

SAW DEVICE IMPULSE RESPONSE MODELING USING BROADBAND DIFFRACTION THEORY

J. H. Hines, D. C. Malocha,^{†,‡} and R.B. Brown,

Sawtek Inc., P.O. Box 609501, Orlando, Florida 32860

[†] Electrical Engineering Department, University of Central Florida, Orlando, Florida 32816

[‡] Currently on sabbatical at the Advanced Technology Center, GEG, Motorola, Phoenix, Arizona

ABSTRACT

A unique approach to obtaining a two-dimensional impulse response diffraction model valid for the broadband case has been developed previously[1]. This approach utilizes a double integral reduction technique to determine the tap-to-tap response, and has been used to analyze various tap configurations on both isotropic and anisotropic substrates.

This paper presents an extension of this analysis technique to model the effects of diffraction on the impulse response of a complete SAW device. Both isotropic and anisotropic substrates are treated. The current work also considers the implications of the two-dimensional nature of the mathematical formulation of the model, and how the results of this formulation influence the validity of the model. Comparison is made between theoretical and experimentally observed device performance. The potential exists for this analysis technique to be applied to broadband diffraction compensation.

INTRODUCTION

In previous work[1,2], a point source impulse response, valid for all frequencies, was obtained by applying an impulse driver to the two dimensional wave equation.

When integrated over a source distribution in the time domain and Fourier transformed, this impulse response yields a true broadband SAW device impulse response which includes the effects of diffraction. Arbitrary anisotropy can be taken into account quite easily during the source distribution integration, provided data is available for velocity as a function of propagation direction on the substrate of interest. Double integral reduction[3] was used to reduce the number of calculations involved.

The time domain point source impulse response previously obtained[2], however, proved cumbersome to calculate due to a branch point in the denominator, and the required spatial integrations were not fast enough for use in practical design applications. Thus, in the present approach a simpler approximation to the point source impulse response is used. This provides a much faster and more computationally efficient means of evaluating the diffraction patterns created by arbitrary transducer geometries and substrate anisotropies.

THEORY

The following equation is used as an approximation to the scalar two dimensional impulse response of an ideal point source[4]

$$U(r, \omega) \approx \frac{e^{-j\omega r/c}}{r^{1/2}} \quad (1)$$

It is assumed that this function is valid for all frequencies, and for the reasonably short separations from the source under consideration. Taking the inverse Fourier transform yields a time domain point source impulse response given by

$$u(r, t) \propto \frac{\delta(t - \frac{r}{c})}{r^{1/2}} \quad (2)$$

where r is the radial distance from the point source and c is the surface wave velocity.

Using Huygen's principle, the response at any given observation point to an impulse applied to a tap can be found by integrating the point-to-point impulse response along the tap. Ignoring constants of proportionality, this expression can be written as:

$$h_{t \rightarrow p}(y_p, t) = \int_0^L \frac{\delta(t - \frac{r}{c})}{r^{1/2}} dy_T \quad (3)$$

where y_T is the position on the transmitting tap, y_p is the position of the observation point relative to a line parallel to the bottom of the transmitting tap, and L is the tap length, as shown in Figure 1. Equation (3) can be used to generate transverse beam profiles and three-dimensional plots of impulse responses.

The impulse response of a pair of parallel taps of arbitrary lengths and positions relative to one another can be obtained by integrating Equation (3) over the receiving tap. This tap to tap response can be expressed as

$$h_{T-T}(t) = \int_{y_T = -b}^{L-a} \int_{y_R = a}^b \frac{\delta(t - \frac{r}{c})}{r^{1/2}} dy_R dy_T \quad (4)$$

where y_R is the coordinate along the "receiving" tap, y_T is the coordinate along the "transmitting" tap relative to a horizontal line through y_R , and a , b , L , D , and r are as shown in Figure 2. Using double integral reduction[5],

