

Mixed Modeling of a SAW Delay Line using VHDL

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ABSTRACT

To aid in the development of SAW sensors for aerospace applications we have created a model of a SAW Delay line using VHDL. The model implements the Impulse Response method to calculate the frequency response, impedance, and insertion loss. The model includes optimization for the number of finger pairs in the IDTs and for the aperture height. This paper presents the model and the results from the model for a SAW delay line design.

1. INTRODUCTION

Integrated structural health monitoring of aerospace vehicles require rugged sensors that are reduced in volume, mass, and power, and are capable of measuring temperature, pressure, strain, vibration, ultrasonic waves and chemicals species [1]. We would like to have large numbers of sensors distributed across the vehicle. Passive Surface Acoustic Wave (SAW) devices have proven their ability to sense a large number of phenomena such as: temperature, pressure, strain, chemical species, mass loading, acceleration, and shear stress. SAW technology is low cost, rugged, lightweight, extremely low power and operates over a wide range of temperatures. For these reasons we are investigating the use of new SAW sensors for aerospace applications.

The SAW Delay line structure is composed of two sets of InterDigitated (IDT) fingers on a piezoelectric substrate (Figure 1). This configuration can be used as a delay line or as bandpass filter. Sensors can be developed by adding a sensing medium between the two IDTs. When one of the IDTs is excited by a sinusoidal electrical signal the piezoelectric effect generates mechanical waves. The waves that travel to the other IDT generate an electrical signal through the inverse piezoelectric effect. SAW devices can be designed so that there is very little dispersion, attenuation, or diffraction [2].

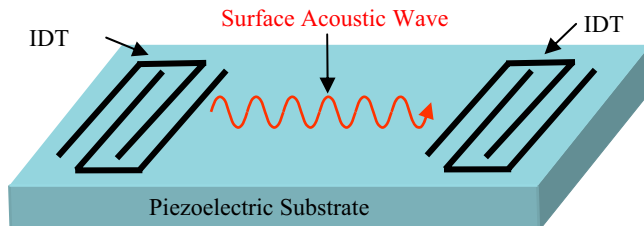


Figure 1. Basic SAW Delay line Device.

2. BACKGROUND

The hardware description language VHDL was chosen to implement the Impulse Response model. It was chosen because our legacy code for digital systems was modeled in VHDL. Another reason for choosing VHDL was that we hope to migrate to VHDL-AMS in the future. VHDL-AMS can implement differential equations in multiple energy domains such as electronic (digital and analog), mechanical, thermal, fluidic, etc [3]. For an introduction to VHDL-AMS see [4] or [5]. VHDL-AMS would enable the possibility of simulating complete systems including analog and digital electronics, SAW devices, sensing mediums, and mechanical devices such as Microelectromechanical Systems (MEMS).

VHDL-AMS models of SAW devices have been previously created by others [6 and 7]; however, the Impulse Response model using VHDL or VHDL-AMS was not implemented. One possible reason may be the lack of support for frequency domain analysis. Although frequency domain analysis exists in the language it is rudimentary and is not considered sufficient by some for general frequency domain modeling [3]. Our approach performs frequency domain calculations within the time domain analysis in VHDL, but in the future we plan to use VHDL-AMS and create models that can be integrated with other components. We employed a time variable and wait statements to calculate the frequency response. The figures in section 4 are plotted using this technique. Wait statements are used within the architecture to link the frequency variable (f) to the time scale of the simulations. In this manner the frequency response of the SAW delay line can be calculated. The results can be plotted using the standard plot features of the simulator in the time domain using time as the dependent variable. To achieve a frequency plot, the automatic units for time must be replaced with units of frequency in the plot axis labels. We simulated the code from Listing 1 to create the frequency response plot of Figure 3. We used seconds to represent each MHz. We could have used any time scale because the Impulse Response model we implemented is calculated concurrently with any other modeling we chose to add. Note that the current Impulse Response model implementation would require that frequency be used as an input if it is combined with other device models. Also, the use of wait statements is only required for plotting and is not necessary for modeling the behavior of a SAW device.

