Voltage Controlled SAW Oscillator
Mechanical Shock Compensator

ECE 4901 - Senior Design I
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Final Project Proposal

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Summary:

Voltage controlled SAW (surface acoustic wave) oscillators experience a significant frequency shift for their applications when subjected to mechanical shock. As a world leader in the SAW industry, Phonon Corporation is looking to improve the shock sensitivity of its devices to provide more reliable products. To achieve the goal of three axis mechanical shock compensation, the shock experienced by the system will be measured by an accelerometer, filtered, and fed into the frequency control pin of the VCSO. As a result, any frequency shift due to shock will be canceled by an equal and opposite shift from the VCSO’s control circuit. A test method produced by a previous team will be utilized and improved to discover the shock sensitivity of a VCSO, as well as find the accelerometer and analog filtration circuit to achieve the most compensation possible.

Background:

Phonon Corporation was founded in 1982 in Simsbury, Connecticut. They are the global leader in the design and manufacturing of SAW components and devices. These components are primarily targeted towards defense and space applications, and so require a very high level of stability. One very important device that incorporates this SAW technology is the VSCO (Voltage-Controlled SAW Oscillator), which Phonon happens to manufacture. In a defense/space setting these devices can be used in many systems such as radar, communication, navigation, and even electronic warfare. For these systems to operate correctly they require that a signal output from a VCSO must contain as little phase noise as possible. Ideally, this means that the VCSO must be completely protected from disturbances such as mechanical shock. For example, if an uncompensated shock were to be applied to a VCSO which was feeding into a radar system, the shock could easily shift the phase of the output signal of the VCSO. This could cause the radar system to not locate specific targets correctly, rendering it useless. Therefore, the purpose of this project is to minimize the effects that mechanical shock introduces to the output of a VCSO by means of an analog circuit that can attenuate the effects of shock by at least 20dB. The initial stages of this project had been started last year, where a few things had already been accomplished. The most important thing carried over from last year was the creation of a mechanical shock tower used for testing. Tests for shocks in one axis had also been started, which is where this year’s project had started. Provided that desirable data has been obtained by the end of the semester, testing in all three axes will start at the beginning of next semester.

VSCO Theory:

The Voltage-Controlled SAW (surface acoustic wave) Oscillator we are using is the 101654.101 oscillator listed on Phonon’s product library. The oscillator is essentially an amplifier circuit which outputs a signal at a desired frequency. The voltage controlled oscillator takes advantage of feedback and allows a reading of the output voltage to both stabilize and
change the output frequency if necessary. This section will be a basic understanding of the background of Oscillator circuits and how voltage control is used in the oscillator of this project.

By using feedback circuits, the variance from ideal output frequency can be measured and fed back into the amplifier, in a self-correcting manner. Due to the Barkhausen criterion for stability, it has been established that to create an oscillating output the closed loop gain of the amplifier circuit must be greater than unity. If it is exactly unity, a perfectly sinusoidal wave will result, but greater than unity gain will still provide an oscillating output signal. It is also necessary for phase shift to be 0 or some multiple of $2\pi$.

![Figure 1: A simple feedback system with amplifier A and feedback network $\beta$](image)

\[
|\beta A| \geq 1 \tag{Equation 1}
\]
\[
\angle \beta A = 0, 2\pi, 4\pi, \ldots \tag{Equation 2}
\]

In this particular oscillator, with no control voltage applied, the frequency is set to 400 MHz, meaning the expected output should be centered around a 400 MHz signal when it is turned on. This is a simple XO, also known as a saw oscillator.

In VCSOs it is sometimes necessary to alter the output frequency by pulling or pushing the frequency. In these types of circuits a crystal oscillator is used. Crystal oscillator circuits have discrete circuit equivalents and can be represented as a schematic through RLC circuit components. Oscillation can be achieved by using either op-amp or transistor amplifier circuits. By adding capacitances and inductances in, the circuit can be tuned at the input or the output. The advantage of the crystal over the lumped component counterpart is the high-Q properties which allow for reduced phase noise at high frequencies. Phase noise is the frequency domain representation of jitter, which is undesirable in timing sensitive circuits such as oscillators. A quartz crystal is a typical material for these operations, because of their unique piezoelectric properties. When a mechanical stress is applied across the face of the crystal, a potential develops across the material. By the same token, applying a voltage across the material will result in distortion of the crystals physical structure. The crystal will have a natural resonant frequency which will be the output it would naturally like to operate at. In the RLC equivalent circuit, this is similar to choosing values of L and C where the resonant frequency occurs at $\frac{1}{\sqrt{LC}}$. 
In order to sway the output voltage away from its natural frequency, the crystal is put in series with a capacitor. This capacitor will alter the reactance of the RLC equivalent circuit and the resonant frequency will change. In the case of the Voltage Controlled Oscillator, a variable capacitor diode also known as a varactor is placed in series, and is controlled by an applied control voltage, ranging from 0-5 volts. A varactor is a specialized reversed biased diode, where the applied voltage will increase or decrease the depletion region between the P and N type material. A low bias voltage will result in a narrow depletion region, resulting in higher capacitance, because the distance between charged surfaces is small (See equation 3). This larger depletion region reduces the capacitance from bulk to contact, meaning that the capacitance is controlled via our applied voltage. By using this variable capacitance in series with the crystal, an oscillating output of our choice can be established.

\[ C = \frac{\varepsilon A}{d} \]  
(Equation 3)

Capacitance is a result of the permittivity of the material times the surface area of the charges, but is reduced when the surfaces are far apart.