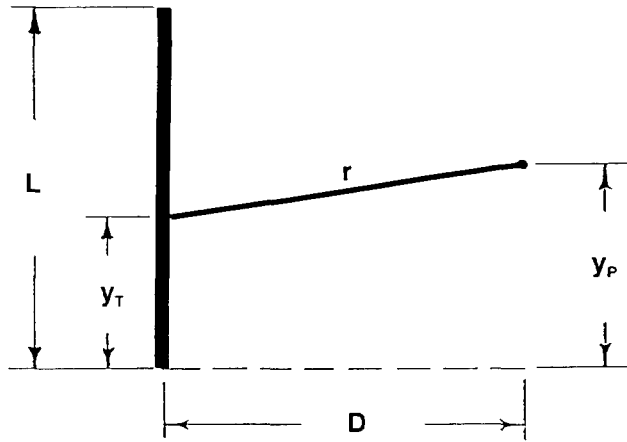


Figure 1. Coordinate system for tap to point integration

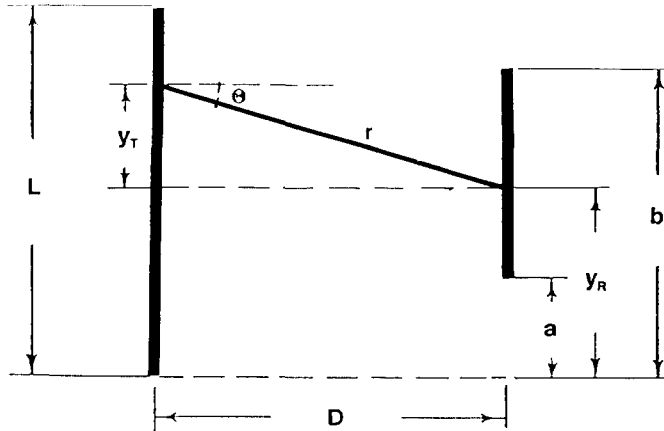


Figure 2. Coordinate system for tap-to-tap double integral

Equation 4 can be reduced to a single integral for use in calculations. To a first approximation, arbitrary anisotropy can be included in this model by allowing the velocity (c) and acoustic coupling coefficient (K^2) to vary as a function of angle.

The overall SAW device impulse response can be obtained through superposition of tap-to-tap responses. If we consider two arbitrarily apodized transducers, the first with center frequency f_{01} and M fingers and the second with center frequency f_{02} and N fingers separated by a center-to-center distance of Z_0 (see Figure 3), the overall device impulse response in the time domain will be given by^[1]

$$h(t) = \sum_{i=1}^M \sum_{j=1}^N h_{ij}(t) \quad (5)$$

where h_{ij} represents the tap to tap impulse response given by equation (4), with an appropriate sign included

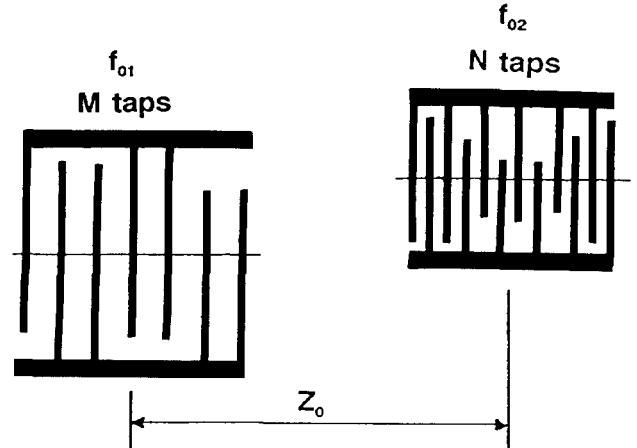


Figure 3. Example of a pair of transducers with arbitrary geometry

to take into account the tap polarities. This brute force calculation method involves $M \cdot N$ calculations of the diffraction integral.⁷ Some simplifications result when the two transducers have equal center frequencies and one or both of the transducers are unapodized. Despite the large number of calculations involved for a realistic device, use of equation (2) allows the integrals to be performed very rapidly in the time domain.

Once a time domain impulse response has been obtained, it can be Fourier transformed to yield the desired broadband frequency response for the device. Since the actual SAW device does not consist of ideal line charge sources, a term^[5,6] which approximates the effects of the source charge distribution (or element factor) can be included when finding the frequency response.

THEORETICAL RESULTS

In addition to being a fast, efficient method of obtaining a response valid for all frequencies, performing the diffraction calculation in the time domain provides valuable insight into what is physically occurring during the process of diffraction. Two and three dimensional plots can be generated, aiding in the visualization of the diffracting beam.

One example of an individual tap-to-tap response is shown in Figure (4). Part (a) illustrates the tap geometry under consideration. The two-dimensional time domain response, shown in Figure 4(b), exhibits the expected behavior. No response is observed until the signal has had time to propagate directly from the transmitting to the receiving tap. Thus, a jump is observed when the signal is first received. If no diffraction were present, the response would drop to zero immediately, yielding an impulse. Due to diffraction, however, energy will travel from every point on the transmitting tap to every point on the receiving tap,

¹Note: a tap impulse response analysis is used in this approach rather than an overlap or 'gap' analysis.

causing the time domain response to last considerably longer.