3. MODEL IMPLEMENTATION

The Impulse Response method [8] was used to model the SAW device. This is a first order model that does not take into account any second order effects such as reflections. This technique does model the piezoelectric, mechanical and electrical behaviors of the SAW device. This model is only valid for transducers where the IDTs are un-weighted. The model assumes that the finger overlap or aperture is constant and that the metallization ratio between the fingers and spaces is 0.5. This model calculates the frequency response, conductance, impedance, admittance and other electrical parameters. The Impulse Response method uses the Mason equivalent circuit shown in Figure 2. In the circuit $G_a(f)$ is the radiation conductance, $B_a(f)$ is the acoustic susceptance, and C_T is the total capacitance.

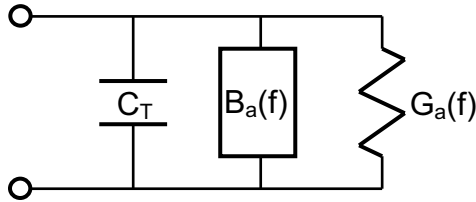


Figure 2. Mason equivalent circuit model.

3.1 Frequency Response

The frequency response of a SAW system is the first item to be implemented using the Impulse Response method. For a single IDT, the frequency response is shaped by the sinc function, and is calculated by the following equation [8]:

$$|H(f)| = 2k\sqrt{C_s f_0} N_p \frac{\sin(X)}{X} e^{-\frac{j2\pi f N_p}{2f_0}} \quad (1)$$

where f is the frequency, f_0 is the center or synchronous frequency, N_p is the number of finger pairs in the IDT, k is the piezoelectric coupling coefficient, C_s is the capacitance for a finger pair per unit length. The variable X [8] is used to simplify the equation and is defined as

$$X = N_p \pi \frac{(f - f_0)}{f_0} \quad (2)$$

When two IDTs are used as in the case of a SAW delay line the frequency response for the system is found by combining the frequency response for each IDT [8]:

$$H_T(f) \cong H_1(f) \cdot H_2(f) \quad (3)$$

Listing 1 contains the three functions that implement equations (1), (2), and (3) in VHDL. Function “H” implements equation (1), function “x” implements equation (2), and function “FR1” implements a normalized version

of equation (3). Note that function “FR1” implements a frequency response calculation in the time domain by the use of the variable f and wait statements. These functions together calculate the frequency response of an IDT. Also, note that the function “x” returns 1×10^{-12} to avoid overflow errors in our simulator that would occur when $f = f_0$.

Listing 1. SAW delay line frequency response.

```

Library IEEE;
Use IEEE.Math_Real.all;
Use IEEE.Fundamental_Constants.all;

Entity Freq_Response is
  Port (Signal f0, Np, Cs, k : in real;
        Signal HT : out real);
End Freq_Response;

Architecture Freq_Domain of Freq_Response is
  Signal f, fmax, fmin: real := 1.0;

  Function x (f, f0, Np : real) return real is
    Variable result : real := 0.0;
    Begin
      If f = f0 then
        result := 1.0e-12;
      Else
        result := math_pi*Np*((f-f0)/f0);
      End If;
      Return result;
    End Function x;

  Function H (f, f0, Np, Cs, k : real) return real is
    Variable result : real;
    Begin
      result := 2.0*k*sqrt(Cs*f0)*Np*((sin(x(f,f0,Np)))/(x(f,f0,Np)))
        math_e**(-math_cbase_j*math_pi*f*Np/(2*f0));
    Return result;
  End Function H;

Begin
  FR1: process is
    Begin
      Wait for 1fs;
      f <= f0*0.5;
      fmax <= f0*1.5;
      fmin <= f0*0.5;
      HT <= 20.0*log(abs((H(f,f0,Np,Cs,k)**2.0) /
        H(f0,f0,Np,Cs,k)**2.0));
      Wait for f0*0.5*1.0e-6;
      While f <= fmax loop
        HT <= 20.0*log10(abs((H(f,f0,Np,Cs,k)**2.0) /
          H(f0,f0,Np,Cs,k)**2.0));
        Wait for f0*1.0e-10;
        f <= f+(f0*1.0e-4);
      End Loop;
    End Process FR1;
End Architecture Freq_Domain;

```

3.2 Radiation Conductance

The real part of the input admittance is called the radiation conductance. The radiation conductance is also shaped by the sinc function [8] and is found by:

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

where W_a is the aperture or overlap height of the fingers. The radiation conductance is implemented as a function in VHDL. Listing 2 is the code which calculates the radiation conductance using equation (4).

