Designing with Piezoelectric Devices

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Abstract
This application note illustrates the modeling and simulation of circuits that employ piezoelectric devices. A 4-section bulk-quartz resonator 9 MHz ladder bandpass filter and a SAW resonator 900 MHz oscillator are used to illustrate a few selected techniques for circuits with piezoelectric devices including:

- Synthesis
- Equation defined parameters
- Component influences
- Standard values
- Component tolerances
- Resonator cross coupling
- Oscillator design methodology
- Oscillator loaded Q
- Device current
- Optimization
- Load pulling

Synthesis
Given in Figure 1 below is a screen from the FILTER synthesis module of GENESYS. This module creates L-C filters from user specified requirements. The user selects a general topology and enters specific requirements, in this case a series resonator, shunt-C coupled, 4-section Chebyshev response bandpass from 9.0000 to 9.0008 MHz (800 Hz bandwidth). This topology was chosen because it allows the user to enter a series inductor equal to the motional inductance of a specific bulk-quartz resonator. From these requirements FILTER computes and displays the remaining filter element values.

L-C synthesis is appropriate for piezoelectric circuits when behavior is well modeled by lumped equivalents, as is the case with bulk-quartz resonator filters and SAW oscillators. For circuits incorporating SAW filters, S-parameter data is used to characterize the SAW device.

FILTER automatically generates a schematic for GENESYS. This schematic then belongs to the user and may be modified as desired. Here we replace the series L-C resonators with the internal bulk-quartz resonator model which includes motional inductance, motional capacitance, motional resistance and static capacitance. We enter motional inductance and capacitance equal to the FILTER values and motional resistance and static capacitance of the
bulk-quartz resonators. The modified schematic is given in
the schematic window as shown in Figure 2 below.

Also shown in Figure 2 are the transmission amplitude
and group delay responses on a rectangular graph at the lower
left and the input return loss plotted on a unity radius Smith
chart at the lower right.

**Equation Defined Parameters**
The shunt capacitor values are defined by simply placing a
number in the components dialog box. Selecting “tune” by
a parameter on the component dialog box makes that value
available to tune, optimize, or analyze statistically.

If a number is replaced with a text string, such as Rs, then it
is recognized as a variable that is defined in the Equation
folder. In this way, the motional resistance, the static
capacitance and the motional inductance were defined as
one variable that affect all of the resonators.

All parameter values that were preceded with a "?" are
listed in the tune window displayed in the upper left of
Figure 2. In this case each of the shunt coupling capacitors,
the motional resistance, inductance and static capacitance of
the crystals and the individual motional capacitors were set
as tunable parameters.

**Component Influences**
GENESYS conveniently determines the influence of device
parameters on circuit behavior. The bold traces in Figure 2
depict responses with a motional resistance of 31 ohms.
The lighter dashed responses depict zero motional
resistance. Evaluation of component influences advances
simulation beyond "how does the design work" to "what
parameters are required to satisfy a requirement". For
example, what motional resistance is required to achieve a
maximum mid-band insertion loss of 4 dB? Markers may
be placed on the plots for a digital readout of plot values as
is illustrated in a later figure. Real-time tuning of a
parameter quickly answers these questions.

Similarly, the influence of other parameters such as the
static capacitance is easily evaluated real time by simply
tuning these parameter values.

**Standard Values**
Element values that exactly define a 4-section 0.0432 dB
ripple Chebyshev filter are not standard values. What is the
impact of placing values on the nearest standard values?
This question is easily answered via circuit simulation. In
this case setting the shunt coupling capacitors to 62, 160,
200, 160 and 62 pF, respectively, has little effect.

![Figure 2: Modified filter schematic and s-parameters.](image)
Component Tolerances

In Figure 3 above we define the tolerance of components in the Monte Carlo Set-up dialog box. The lumped capacitors tolerances are defined as ±5%, Rs as ±10%, Co as ±2% and Cm as ±0.002% (±10 ppm in frequency for the resonators).