A three dimensional plot of the time domain impulse response is shown in Figure 4(c). This plot dramatically illustrates the behavior of the surface wave, allowing one to visualize cross sections of the wave that

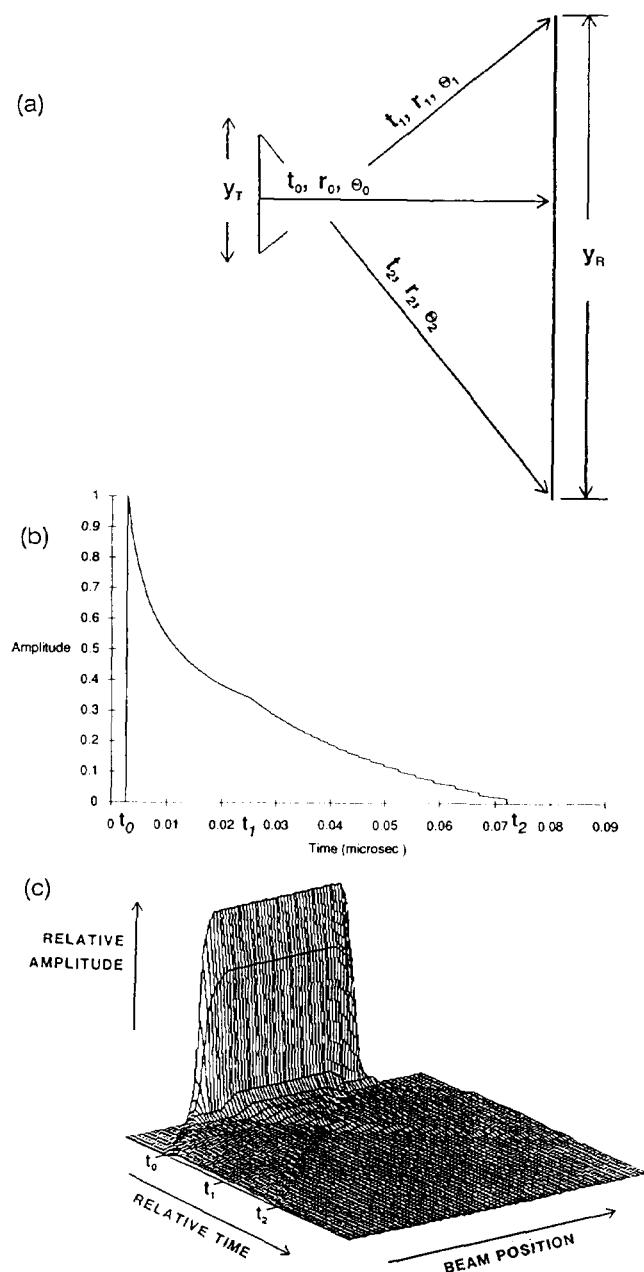


Figure 4. Tap-to-tap impulse response

- Geometry for tap-to-tap impulse response calculation
- Two-dimensional time domain tap-to-tap response
- Three-dimensional time domain tap-to-tap response

would be detected by the receiving tap as time increases. The nominal pulse delay will be determined by the tap separations. Initially, the pulse is well defined and a majority of the energy stays within the beamwidth in which it was launched. A large peak is seen when this energy first reaches the output tap. The amplitude of the response dies off rapidly, since no more "direct" energy is being received. Rather, the energy picked up at the output tap after the initial pulse is due to portions of the launched wave diffracting, thereby taking a longer path and a longer time to reach the output tap. Note the symmetric spreading of energy in the transverse direction, due to diffracted energy reaching the output tap.

Although the three-dimensional plots become complicated when many taps are used, a few simple examples of transducer-to-single-tap responses are illustrative and interesting to consider. First we consider a five-tap apodized transducer interacting with a single receiving tap. The normalized tap weights for the launching transducer are 0.25, -0.5, 1.0, -0.5, and 0.25 respectively, and there is no slant to the apodization pattern. The launching transducer has a center frequency of 100 MHz and an aperture of 35λ , and the receiving tap has an aperture 50λ wide. The substrate assumed for this plot is ST-quartz and the wave is launched on a pure mode axis.