Listing 2. Radiation Conductance function.

```
function g (f,f0,Np,Cs,k,Wa : real) return real is
  variable result : real;
  begin
    result := 8.0*(k**2.0)*Cs*f0*(Np**2.0)*Wa*
              (abs((sin(x(f,f0,Np)))/(x(f,f0,Np))))**2;
  return result;
end function g;
```

3.3 Acoustic Susceptance

The third element of the model is the imaginary part of the input admittance which is also called the acoustic susceptance. The acoustic susceptance is the acoustic wave phenomena modeled as an electrical parameter. The acoustic susceptance is found by taking the Hilbert transform of the radiation conductance [8] and is given by:

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

The acoustic susceptance is also implemented as a function in VHDL. Listing 3 is the code which calculates the acoustic susceptance using equation (5).

Listing 3. Acoustic Susceptance function.

```
function b (f,f0,Np,Cs,k,Wa : real) return real is
  variable result : real;
  begin
    result := g(f0,f0,Np,Cs,k,Wa)*(sin(2.0*x(f,f0,Np))-
              2.0*(x(f,f0,Np)))/(2.0*(x(f,f0,Np))**2.0);
  return result;
end function b;
```

3.4 Admittance and Impedance

The total admittance [9] is found by combining the radiation conductance, the acoustic susceptance and the total capacitance. 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 (W_a) times the number of fingers pairs (N_p).

$$C_T = N_p C_s W_a \quad (7)$$

Equation (7) is easily implemented as a single line of code in VHDL (Listing 4).

Listing 4. Total static capacitance.

```
Ct <= Np*Wa*Cs;
```

If equation (6) is inverted it will yield the impedance of the system [9]:

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

To simplify the code the impedance was implemented in two functions, one for the real (Z_Real) and one for the imaginary (Z_Im) part. Listing 5 is the VHDL code which calculates both the real and imaginary parts of the impedance using equation (8).

Listing 5. Impedance functions.

```
function Z_Im (f,f0,Np,Cs,k,Wa : real) return real is
  variable result : real;
  begin
    result := (2.0*math_pi**Cs*Np*Wa+
              b(f,f0,Np,Cs,k,Wa))/((g(f,f0,Np,Cs,k,Wa)**2.0) +
              (2.0*math_pi**Cs*Np*Wa+b(f,f0,Np,Cs,k,Wa))**2.0);
  return result;
end function Z_Im;

function Z_Real (f,f0,Np,Cs,k,Wa : real) return real is
  variable result : real;
  begin
    result := g(f,f0,Np,Cs,k,Wa)/((g(f,f0,Np,Cs,k,Wa)**2.0)
              + (2.0*math_pi**Cs*Np*Wa+b(f,f0,Np,Cs,k,Wa))**2.0);
  return result;
end function Z_Real;
```

3.5 Insertion Loss

It is a very useful to calculate the insertion loss of electrical systems. For SAW devices the insertion loss is a function of frequency, and is calculated using conductance, susceptance, and the load resistance R_g [10]:

$$IL(f) = -10 \log \left[\frac{2G_a(f)R_g}{(1+G_a(f)R_g)^2 + [R_g(2\pi f C_T + B_a(f))]^2} \right]. \quad (9)$$

The minimum insertion loss occurs when $f = f_0$ the synchronous frequency. Listing 6 is the VHDL function code which calculates the insertion loss using equation (9).