This system has proven very effective in controlled environments free of shock. Our task is to design a system which can continue this form of controlled signal generation, even under systems with external shock. The main problem is the crystal itself, which operates with piezoelectric properties. Due to these inherent qualities, any external force applied will distort the output frequency so that we will see more noise and frequency shifts. What our group would ideally like to accomplish is to measure the displacement of the shock using an accelerometer. Using this known displacement analog feedback components should be designed which will pass a compensated signal to the control voltage, nullifying the effect of the shock. We have already seen that simple resistive components have some effect and more research will be done to find out what effects non-linear components will provide.

Accelerometer Theory:

An accelerometer is a device which detects motion of an object and converts this response to an electrical response. In this project, a MEMS accelerometer is mounted inside a square housing which is in contact with the saw oscillator. When the saw oscillator is shock by the shock tower upwards in the z direction, the MEMS accelerometer records the vibration of the saw in single axis and feed this signal to a control pin on the saw oscillator. The amplitude of the signal sent by the accelerometer determines the output power of the saw which is measured in dBm, and this output is then sent to the phase frequency detector which manipulates the change in frequency between the saw oscillator and frequency generator. Currently a single axis accelerometer is being used to generate the responses of the shock, but as the research advances, and a need for 3 axis compensation becomes more relevant, a 3 axis accelerometer will be needed detect vibrations along all three axes. In choosing an accelerometer that is ideal for this project, there are some basic parameters which have to be considered before choosing this
component. The primary characteristics are the dynamic range, frequency response, sensitivity, size and mass of accelerometer and finally its ability to detect motion in 3 axes.

The dynamic range is the maximum amplitude an accelerometer can detect shock without clipping or distorting the output signal. Currently testing purposes require that the accelerometer can detect shock up to 400Gs. This is critical since the output of the signal should reflect the true impact of the shock, otherwise the integrity of the data will be compromised. The frequency response is the allowable bandwidth that the accelerometer will detect motion and give an output while the sensitivity addresses the range of accuracy that this component will effectively retrieve data. Even though great emphasis is currently been place on acquiring accurate data, an accelerometer which is too sensitive may be problematic, since it may produce excessive noise in our data, while one which does not have good sensitivity may degrade the quality of our results. This ultimately means that choosing the right accelerometer depends on somewhat being intermediate between these two conditions. Another characteristic is the size and mass of the accelerometer. In general when choosing an accelerometer the mass of this component should always be significantly smaller than the mass of the object being measured to achieve good data, and the size of accelerometer should also be small enough to fit in the housing of the shock tower to provide proper contact. Finally, since 3 axis compensation will ultimately be required, we will have to make sure that the accelerometer can detect shock in all three axes, while maintaining the other characteristics as stated earlier.

**Solution Approach:**

The specifications required by Phonon state that the final mechanical shock compensation system must achieve at least 20 dB of compensation for shock or vibration, along any axis, of frequencies less than 2 kHz. The final compensating circuit must be composed of analog components, small enough to fit in Phonon’s existing 1”x1” flat-pack casing along with the VCSO, and inexpensive enough so as not to drastically effect the price of VCSOs. To realize these goals, the following topology has been developed and shown to be effective by the previous senior design team and Phonon.
In this design, an accelerometer is used to measure the shock experienced by the system. The output of the accelerometer, a voltage that is linearly related to the amount of acceleration, is then used to adjust the frequency of the VCSO. The VCSO itself has a frequency control pin that accepts a voltage between 0 and 5 volts, allowing for fine adjustments up to about 70 kHz in the 400 MHz oscillator being studied. The accelerometer must be three axis, compact, have a bandwidth of at least 2 kHz, able to measure high levels of shock, and inexpensive. Finding an accelerometer that meets these expectations is one of the first major objectives of this project.

Before the output of the accelerometer reaches the VCSO, it will be passed through an analog filter. A 0\textsuperscript{th} order resistive voltage divider has been shown by Phonon to provide significant shock compensation. These results will be verified in this study, and higher order filters will be explored to see if they yield better results. It can be assumed that the relationship between the amount of shock and the amount of disturbance is linear. The frequency adjustments caused by the control pin on the VCSO, however, are not linear, and may present one factor that requires higher order compensation. If the most linear region of the VCSO control input can be discovered, this will greatly improve 0\textsuperscript{th} order results, since compensation operates in a very small control voltage region. This should then affectively remove all acceleration dependent frequency shifting and make it clear if there are any vibration frequency dependent changes occurring. This will warrant the design of a high order filter with a customized frequency response.