The two-dimensional response is shown in Figure 5(a). As shown, the first jump occurs when the energy launched by the first (0.25 long) tap in the apodized transducer reaches the output tap. When the pulse generated by the second tap (-0.5 tap weight) reaches the receiving tap, a larger jump in a negative direction is observed (sign change is due to second tap in launching transducer being negative). This pattern of positive and negative jumps continues until the energy launched in a direct path from each of the taps in the apodized transducer has interacted with the output tap. The response then drops off rapidly, as for tap-to-tap case.

Figure 5(b) is a three-dimensional plot of this response, once again showing how energy diffracts further to the sides of the beam as time increases. Note that the distribution of energy in the beam remains symmetric as the wave propagates. This is true only in the case of a wave launched on a pure mode axis of the crystal, and for an apodized transducer where the apodization pattern is not slanted. Transverse beam profiles at four different times are given in Figure 5(c)-(f). Once again, the beam spreads symmetrically, although the pulse shape is more complicated than that of the single tap considered in Figure 4.

Figure 6 shows a three-dimensional plot of the response obtained for a five tap launching transducer with the same tap weights as previously used, but with a slanted apodization pattern. All other factors are the same as those for Figure 5. The overall time response [not shown] is quite similar to the unslanted case, since the overall response effectively shows an integration across the beam width, and therefore will not be affected by where the energy is received along the output tap. The three-dimensional plot clearly demonstrates the spatial nonuniformity of the surface wave launched by the slanted apodization pattern.

When a wave is launched in a direction other than a pure mode axis on an anisotropic substrate, the phase

velocity and group velocity are no longer colinear. This causes the wave energy to "walk" off axis, an effect known as beam steering or power flow. Figure 7 demonstrates this effect for an unweighted, three tap transducer with a 25λ aperture launching energy towards a single 300λ long tap on YZ-LiNbO₃. The separation is 300λ , and the wave is launched at an angle of five degrees from the Z axis.

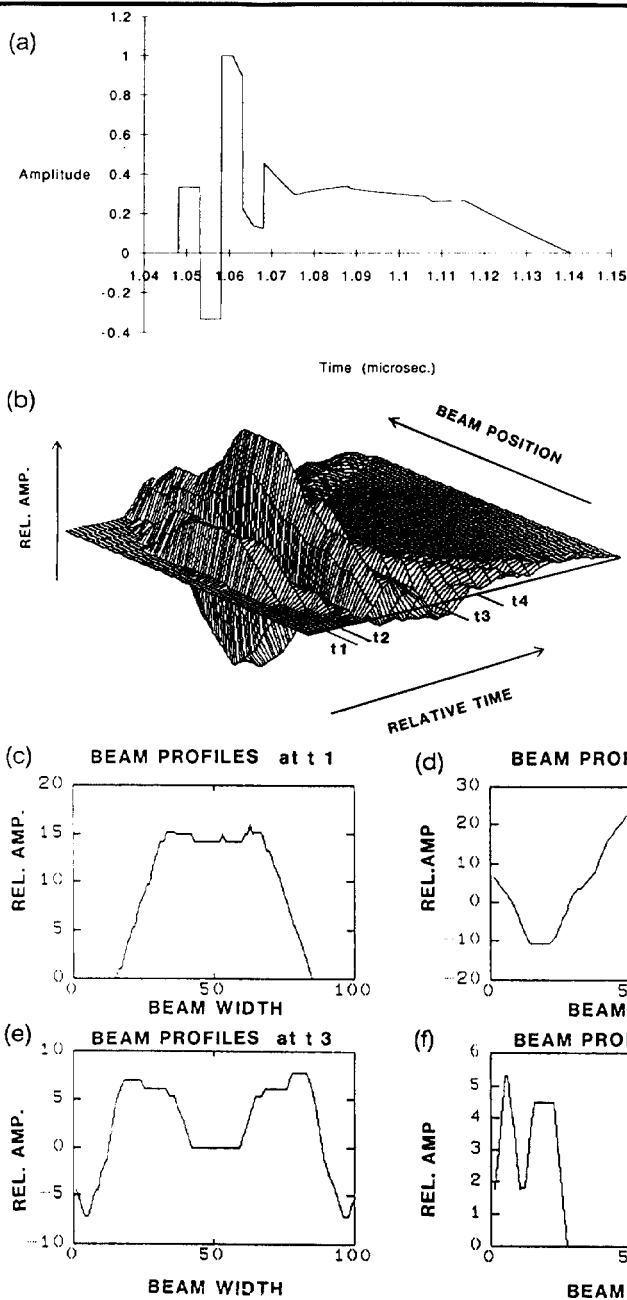


Figure 5. Diffraction of a 5 tap apodized transducer without slant to single tap
(a). Two-dimensional time domain response
(b). Three-dimensional time domain response
(c) - (f). Transverse beam profiles taken at various times as indicated by t1 - t4

