

# Frequency Domain Modeling of SAW Devices

W. C. Wilson\*, G. M. Atkinson\*\*

\*NASA Langley Research Center, Hampton, VA, USA, w.c.wilson@larc.nasa.gov

\*\*Virginia Commonwealth University, Richmond, VA, USA, gmatkins@vcu.edu

## ABSTRACT

New SAW sensors for integrated vehicle health monitoring of aerospace vehicles are being investigated. SAW technology is low cost, rugged, lightweight, and extremely low power. However, the lack of design tools for MEMS devices in general, and for Surface Acoustic Wave (SAW) devices specifically, has led to the development of tools that will enable integrated design, modeling, simulation, analysis and automatic layout generation of SAW devices. A frequency domain model has been created. The model is mainly first order, but it includes second order effects from triple transit echoes. This paper presents the model and results from the model for a SAW delay line device.

**Keywords:** Modeling, simulation, surface acoustic waves microelectromechanical systems, MEMS.

## 1 INTRODUCTION

The lack of integrated design tools for Surface Acoustic Wave (SAW) sensors has led to the development of models for these devices. Frequency domain models have been developed using the time domain analysis within VHDL [1]. However, lack of support for transcendentals within the Differential Algebraic Equation (DAE) framework prevented frequency domain analysis. Although frequency domain analysis exists in the language it is not sufficient for general frequency modeling [2]. A similar issue exists in all analog extended Hardware Description Languages (HDLs) that use DAEs at this time. Although in the future, SystemC-AMS may incorporate non-linear solvers [3].

Therefore, to aid in the design and analysis of SAW devices, a SAW delay line model has been created. Because Simulink® provides a graphical interface for the development of dynamic multi-domain (electrical, mechanical and piezoelectric) simulations, it was used for this effort. This modeling environment does not exhibit any of the issues found in HDLs, thus allowing both time and frequency domain analysis. The model calculates the radiation conductance, the acoustic susceptance, and the frequency response for the system. The model includes optimization for the aperture height. The effects of triple transit echoes have been added to the model. The model outputs plots for analysis and a text file of parameters that are used for automatic layout generation. The model allows quick design and analysis of SAW delay line devices, followed by automatic layout generation and fabrication.

## 2 IMPULSE RESPONSE MODEL

The Impulse Response method [4] was used to model the SAW device. This method is valid only for transducers where at least one of the two Inter-Digitated Transducers (IDTs) has a constant aperture or finger overlap [5]. This modeling technique does not take into account second order effects such as reflections or triple transit echoes, but it does model both the mechanical and electrical behavior of a SAW device and therefore it is sufficient for use as a first order model. The model calculates the frequency response, the loss of the system, the admittance, and the electrical parameters for circuit simulators. This model assumes a constant metallization ratio of 0.5 (equal spacing and finger widths). A simple circuit model (Figure 1) can be used to convey the basic elements of the Impulse Response Model. The figure shows the source voltage and both the source and load impedances which are not part of the model. In the circuit model  $C_T$  is the total capacitance,  $B_a(f)$  is the acoustic susceptance, and  $G_a(f)$  is the radiation conductance.

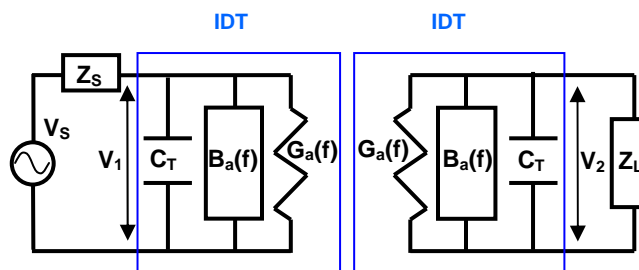


Figure 1. Circuit model used in the Impulse Response Modeling.  $C_T$  is the total capacitance,  $B_a(f)$  is the acoustic susceptance, and  $G_a(f)$  is the radiation conductance.

From the Impulse Response model one can calculate the wavelength ( $\lambda$ ), and the number of finger pairs ( $N_p$ ) using the following equations:

$$\lambda = \frac{v}{f_0} \quad (1)$$

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

where  $v$  is the acoustic velocity in the media,  $f_0$  is the center

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or synchronous frequency, and NBW is the Null BandWidth or fractional frequency.

