverse broadband and passband responses are shown in Figure 33 and Figure 34, respectively. Figure 34 also shows the forward response as a dotted line for comparison. The forward response group delay was determined and is shown in Figure 35.
Figure 31. Broadband forward response

Figure 32. Passband forward response
Figure 33. Broadband reverse response

Figure 34. Passband reverse response
Figure 35. Forward response group delay

These results are compared to a three-phase UDT design by Malocha and Gopani [3]. Figure 35 shows a comparison of filter frequency characteristics between a similar CAD routine, the simple impulse response model and actual device data for the published design and the impulse response model and CAD model for the example design. Recall that these are similar but not identical designs.

<table>
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<th>array factor</th>
<th>program</th>
<th>actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>BW1.5 (MHz)</td>
<td>2.80</td>
<td>3.46</td>
<td>3.40</td>
</tr>
<tr>
<td>BW15 (MHz)</td>
<td>6.78</td>
<td>7.04</td>
<td>7.40</td>
</tr>
<tr>
<td>BW20 (MHz)</td>
<td>7.23</td>
<td>7.47</td>
<td>7.81</td>
</tr>
<tr>
<td>sidelobe</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rejection (dB)</td>
<td>&gt;50</td>
<td>&gt;47</td>
<td>&gt;42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>array factor</th>
<th>program</th>
<th>actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>published</td>
<td>3.54</td>
<td>4.48</td>
<td></td>
</tr>
<tr>
<td>example</td>
<td>6.80</td>
<td>7.20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.52</td>
<td>7.84</td>
<td></td>
</tr>
</tbody>
</table>

>60 >55

Figure 36. Comparison of analysis results
From Figure 36 a comparison of the predicted effects of the complete transducer on the passband bandwidth for the published analysis and the example is given by the ratio of array factor bandwidth to program bandwidth as follows:

\[
\begin{align*}
\text{published analysis:} & \quad \frac{3.46}{2.80} = 1.24 \\
\text{example:} & \quad \frac{4.48}{3.54} = 1.27.
\end{align*}
\]

For the sidelobe rejection the ratios are:

\[
\begin{align*}
\text{published analysis:} & \quad \frac{47}{50} = 0.94 \\
\text{example:} & \quad \frac{55}{60} = 0.92.
\end{align*}
\]

Recall that these designs are not identical, but it can be seen that the analysis model is consistent with previous work. It would have been preferable to have an actual device from which to analyze a design and determine the accuracy of the transducer model.
CHAPTER V
CONCLUSIONS

The three-phase UDT represents a solution to the need for a broadband low-loss SAW transducer. This transducer's structure and operation has been evaluated in comparison to other UDT technologies. In light of the other approaches, what at first appears to be a complex phasing and matching network has been shown to require only four reactive elements, the determination of which is part of the SAW CAD system. A broadband model including all first order transducer model parameters and electrical network effects of the necessary phasing and matching components is presented. The elements of this model are determined by the CAD system from fundamental substrate and package parameters. This model is implemented in FORTRAN 77 code for use in computer analysis and has been shown to predict the forward and reverse frequency response of a given transducer design. The model can include any electrical effects a designer might want to analyze. An analysis example shows the capability to perform complex interactive analysis in a relatively short time with the use of CAD techniques.
APPENDIX

COMPUTER PROGRAMS
This FORTRAN 77 source code file contains subroutine 'input' which calculates the transducer equivalent circuit model component values from device parameter obtained from the user and from the time impulse response model.

subroutine input

dimension bc(10)
character cPause*1
complex yc,zc

common /file/ amp(4096),phase(4096),nfft,itype
common /dat/ fortflo,tfhi,num
common /dPar/ idev,ca,co,rp,cp,xxx,Phsh

call erscn
10 if(itype.eq.1) then
    write(6,*) ' must use time file so to file
    endif
11 if(itype.eq.0) goto 11

clear screen
call erscn
write(6,*)
write(6,*), 'ENTER material parameters:
write(6,*), ' Coupling Coefficient >
read(5,*), Cceu

write(6,*), ' Substrate Velocity (m/sec) >
read(5,*), vo
vo=vo*1.0e+2

write(6,*), ' Beam width >
write(6,*), ' (in units of wavelengths) >
read(5,*), bw

write(6,*), ' Substrate capacitance (pf/cm) for unit width >
read(5,*), cs

write(6,*), ' Electrode duty factor >
read(5,*), eta

write(6,*), ' Metal resistivity in ohms/cm >
read(5,*), rho

calculate other parameters
fo=fo*1e6
flam=vo/fo
\eta=4*atan(1.0)
delt=(tfhi-tflo)/(num-1)
fs=1.0/delt
fs=fs*1e6
cs=cs*1e-12
c0=4.0*cs*bw*flam/f1