Listing 6. Insertion Loss.

```

function Insertion_Loss (f,f0,Np,Cs,k,Wa,Ct,Rg : real) return real is
  variable result : real;
  begin
    result := -10.0*log10(2.0*g(f,f0,Np,Cs,k,Wa)*Rg) /
      (((1.0+g(f,f0,Np,Cs,k,Wa)*Rg)**2.0) +
      ((Rg*(2.0*math_pi*f*Ct+b(f,f0,Np,Cs,k,Wa))**2.0));
    return result;
  end function Insertion_Loss;

```

3.6 Aperture Optimization

An optimal design must match the IDT resistance (real impedance) to the input resistance. The device aperture (W_a) is often adjusted so that the IDT design achieves the correct IDT resistance. The following equation was used to optimize the input resistance in terms of the aperture:

$$W_a = \frac{1}{R_{in}} \left(\frac{1}{2f_0 C_s N_p} \right) \frac{(4k^2 N_p)}{(4k^2 N_p)^2 + \pi^2} \quad (10)$$

where R_{in} is the input resistance. The aperture is implemented as a function in VHDL. Listing 7 is the code which calculates the optimal aperture height using equation (10).

Listing 7. Aperture function.

```

function Wa_Optimized (f0,Np,Cs,k : real) return real is
  variable Wa_opt1,Wa_opt2 : real := 1.0;
  begin
    Wa_opt2 := (1.0/(2.0*Rin*Np*f0*Cs))* (4.0*Np*k*k)/(((4.0*Np*k*k)**2)
      +(math_pi**2));
    return Wa_opt2;
  end function Wa_Optimized;

```

4. SAW DELAY LINE EXAMPLE

To demonstrate the model we will use a simple SAW delay line that consists of two identical IDTs. The synchronous frequency is 225.571 MHz. The substrate is ST cut Quartz. The Null BandWidth (NBW) is 2.0 MHz. The delay length between the two IDTs is 7 wavelengths. Both the load and input resistance are assumed to be 50Ω . 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 [11]. Using these values in equation (10) yields an optimized aperture of $471.0 \mu\text{m}$. From the Impulse Response model we can calculate the wavelength (λ), and the number of finger pairs (N_p) using the following equations:

$$\lambda = \frac{v}{f_0}. \quad (11)$$

$$N_p = \text{round} \left(\frac{2}{NBW} f_0 \right). \quad (12)$$

For this example the wavelength is $14 \mu\text{m}$, and the optimal number of finger pairs is 226. See Figure 7 for a list of the parameters calculated in this example. Figure 3 is a plot of the frequency response. Note that the values are normalized by using the log equation:

$$IL(f) = 20 \log \left(\frac{H_1(f)H_2(f)}{H_1(f_0)H_2(f_0)} \right). \quad (13)$$

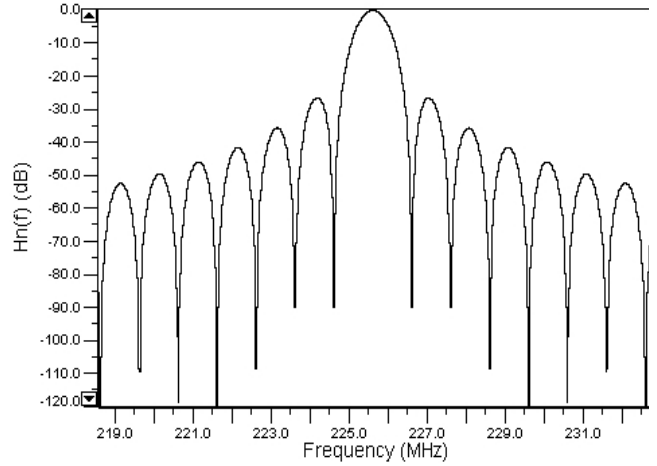


Figure 3. Frequency response of the SAW delay line.