## 2.1 Radiation Conductance

To begin the discussion on the Impulse Response model, first the variable X is defined as [4]:

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

where f is the frequency. The real part of the input admittance is called the radiation conductance. The radiation conductance is shaped by the sinc function and is found by [4]:

$$G_a(f) = 8k^2 C_s H_a f_0 N_p^2 \left| \frac{\sin(X)}{X} \right|^2. \quad (4)$$

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

## 2.2 Acoustic Susceptance

The second element of the model is the imaginary part of the input admittance which is called the acoustic susceptance. The acoustic susceptance is the acoustic wave modeled as an electrical parameter. The acoustic susceptance is found by taking the Hilbert transform of the radiation conductance and is given by [4]:

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

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

## 2.3 Admittance and Impedance

The total admittance is found by combining the radiation conductance, the acoustic susceptance and the total capacitance [6]. The total admittance is given by

$$Y = G_a + j(2\pi f C_T + B_a). \quad (6)$$

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

$$C_T = C_s H_a N_p. \quad (7)$$

Inverting (6) yields the impedance of the system [4]:

$$Z(f) = \frac{1}{(G_a + j(2\pi f C_T + B_a(f)))}. \quad (8)$$

## 2.4 Frequency Response

For SAW devices the frequency response or transfer response is calculated using [4]:

$$H(f) = 20 \log \left( 4k^2 C_s f_0 N_p^2 \left( \frac{\sin(X)}{X} \right)^2 e^{-j \left( \frac{N_p + D}{f_0} \right)} \right) \quad (9)$$

where D is the delay between IDTs in wavelengths.

## 2.5 Aperture Optimization

An optimal design must match the IDT resistance (real impedance) to the source resistance. The device aperture ( $H_a$ ) is adjusted so that the IDT design achieves the correct resistance. The following equation is used to optimize the aperture in terms of the source resistance ( $R_{in}$ ):

$$H_a = \frac{1}{R_{in}} \left( \frac{1}{2f_0 C_s N_p} \right) \frac{(4k^2 N_p)}{(4k^2 N_p)^2 + \pi^2}. \quad (11)$$

## 2.6 Second Order Effects

The model has been extended to include the second order effect from triple transit echoes. These occur when a small amount of signal travels from the receiver to the transmitter and then back to the receiver again. The frequency of the signal is  $\frac{1}{2}f_0$  and the amplitude is  $\frac{1}{64}$  of the power of the original [7]. The signal is large enough to cause discernable ripples in the frequency response.

## 3 IMPLEMENTATION

The SAW model developed is modular and hierarchical as can be seen in the Impulse Response block (Figure 2).

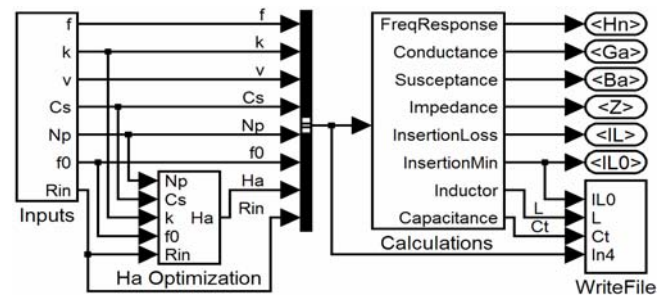


Figure 2. Impulse Response Block.

The input parameters and material constants are contained in the Inputs block. The frequency variable is generated in the Inputs block as well. The Aperture optimization is calculated using equation (11) in the  $H_a$  Optimizer block. The values for all of the variables are calculated in the Calculations block. Within the Calculations block (Figure 3) functions and sub-blocks are necessary for the implementation of equations given earlier. The Calculation block also determines the minimum insertion loss, the size of the matching inductor and the total capacitance of the IDT. The parameters necessary for fabrication of the device are all written to a text file in the WriteFile block.