if((fs-3.0*fo).eq.1) then
  write(6,*), '<< WARNING >>
  write(6,*), ' The sampling frequency of the data is not 3 times the synchronous frequency'
  write(6,*), ' ENTER option :'
  write(6,*), ' 1 = continue at your own risk'
  write(6,*), ' 2 = return to analysis menu'
  read(5,*), iansw
  if(iansw.eq.2) return
endif

zero every second and third sample in design time file for analysis using superposition (element factor)

deltu=num/2+1

calculate: vsun = Neff - vector sum of tap weights
sum = N - total electrode length
sumso = Ns - sum of squared values of tan weights

vsun=0.0
sum=0.0
sumso=0.0
do 1000 i=1,num
if(abs(idexto-i)/3.0 > abs(idexto-i)) amp(i)=0.0
ai=amp(i)*cos(Phase(i))
vsun=ai+vsun
sum=vsun+abs(ai)
sumso=ai*ai+sumso
continue

the conductance is a function of vsun
the capacitance is a function of sum

calculate center frequency conductance
wave amplitude=ua and is a function of eta

ua=ccsa*(.56*eta+.54)*vsun
z0=ccsa/(2*pi*cs*vo)
sa0=.75*2*(ua**2)*bw/z0

calculate finite capacitance
look over 10 electrodes in either direction

do 2000 n=1,10
bc(n)=1.0/(4.0*n*n-1.0)
include effects of duty factor for first 2 terms
bc(1)=bc(1)*exp(1.75*(eta-.5))
b(2)=bc(2)*(eta-.5)**2
the normalized finite capacitance
is for a 2*fo sampled transducer+bt
bt=2*(bc(1)+bc(2)+bc(4)+bc(5)
+bc(7)+bc(8)+bc(10))

calculate resistive loss due to thin film

calculate resistance for a single electrode is

rho=ohms/su,
bw=beam width in wavelengths
The total parasitic conductance is:

g_e = (2 * pi * f0 * c) * (2 * pi)

Clear screen
Call escrn
Write(6,*)
Write(6,*)
Write(6,*)
Write(6,*)
Write(6,*)

Before outputting information

Divide by 3 for each phase of UDT

\[ sa0 = sa0 / 3.0 \]
\[ de = se / 3.0 \]
\[ ca = ca / 3.0 \]
\[ dt = sa0 + se \]
\[ bt = 2.0 * pi * f0 / ca \]
\[ wc = c * c / (c^2 + 1) \]
\[ zc = 1.0 / wc \]
\[ sa0 = sa0 * e6 \]
\[ ca = ca * e6 \]
\[ se = se * e3 \]
\[ oo = a * a * (wc) / (a * a) \]
\[ rp = 1.0 / se \]

Write(6, 2900) vsum
Write(6, 2900)

\[ \text{Acoustic conductance} = \frac{1}{f9.3} \, \text{micromhos} \]
\[ \text{Electrode capacitance} = \frac{1}{f9.3} \, \text{pf} \]
\[ \text{Thin film conductance} = \frac{1}{f9.3} \, \text{micromhos} \]

Write(6, 3050) rp / e6

\[ \text{Parasitic resistance} = \frac{1}{f11.5} \, \text{Mes-ohms} \]
write(6,*')
write(6+3100) vc, ze
3100 format('input admittance: conductance='''%9.3f''' ' mhos.'',',
susceptance='''%9.3f''' ' mhos.'',',
input impedance: resistance='''%9.3f''' ' ohms.'','
reactance = '''%9.3f''' ' ohms.'',')

write(6,*')
write(6,*')
write(6+3110) go
3110 format('transducer Qo = '''%f''' .2)

cwrite(6,*')
cwrite(6,*')
cwrite(6,*') <<< ENTER return to continue >>>
cread(5,1001) cause
1001 format(a1)
c
creturn fo to MHz
cfo=fo/1.0e6
c
call erscrn
creturn
end
match2.f

For more information contact: Don C. Malocha
Sam M. Richie

Date last revision: 06-10-83

Compatibility: SAWCAD Version 2.0

This FORTRAN 77 source code file calculates the phasing components required for three-phase UDT's in both two-element series and two-element parallel forms and for both UDT's and BDT's the two-element series/parallel and the two-element parallel matching network components are determined and passed to the network analysis program for use in calculating the device response, if desired.