Next we used the Impulse Response model to calculate the radiation conductance using equation (4). The results are plotted in Figure 4. Again the results have been normalized by using the following equation:

$$G_n(f) = \frac{G_a(f)}{G_a(f_0)}. \quad (14)$$

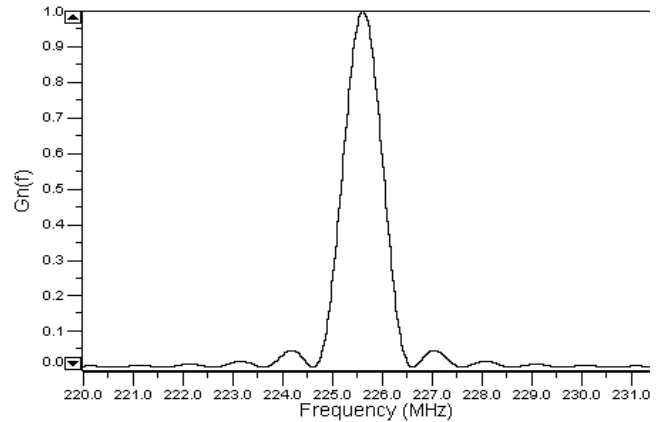


Figure 4. Normalized Radiation conductance of the SAW delay line.

We used the Impulse Response model to calculate the acoustic susceptance using equation (5). The results are plotted in Figure 5. The results have been normalized by using the following equation:

$$B_n(f) = \frac{B_a(f)}{G_a(f_0)} \quad (15)$$

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

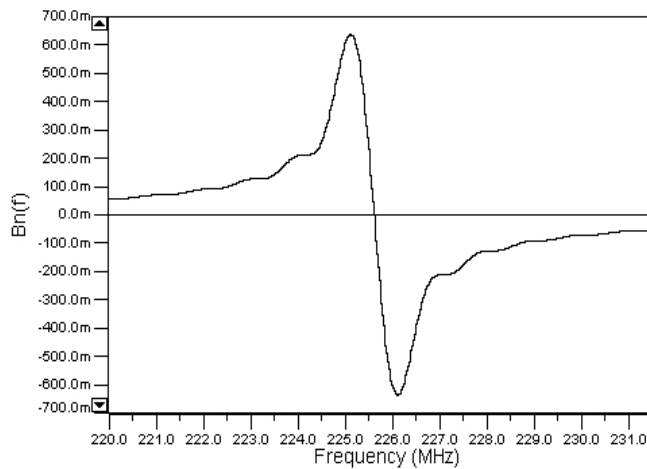


Figure 5. Acoustic susceptance of the SAW delay line.

We calculated the insertion loss of the system using equation (9) and plotted it in Figure 6. Figure 6 is the insertion loss if we zoom in about the center or synchronous frequency. This figure shows us the minimum insertion loss for the system, which naturally occurs at the synchronous frequency.

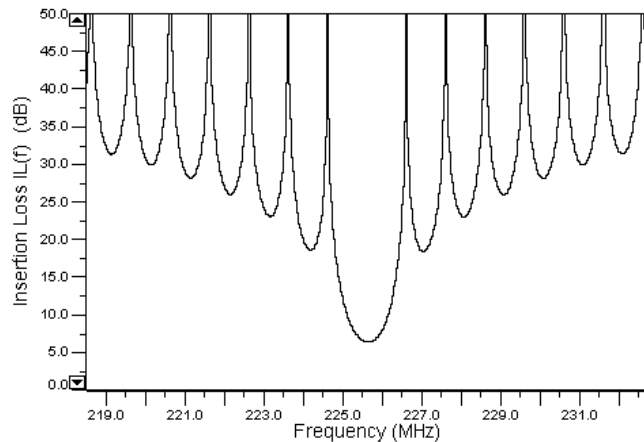


Figure 6. Insertion loss of the SAW delay line.