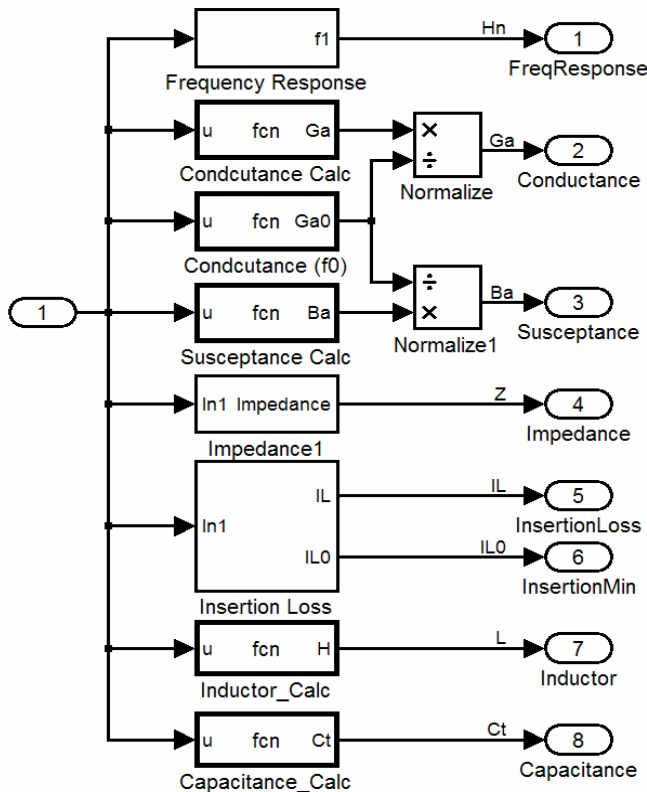


Figure 3. Calculations Block.

#### 4 SAW DELAY LINE PROTOTYPE

To demonstrate the model a simple SAW delay line that consists of two identical IDTs was chosen. The synchronous frequency is 78.95 MHz. The null bandwidth (NBW) is 1.5 MHz. The delay length between the two IDTs is 5 wavelengths. Both the source and load resistances are assumed to be  $50 \Omega$ . The substrate is ST cut Quartz. The selection of a substrate material determines the capacitance  $C_s = 0.503385$  pf/cm, the piezoelectric coefficient  $k = 0.04$ , and the acoustic velocity  $v = 3158$  m/s for the SAW device [8]. Using these values in equation (13) yields an optimized aperture of  $1560.0 \mu\text{m}$ . For this example the wavelength ( $\lambda$ ) is  $40 \mu\text{m}$ , and the optimal number of finger pairs is 105.

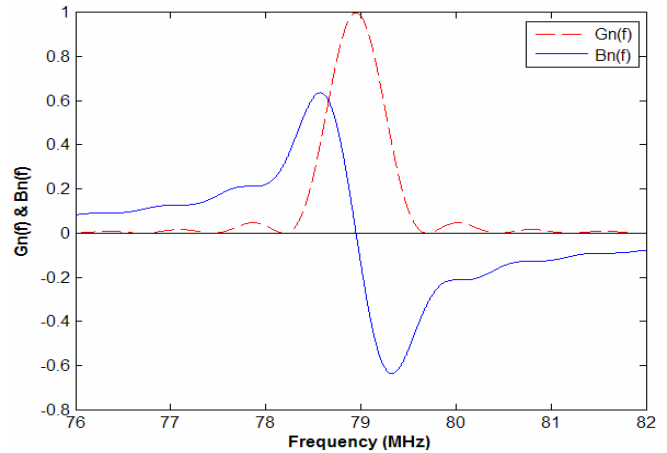


Figure 4. Radiation Conductance ( $G_n(f)$ ) and Acoustic Susceptance ( $B_n(f)$ ).

Figure 4 is a plot of both the normalized radiation conductance and normalized acoustic susceptance using the values for the prototype device. This plot is used for analysis of the device design before the device layout is performed.

After the modeling tools are used to develop a design concept, the parameters from the model are written into a file that is used by the Layout Editor tools. Parameterizable library components were developed previously that enable automatic layout generation of SAW devices [9] using the Layout Editor tools. This process was used to create a layout of the device. The prototype device was then fabricated from the layout (Figure 5).

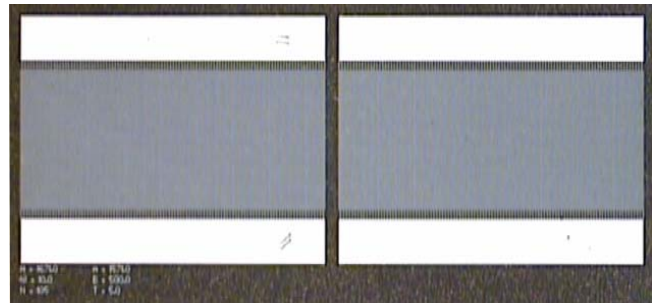


Figure 5. Prototype device with 105 aluminum finger pairs per IDT, on a ST-cut Quartz substrate.