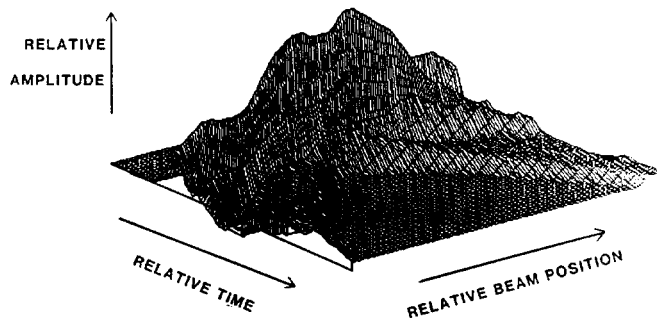


Figure 6. Diffraction pattern of a 5 tap slanted apodized transducer to a single tap

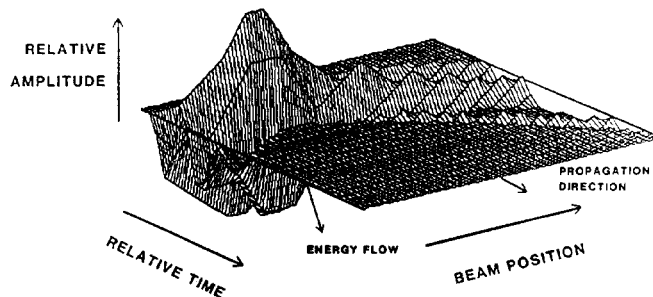


Figure 7. Diffraction pattern of a 3 tap transducer misaligned with pure mode axis of YZ-LiNbO₃ by 5°.

The propagation direction indicates the direction in which the wave was launched. As illustrated by the arrow indicating the direction of energy flow, the entire response moves transversely due to the effects of beam steering, causing the wave to "walk" off to one side. Note that this effect is different than the simple asymmetrical distribution of energy in the field of a slanted apodized transducer, seen in Figure 6. It is also interesting to note that power flow appears as a natural consequence of the interaction of point source responses used in this analysis. The reasonable agreement of the predicted power flow angles with values established using plane wave diffraction theory for various substrates indicates that the first order approximation used to incorporate anisotropy into our model is valid.

EXPERIMENTAL RESULTS

Although the three dimensional plots of diffracted transducer responses in the time domain are interesting and add a great deal of insight into the nature of the diffraction process, they are not generally useful for

comparing theoretical and experimental results. Nor are these calculations used in finding frequency domain device impulse responses, since it is much faster and computationally more efficient to keep track of only the total amount of energy being received by an output transducer at any point in time, rather than keeping track of the amount of energy arriving at each spatial location at each time separately. Thus, equation (5) can be evaluated to find the time domain response for an arbitrary set of transducers, and Fourier transformed to yield the desired frequency response.

Experimental devices consisting of an in-line apodized to unweighted transducer pair were implemented on YZ-LiNbO₃. The Blackmann function was used to weight the apodized transducer. Various aperture combinations and separation distances were evaluated, but due to space limitations, only one case (50λ to 50λ apertures, 100 mil separation) will be presented here. Figure 8 shows the comparison of actual device performance with the ideal response and the theoretical response predicted using the impulse response diffraction model. Agreement between theory and experiment is quite good, despite the fact that the electrode charge distribution and electrical network effects were not taken into account in the analysis. Further work is being done to incorporate such effects. It is particularly interesting to see the extent to which the device sidelobes deviate from the ideal case due to diffraction considerations alone.