5. ANALYSIS AND LAYOUT

The plots presented in the previous example are available for use in the analysis of the design. Also, several parameters are calculated and written into a summary report to aid in analyzing the design (Figure 7). As shown in Figure 7 the width of the fingers is 3.5 μm , the number of fingers is 226, and aperture height is 471.0 μm . The first eight parameters are required for the automatic layout generation. The aperture height is the second parameter that is optimize in our code. It is found by a search algorithm that adjusts the aperture value until the IDT impedance matches 50 Ω [12]. Since most test equipment has an input and output impedance of 50 Ω that is the value that was chosen for our example and designs. Human intervention is necessary during the analysis phase to check over the plots, but in the future we hope to incorporate automatic checking of the parameters, and automatic optimization tools that would further reduce the amount of human interaction that is needed.

<<< SAW Delay line Summary Report >>>

Finger Height	= 5.710000e-004
Aperture Height	= 4.710000e-004
Finger Width/Spacing	= 3.500007e-006
Number of Finger Pairs	= 2.260000e+002
Bus Bar Height	= 2.000000e-004
Delay Length (in wavelengths)	= 7.000000e+000
X Offset	= 0.000000e+000
Y Offset	= 0.000000e+000

Wavelength	= 1.400003e-005
Synchronous Frequency	= 2.255710e+008
Acoustic Velocity	= 3.158000e+003
Series Matching Inductor	= 9.290608e-008
Minimum Insertion Loss (@f0)	= 6.393332e+000
Total Capacitance (single IDT)	= 5.358332e+012

Figure 7. Summary report the SAW delay line parameters.

The Impulse Response model and analysis tools are used to develop a design concept. Then the automatic layout generator can be used as an interface to Layout Editor tools to create a layout of the device.

A number of assumptions must be made before the parameters that have been calculated can be used to realize a layout. The assumed values are input as constants in the VHDL code. These values are the height of the bus bars on the top and bottom of the fingers, the length of the fingers that are not overlapped (not part of the aperture), and the X and Y offset values. For the example given earlier we used a bus bar height of 200 μm , and un-overlapped finger length of 100 μm , and for simplicity an offset of (0.0, 0.0). Using these values and those of the example SAW delay line in Section IV, we performed automatic layout generator to create the layout in Figure 8.

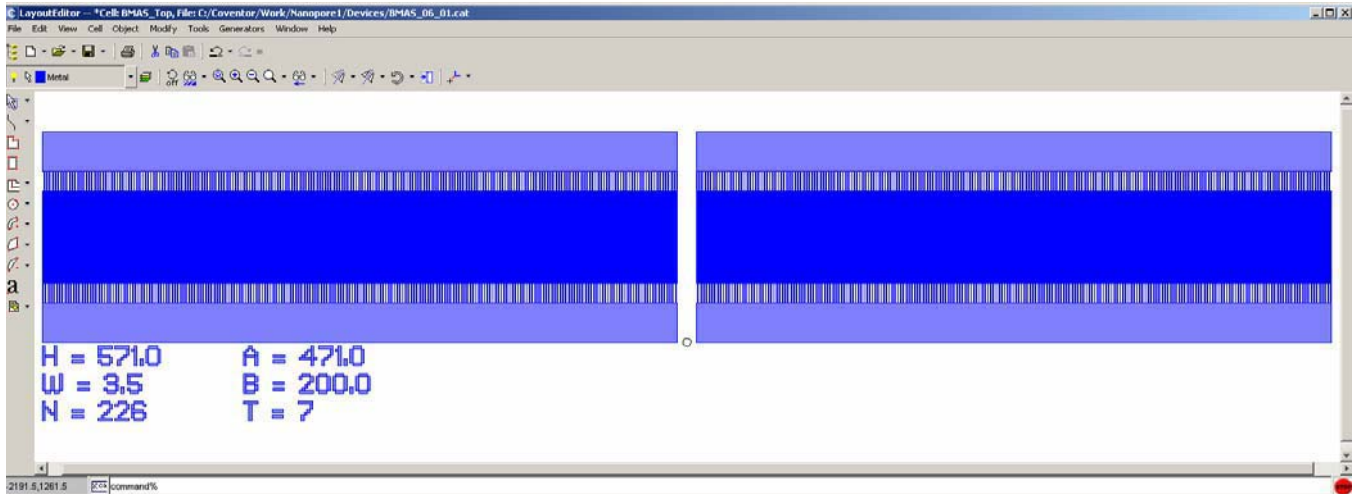


Figure 8. Automatically generated layout of the SAW delay line from the example.