The frequency response of the system is calculated using equation (11) and is plotted in (Figure 6) along with the measured frequency response from a fabricated device. This figure shows that the minimum insertion loss for the system naturally occurs at the synchronous frequency. A comparison between the calculated frequency response and the measured frequency response demonstrates that the first order model captures the main characteristics of the central lobe and the first side lobes. The addition of the triple transit echo signal to the model makes the response more accurate and can be seen as the small ripple on the top of each lobe.

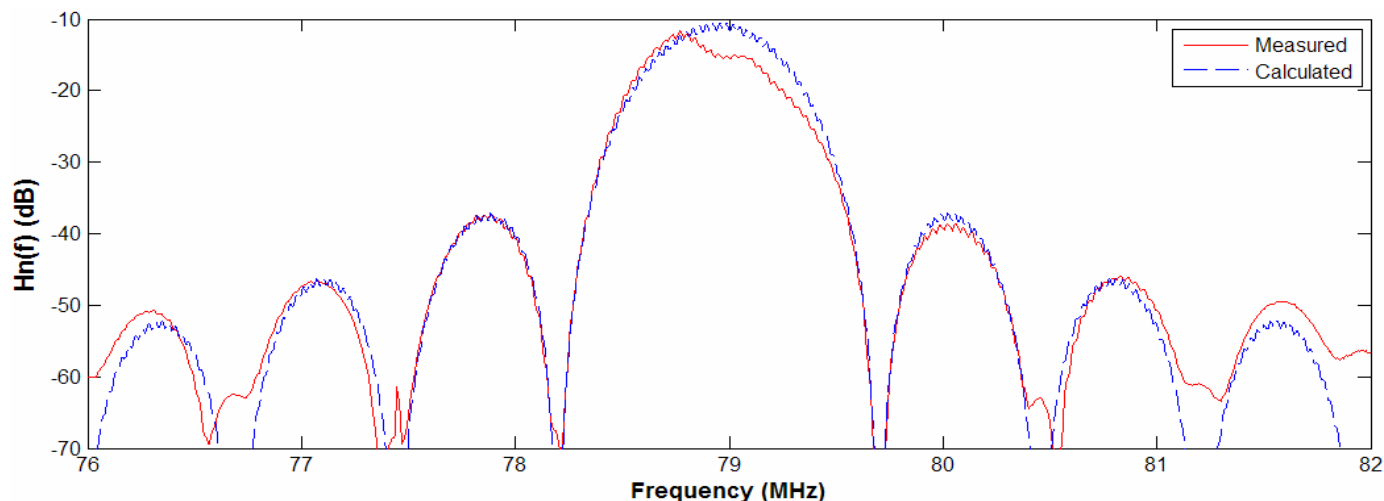


Figure 6. Frequency Response of the SAW Delay line on Quartz ST cut substrate.

Noise in the measured results has distorted the second and subsequent side lobes. The ripples and peaks on the top of the main lobe are caused by second order effects such as internal reflections and triple transit echoes. Extensions of this work will include the addition of more second order effects into the frequency response models.

## 5 CONCLUSIONS

The frequency domain model of a SAW delay line has been created. Simulink<sup>®</sup> was used because it provides a graphical interface for the development of dynamic multi-domain simulations and does not exhibit any of the issues found in HDLs, thus allowing both time and frequency domain analysis. The model is reasonably accurate for the main lobe and first side lobes of the frequency response. The model is based upon the Impulse Response method which is a first order model only. However, the model has been extended to include one second order effect, that of triple transit echo signals. The model implemented calculates the frequency response, insertion loss, radiation conductance, acoustic susceptance, impedance, total capacitance, and triple transit echo signal.

The model was used to analyze a 78.95 MHz device and to determine the optimal parameters so that a prototype device could be developed. The device was fabricated and the measured results were compared to the model, thus verifying the models accuracy.

The frequency domain model of SAW devices that has been developed will allow for quick design, analysis and fabrication of prototype SAW devices for aerospace applications such as integrated vehicle health monitoring.

In the future, frequency domain models that cover more second order effects will be developed. These models should allow more accurate modeling of internal and external reflections.

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