subroutine match

real r(10*10),1(10*10),c(10*10),rbn(2),xn(2)
complex a(10*10),x(10),b(10),bsave(10),ya,zo,yo
character cparam

common /file/ amp(4096),phase(4096),nfft,type
common /dat/ for,tfor,fh1,num
common /dpar/ idev,ca,go,pp,cp,ppx,phsh
common /dmp/ pp(2),sf(2),pm(2),sm(2),ipcom
common /rlc/ rl,rc,nodes,bsave

data pp,sf,pm,sm /8*0.0/
data idev,ca,go,pp,cp,ppx,phsh /3*0.0,1e30,3*0.0/
initialize flags and component arrays

pi=4.0*atan(1.0)
ipcom=0

do 100 i=1,10
bsave(i)=cplx(0.0,0.0)
do 100 j=1,10
r(j,i)=1.0e-35
1(j,i)=1.0e-35
c(j,i)=1.0e-35
100 continue

write(6,*),<<< NETWORK INITIALIZED >>>

set device parameters from user
call mini

calculate device parameters

wo=2.0*pi*fo
da0=(wo*ca/ao)-1/rr

d0=wo*(ca+cp)/(da0+1/rr)

bca0=wo*(ca+cp)
s=P*(ao)*fo

if idev=1 for UDT then determine phasing elements
inductors will have negative values and
 capacitors will have positive values

bn - parallel elements
xn - series elements

if(idv.eq.1) then
  sart3=sqrt(3.0)
  bn(1)=-1.0+(sart3/ae)
  bn(2)=-1.0+(sart3/ae)

  write(6,'(bn1,2=','bn(1),bn(2))
  xn(1)=(ae*ae-sart3*ae)/(3*(1+ae*ae))
  xn(2)=(ae*ae+sart3*ae)/(3*(1+ae*ae))

  do 200 i=1,2
     if(bn(i).lt.0) then
       ppi(i)=1.0/(bn(i)*wo*bca0)
     endif

     if(bn(i).gt.0) then
       ppi(i)=(bn(i)*bca0)/wo
     endif
  200

  do 300 i=1,2
     if(xn(i).lt.0) then
       spr(i)=-xn(i)/(wo*bca0)
     endif

     if(xn(i).gt.0) then
       spr(i)=-bca0/(wo*xn(i))
     endif
  300

  display phasing component values and load into
network element arrays if desired

  iret=1
  call comld(iret)
end considerations for UBT's
end!

clear screen
call etscrn

nodes is equal to the number of network nodes
it just so happens that it can be found by:

nodes=ipcom+1

set correct excitation for matching
if(ipcom.eq.0) bsave(1)=cmplx(1.0,0.0)
if(ipcom.eq.1) bsave(1)=cmplx(1.0,0.0)
if(ipcom.eq.2) bsave(3)=cmplx(1.0,0.0)

set node at which to calculate input impedance
if(ipcom.eq.0) nodz=1
if(ipcom.eq.1) nodz=1
if(ipcom.eq.2) nodz=3

write(6,'*') 'Do you wish to add any components to the'
write(6,'*') 'device model or network before calculation'
write(6,'*') 'of the matching components? (y/n)'
read(5,1000) cpause
format(a1)
if(cpause.eq.'y', or, cpause.eq.'Y') then
call rclin
write(6,'*') '
write(6,'*') 'ENTER node for matching: [PV = ',nodz,']'
read(5,*) nodz
endif

calculate acoustic admittance
bca=1.0
da=(sao+1/ri)/bca0
va=cmplx(sar,bca)

convert component arrays to admittance array
call admit(workbca0,mar,ar,h)

perform gaussion elimination on network
call gauss(ar,br,nodes)

calculate nodz impedance
input load impedance for matching calculation

call erscrn

\[ x(nodz) = x(nodz) / (\text{cmplx}(bca0, 0.0) \times \text{bsave}(nodz)) \]

write(6, *) 'ENTER load impedance: real, imaginary
read(5, *) xor, zoi

calculate matching components: inductors will have negative values
 capacitors will have positive values

\[ \begin{align*}
  &\text{pm} - \text{parallel/series components} \\
  &\text{sm} - \text{series/parallel components}
\end{align*} \]

call erscrn

\[ \begin{align*}
  \text{zo} &= \text{cmplx}(\text{xor} - \text{zoi}) \\
  \text{yo} &= \text{cmplx}(1.0 \times 0.0) / \text{zo} \\
  \text{do} &= \text{real}(\text{yo}) \\
  \text{bo} &= \text{aimag}(\text{yo}) \\
  \text{rn} &= \text{real}(x(nodz)) \\
  \text{xc} &= \text{aimag}(x(nodz))
\end{align*} \]