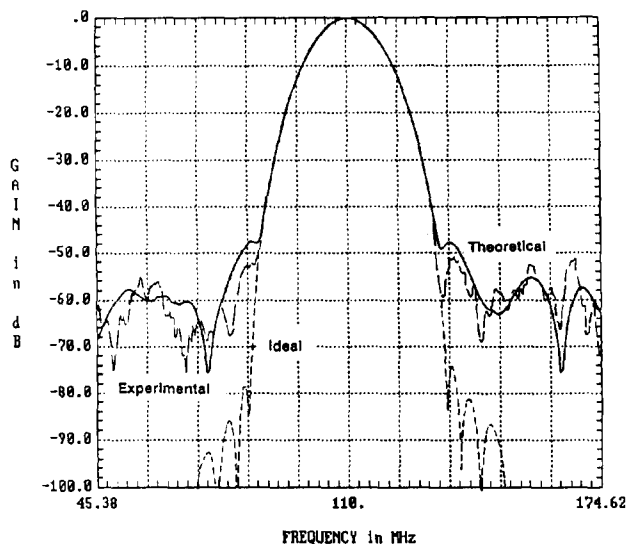


Figure 8. Comparison of actual device performance with the ideal frequency response and that predicted by the impulse response diffraction model.

CONCLUSION

This work has succeeded in generating a two-dimensional diffraction analysis applicable to arbitrary transducer geometries and substrate anisotropy. The time domain approach provides an analysis which is simple, elegant, and fast enough to be practical for use

in design and compensation applications. Since a time domain impulse response is used, the method is inherently broadband.

In addition, the method of integrating point source responses over a source distribution is complete general, and can therefore be applied to analyzing arbitrary device configurations. Some examples of devices where diffraction modeling might be useful include dispersive devices, RACs, and focused IDTs. A great deal of insight into the process of diffraction can be gained from the three-dimensional plots of diffraction patterns. Although the three-dimensional plots shown are not very useful in evaluating bandpass filter behavior, it is possible that they could be useful in applications such as those mentioned above. One example is focused interdigital transducer systems, where three-dimensional plots could be used to predict the location of focal points for a given geometry.

REFERENCES

1. Hines, J. H., "A New Method for Broadband Surface Acoustic Wave Diffraction Analysis." Master's Thesis, University of Central Florida, 1988.
2. Hines, J. H., B. Abbott, M. West, and D. C. Malocha, "A New Approach to Broadband SAW Diffraction Theory." IEEE Ultrasonics Symposium Proceedings, pp. 47-51 (1988).
3. Datta, S. 1978. "Design of SAW Filters with Diffraction Compensation." Master's Thesis, University of Illinois, Urbana, IL.
4. Hagon, P. J. and K. M. Lakin. "The Influence of Near Field Acoustic Diffraction on SAW Device Performance." 1974 IEEE Ultrasonics Symposium Proceedings, p. 341-344.
5. Datta, S. and B. J. Hunsinger. "Element Factor for Periodic Transducers." IEEE Transactions on Sonics and Ultrasonics, Vol. SU-27, No. 1, January 1980 p. 42-44.
6. Datta, S., B. J. Hunsinger, and D. C. Malocha. "A Generalized Model for Periodic Transducers with Arbitrary Voltages." IEEE Transactions on Sonics and Ultrasonics, Vol. SU-26, No. 3, May 1979 p. 235-242.
7. Achenbach, J. D. 1973. *Wave Propagation in Elastic Solids*. New York: North Holland Publishing Company.
8. Andrews, L. C. and B. K. Shivamoggi. 1988. *Integral Transforms for Engineers and Applied Mathematicians*. New York: Macmillan Publishing Company.
9. Anhorn, M., H. E. Engan, and A. Ronnekleiv. 1987. "New SAW Velocity Measurements on Y-cut LinbO₃." *Proceedings 1987 IEEE Ultrasonics Symposium*: 279-283.
10. Baker, B. B. and E. T. Copson. 1969. *The Mathematical Theory of Huygen's Principle*. London: Oxford University Press.
11. Farnell, G. W. 1970. "Properties of Elastic Surface Waves." *Physical Acoustics VI*. Edited by W. P. Mason and R. N. Thurston. New York: Academic Press.
12. Ingebrigtsen, K. A. 1969. "Surface Waves in Piezoelectrics." *Journal of Applied Physics* 40(7) (June): 2681-2686.
13. Lighthill, M. J. 1960. "Studies on Magneto-Hydrodynamic Waves and Other Anisotropic Wave Motions." *Phil. Trans. R. Soc. A* 252 (March): 398-430.
14. Morgan, D. P. 1985. *Surface-Wave Devices for Signal Processing*. New York: Elsevier.
15. Ogg, N. R. 1971. "A Huygen's Principle for Anisotropic Media." *Journal of Physical Acoustics, A: General Phys.* 4: 382-388.

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