For a uniform distribution all component values within the specified tolerance range are equally probable. Normal is a bell shaped distribution where nominal values are more likely. A ten-sample sequence approximates normal.

Figure 4 below is a Monte Carlo run of this filter with random values of the components following guidelines established in the set-up dialog box. This analysis is set at 50 samples. While the amplitude and group-delay responses are affected, the greatest impact is on the return loss. Statistical analysis is useful for assessing the impact of component tolerance on circuit responses.

Resonator Cross Coupling

The synthesis program FILTER creates the initial design, but then the design is owned by the user. Any desired modification may be explored. For example, consider a cross coupling inductor from the input to output. Figure 5 below shows the original transmission responses (dashed) and the responses with a 270 uH cross-coupling inductor (bold). Notice a single inductor provides two transmission zeros, one below and one above the passband.
Oscillator Design Methodology
Given in Figure 6 below is the schematic of a 900 MHz SAW resonator oscillator. This oscillator was created using the OSCILLATOR synthesis module of GENESYS 7.

The amplifier-resonator cascade is analyzed open loop and design involves satisfying Barkhousen's criteria. The open-loop gain and phase are displayed in the lower left. Oscillation occurs at the frequency of the phase zero crossing, in this case about 70 KHz below the center frequency of the plot. The oscillator is formed by connecting the output to the input. Oscillations build until device non-linearity reduces the gain margin to 0 dB.

The system is self-terminating and a valid analysis requires a reasonable match. A reference impedance is selected that best approximates the cascade input and output impedance. The match quality impacts only the error of analysis and unless the gain margin is low this error is not critical. Here a design reference impedance of 50 ohms was chosen. This is convenient for bench verification of the cascade design criteria using a conventional network analyzer. For a detailed description of this design methodology including the impact of non-linearity please refer to Oscillator Design and Computer Simulation [1].

Oscillator Loaded Q
The center plot in Figure 6 below gives the loaded Q (approximately 3064) of the open-loop cascade. Loaded Q is critical in oscillator design as it impacts phase noise, long-term stability and load pulling. A significant advantage of cascade resonator-amplifier simulation is a more direct determination of the loaded Q than is obtained with negative-resistance based oscillator design.

Device Current
Also shown in the lower center of Figure 6 is the SAW device current. This was computed using post-processing. Given below is the Equation folder used to compute device current. Pout is the estimated or measured output power at port three. The difference in the voltage gain from port 3 to 5 (E53) and port 3 to 4 (E43) is used to compute the voltage across the SAW resistance and ultimately the SAW current.

Figure 6: Oscillator schematic and response

Figure 7: Equations to calculate SAW current
Optimization

Notice that the phase does not cross zero degrees at the maximum phase slope and the oscillating frequency is lower than desired. Could this be improved and the loaded Q increased? Tuning is effective for adjusting a few parameters but adjustment of many parameters is more effective with optimization. In Figure 8 above all the values preceded by a "?" in the schematic were optimized for zero degrees phase at 900 MHz, reasonable match, at least 5 dB of gain and Q > 4500. Notice the significant improvements while still maintaining adequate gain margin.

Load Pulling

Shown in Figure 9 on the below is a load pull analysis of the cascade gain and phase. A long (7000 degrees) tunable transmission line was inserted between the oscillator output port and a 25 ohm load. The length of the line is varied using Monte Carlo analysis. This represents a 2:1 VSWR circle with random phase. Notice the peak-to-peak frequency pulling as defined by the phase zero crossing is +8 KHz to -10 KHz. The gain margin varies from approximately 4.6 to 6.2 dB, insuring oscillation for any 2:1 or better VSWR load.

Summary

A number of techniques were applied to a bulk-quartz filter and a SAW oscillator. While not a complete set of available techniques, they represent potential methods available to an imaginative user of GENESYS.

References

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