\[ \text{series/parallel matching} \]

\[ \begin{align*}
  \text{write}(6, '*')' \\
  \text{write}(6, '*') 'Series/Parallel Matching:'
\end{align*} \]

\[ \begin{align*}
  \text{series element} \\
  \text{sm}(1) &= \text{sart}((\text{rn}/\text{do}-\text{rn}\text{rn})) - \text{xc}
\end{align*} \]

\[ \text{parallel element} \]

\[ \begin{align*}
  \text{if}((\text{rn}/\text{do}-\text{rn}\text{rn}).lt.0.0) \text{ then} \\
  \text{write}(6, '*')' \\
  \text{write}(6, '*') 'Series/Parallel Matching non-realizable' \\
  \text{soto 989} \\
  \text{endif} \\
  \text{sm}(2) &= (-\text{rn}/\text{do}) / ((\text{rn}/\text{do}) * \text{sart}(\text{rn}/\text{do}-\text{rn}\text{rn}))
\end{align*} \]

\[ \text{write}(6, '*')' \\
\text{write}(6, '*')'\#1 is the Series element, \#2 is the Parallel element'
\]

\[ \text{do 400 i=1,2} \]

\[ \text{if(sm(i),lt.0)} \text{soto 410} \]

\[ \text{sm}(i) = -\text{sm}(i) / \text{wo} \]

\[ \text{write}(6, '*') 'Matching element \# i, \# -sm(i), \# uH'
\]

\[ \text{soto 400} \]

\[ \text{sm}(i) = 1.0 / (\text{wo} * \text{sm}(i)) \]

\[ \text{write}(6, '*') 'Matching element \# i, \# , sm(i) * 1.0e6, \# F'
\]
Parallel/series matching

\( r_o = \text{real}(z_0) \)
\( xo = \text{aimag}(z_0) \)
\( x(nodz) = \text{cmplx}(1.0, y_0)/x(nodz) \)
\( s = \text{real}(x(nodz)) \)
\( bc = \text{aimag}(x(nodz)) \)

Parallel element

\( P_m(2) = -1.0/(s\sqrt{g/ro-g*g}) - bc \)

Series element

\[
\text{if}((g/ro-g*g) \lt 0.0) \text{ then}
\text{write}(6,*)'Parallel/series matching non-realizable'
\text{soto 787}
\text{endif}
\text{Pm(1) = (xo*g/rotsqrt(g/ro-g*g))/(g/ro)}
\text{write}(6,*)'Parallel/series matching : 1 is the Series element, 2 is the Parallel element'
\text{do 500 i=1,2}
\text{if(Pm(i) \lt 0.0) soto 510}
\text{Pm(i) = -Pm(i)/wo}
\text{write}(6,*)'Matching element \#i: Pmi(1), uH'
\text{soto 510}
\text{Pm(i) = (-1.0/(wo*Pm(i)))}
\text{write}(6,*)'Matching element \#i: Pmi(1) x 1.0e6, PF'
\text{500 continue}
\text{787 return}
\text{end}
This FORTRAN 77 source code file contains the network analysis subroutine "netan". This routine permits the building of an electrical network around the SAW device model and optionally include the system calculated matching components and the system calculated phasing components for the purpose of calculating the total device response (both forward and reverse for UDT's). This requires the system to obtain the impulse response model of the device either already in arrays 'amp' and 'phase' or to be read in from a disk file. (Note this is a time file)

Subroutine netan

```fortran
real r(10,10), l(10,10), c(10,10)
complex bsave(10), x(10), y(10), ra(10,10), rb(10)
character cpause*1

common /file/ amp(4096), phase(4096), nfft, iftype
common /dat/ fortfl, forthfi, num
common /dpar/ idev, ca, ro, pr, cp, rsh, phsh
common /lic/ r, lic, c, rnodes, bsave

initialize network component arrays and source vector
r1=4.0*atan(1,0)

do 100 i=1,10
bsave(i)=cmplx(0.0,0.0)
x(i)=cmplx(0.0,0.0)
do 100 j=1,10
r(j,i)=1.0e-35
l(j,i)=1.0e-35
c(j,i)=1.0e-35

100 continue

give device parameters from user
```
call minp