6. CONCLUSION

We have presented our implementation of the Impulse Response Model for a SAW delay line device using VHDL. We have found that VHDL can be used for frequency domain analysis within the time domain by using wait statements to link the frequency variable to the time variable for plotting. We have presented our VHDL model along with the results from an example SAW delay line. We perform some rudimentary optimization and generate reports with all of the salient design parameters, and automatically generated a layout of our design. Future work will include second order effects such as reflections, triple transit echoes, and temperature effects. We would like to implement a full wireless system including the antenna, SAW device, and sensor medium in VHDL-AMS. We will also continue to look for more efficient ways of incorporating frequency domain modeling of SAW devices in the VHDL-AMS language.

7. ACKNOWLEDGMENTS

We would like to thank Dr. Donald Malocha of the University of Central Florida for his help which saved us a great deal of time and effort.

8. REFERENCES

- [1] William H. Prosser, "Development of Structural Health Management Technology for Aerospace Vehicles", NASA LaRC, JANNAF 39th CS/27th APS/21st PSHS/3rd MSS Joint Subcom. Meeting, Dec. 1-5, 2003; 20031216.
- [2] D. P. Morgan, "Surface-wave devices for signal processing," Studies in Electrical and Electronics Engineering 19, New York, Elsevier, 1985, Chap. 1.
- [3] Wilson, P.R., Ross, J.N., Brown, A.D.; Rushton, A., "Multiple domain behavioral modeling using VHDL-AMS", Circuits and Systems, 2004. ISCAS '04. Proceedings of the 2004 International Symposium on, Vol. 5, May 23-26 2004, pp. V-644 - V-647.
- [4] Christen, E.; Bakalar, K., "VHDL-AMS-a Hardware Description Language for Analog and Mixed-Signal Applications", Circuits and Systems II: Analog and Digital Signal Processing, IEEE Transactions on, Volume 46, Issue 10, Oct. 1999, pp. 1263 - 1272.
- [5] P. J. Ashenden, G. Peterson, and D. Teegarden, *The System Designer's Guide to VHDL-AMS*. Amsterdam: Morgan Kaufmann Publishers, 2nd ed., 2003.
- [6] Qiuyun Fu; Fischer, W.-J.; Stab, H., "Simulate surface acoustic wave devices using VHDL-AMS", Electronics Technology: Integrated Management of Electronic Materials Production, 26th International Spring Seminar on, May 8-11, 2003, pp. 95 - 99
- [7] Qiuyun Fu; Fischer, W.-J.; Stab, H., "Simulation of wirelessly passive SAW ID-tags/sensors using VHDL-AMS", Ultrasonics Symposium, IEEE, Vol. 2, Aug. 23-27 2004, pp. 1541 - 1544
- [8] Hartmann, C.S., Jr.; Bell, D.T.; Rosenfeld, R.C.; "Impulse Model Design of Acoustic Surface-Wave Filters", Microwave Theory and Techniques, IEEE Transactions on, Volume 21, Issue 4, Apr 1973, pp. 162 - 175.
- [9] K. M. Lakin, T. Joseph, D. Penunuri, "Planar Surface Acoustic Wave Resonators", Ultrasonics Symposium, Proceedings, IEEE, Volume 1, Milwaukee, Wisconsin, Nov. 11-14, 1974, pp. 263 - 267.
- [10] Supriyo Datta, *Surface-Acoustic Wave Devices*, Prentice Hall, Englewood Cliffs, NJ, 1986.
- [11] Slobodnik, A.J., Jr., "Surface acoustic waves and SAW materials", Proceedings of the IEEE, Volume 64, Issue 5, May 1976, pp. 581 - 595.
- [12] D. P. Morgan, "Surface-wave devices for signal processing", Studies in Electrical and Electronics Engineering 19, New York, Elsevier, 1985, Chap. 7.