calculate device characteristics

\[ \phi = 4.0 \times \tan(1.0) \]
\[ \omega_0 = 2.0 \times \pi \times \omega \]
\[ \theta_0 = \frac{\omega_0 \times c_a}{\omega_0 - 1} / R \]
\[ \delta w = 2.0 \times \pi \times (tf_1 - tf_2) / (num - 1) \]
\[ f_s = \pi \times \pi \times \pi \times \pi \]
\[ \omega = 2.0 \times \pi \times \pi \times \pi \times \pi \]
if \( \text{idev.eq.1} \) then \( \text{to} = \frac{\phi \times \pi \times \pi \times \pi \times \pi}{\pi} / (180 \times \omega_0) \)
if \( \text{idev.eq.2} \) then \( \text{to} = 0 \)

inquire and load phasings and matching components

write(6,*) ' << NETWORK INITIALIZED >>'
write(6,*)'
iret=0
call comld(iret)

inquire and load any other components

write(6,*)'Do you wish to add any components to the'
write(6,*)'network for calculating the total response ? (y/n)'
read(5,1001) cPause
format(al)
if(cPause.eq.'Y') call rlcin

call erscrn

more terminal input!

iansw=1
if \( \text{idev.eq.1} \) then
write(6,*) ' ENTER option :
write(6,*) ' 1 = calculate UDT forward response'
write(6,*) ' 2 = calculate UDT reverse response'
read(5,**) iansw
endif

write(6,*)'
write(6,*)' ENTER neff to include acoustic susceptance'
read(5,**) iansw

write(6,*)'
write(6,*)' Do you desire to include ELEMENT factor ? (y/n)'
read(5,1001) cPause

if \( \text{iansw.eq.2} \) then \( \text{to} = \text{to} \)

calculate voltage transfer vs. freq
write(6,*)
   ' ' ' ' ' ' ' ' ' ' WORKING ON RESPONSE DATA ' ' ' ' ' ' ' ' ' ' write(6,*)
   c
   c
   c
   ik=nint(wo-2*pi*tflo/delw)+1
   wi=(ik-1)*delw+2.0*pi*tflo
   amp(ik)=(amp(ik)*sin(wi*pi/ws))**2
   c
do 1000 k=1,num
   if(wi.eq.0) wi=1.0e-30
   if(copause.eq.'y',or,copause.eq.'Y') amp(k)=amp(k)*sin(wi*pi/ws)
   fe=anef*pi*(wi-wo)/wo
   if(fo.eq.0) goto 1010
   ba=sao*(sin(2.0*fe)-2.0*fe)/(2.0*fe**2)
   if(fo.eq.0) ba=0.0
   bca=(wi*(catcp)+ba)/bcao
   da=(1.0/rp+sao*amp(k)**2/amp(ik2))/bcao
   ya=cmpx(da,bca)
   c
   call adim(wi,bcao,wa,a,b)
   c
   call sauss(a,x,b,nodes)
   c
   call forex(wi+1,x(1),x(2),to)
   c
   1000 continue
   c
   call escrn
   c
   write(6,*)' Do you wish to normalize the data ? (y/n)'
   write(6,*)
   read(5,1001) cpause
   if(cpause.eq.'y',or,cpause.eq.'Y') then
      write(6,*)
   write(6,*)
   write(6,*)
   call norm
   endif
   c
   write(6,*)' Do you wish to write data to disk now ? (y/n)'
   read(5,1001) cpause
   if(cpause.eq.'y',or,copause.eq.'Y') call writeo
   c
   call escrn
   c
   return
   c
   end
The FORTRAN 77 source code file contains the program to calculate forward or reverse response given the frequency dependent voltages applied to ports.

Subroutine forev(w1, i, v1, v2, to)

Complex v1, v2, hw, ht, h1, h2, h3

Common /file/ amP(4096), Phase(4096), nfft, itype
Common /dat/ forfl0, tfh1, num
Common /dpar/ idev, ca, 0, 0, P1, P2, Phsh

pi=4.0*atan(1.0)

If idev.eq.1 then
    amp(i)=amp(i)*cos(Phase(i))
    Phase(i)=amp(i)*sin(Phase(i))
    hw=cmplx(amp(i), Phase(i))
    h1=v1
    h2=(v1-v2)*exp(cmplx(0.0, wi*to))
    h3=v2*exp(cmplx(0.0, 2*wi*to))
    ht=(h1+h2+h3)*hw
    amp(i)=sqrt(real(ht)**2+imag(ht)**2)
    Phase(i)=atan2(imag(ht), real(ht))
Endif

If idev.eq.2 then
    vol=sqrt(real(v1)**2+imag(v1)**2)
    vol=atan2(imag(v1), real(v1))
    amp(i)=amp(i)*vol
    Phase(i)=Phase(i)+vol
Endif

Return
End
LIST OF REFERENCES