So far, VCSO shock compensation has only been studied in one axis. This project will first verify the single axis compensation observed by the previous senior design team and Phonon, and then seek to expand this result to three axes. This may also present the need for further filtration circuits depending on the vibration sensitivities of the VCSO and accelerometer in different axes.

To summarize, the accelerometer measures the shock on the system, outputs a voltage that is filtered in a manner to be determined, and inputs this voltage to the VCSO’s frequency control. This input will cause an equal but opposite shift in the frequency of the VCSO to the frequency shift caused by the shock. The result will be a continuously stable output of oscillations at the proper frequency.

**Testing Approach:**

In order to test the proposed solution topology, a method was created by last year’s senior design team. Improvements have been made to this previous method to produce better results. The topology of is shown below.
One of the key components of this method is the phase frequency detector. This device mixes two signals together and outputs a triangular waveform whose frequency is the difference in frequency of its inputs. This makes it much easier to view frequency changes in the hundreds of Hertz on a 400 MHz signal. Also, the other equipment available for this project does not have a high enough sample rate to fully realize a 400MHz signal.

Using the Hittite HMC439QS16G phase frequency detector, the output of the VCSO will be compared to the output of a Giga-tronics 6060B signal generator. The signal generator provides a stable reference that exactly matches the normal output of the VCSO. In this way, the difference in their frequencies is 0 Hz, meaning the phase frequency detector’s output is a horizontal line. When a shock occurs on the VCSO, its output frequency shifts, creating an observable change in the output of the phase frequency detector for the duration of the shock pulse. It has recently been discovered that the output of the VCSO is between 10 and 12 dBm and the absolute maximum input of the phase frequency detector is 13dBm. This explains why in past tests, the detectors have deteriorated over time or failed all together. Adding an attenuator in line with the VCSO will protect future detectors and improve the quality of data.

To collect data from the phase frequency detector, a National Instruments X series USB-6353 Data Acquisition Card (DAQ) will be used. MATLAB will be used on a PC as an interface with the DAQ to run trials and start and stop acquisitions, as well as to store, process, and present data. The code used to collect initial data and fire the solenoid is shown below. The DAQ will also be used to initiate the shock on the VCSO for optimal timing. In between the phase frequency detector and DAQ, a filter circuit may be desirable to eliminate noise. A low pass filter, for example would be useful to eliminate high frequency noise as the expected changes in frequency of the VCSO under shock are in the hundreds of Hertz or less.
To shock the VCSO, a shock tower was produced by last year’s senior design team that consists of a 24V solenoid which drives a metal rod against a steal plate to produce a shock. The VCSO rests on this plate and is mechanically shocked as a result. A transistor switching circuit, shown below, will be used to interface the DAQ with the shock tower. Two power BJTs are connected in a Darlington pair configuration to allow the DAQ, which can only provide 5mA at 5V, to fire the solenoid at the relatively higher voltages and currents necessary.

To eliminate all erroneous vibrations, VCSOs are extremely sensitive to vibration, hence the reason for this study, so any shock to the system other than the pulse generated by the shock tower will corrupt data. This includes resonance in the shock tower itself and any loose components in the setup. Vibration damping materials, such as foam, will be used extensively to eliminate such testing errors. The extremely high input impedance of the VCSO control pin also presents a problem as it is sensitive to electromagnetic interference. Even
the slightest change in voltage causes a noticeable frequency change. It may be necessary to introduce shielding, especially from the shock tower solenoid.

To summarize the test process, the signal generator is first set to match exactly the output of the VCSO. Next, a MATLAB program is run that starts data collection through the DAQ from the phase frequency detector, fires the shock tower, and then ends the collection. The data is then processed and displayed in the desired form. The effects of the shock and the compensation circuit on the frequency output of the VCSO can then be observed.

**Preliminary Experimental Results:**

Shown below are graphs produced in MATLAB as the result of uncompensated shock on the VCSO, as well as the setup used to collect the data. The data utilized is the output of the phase frequency detector. When there is no shock, the phase frequency detector shows a relatively flat line, indicating that its two input frequencies are matched. The introduction of a low pass filter would remove the noise seen during this condition. As the shock occurs, a peak forms where the VCSO frequency deviates from the reference frequency. The goal of this project is to make this peak as small as possible, if not eliminated completely.

![Figure 4 Testing Setup](image-url)
Shown in figure 5 are the results of our first attempts at 0th order single axis compensation. The right and left images depict a shock on the VCSO with and without compensation respectively. The compensation was achieved using an ADXL001 single axis accelerometer attenuated by 1/200 with a resistor voltage divider. The accelerometer output is shown in green and the phase frequency detector output in blue. The next challenge is to generate repeatable compensation on every trial.
Timeline:

<table>
<thead>
<tr>
<th>First Semester</th>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Meeting</td>
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<tr>
<td>Project Description</td>
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<td>Project Specifications</td>
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<tr>
<td>Research VCSO</td>
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<tr>
<td>Research Accelerometers</td>
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<tr>
<td>Preliminary Testing</td>
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<td></td>
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<tr>
<td>Proposal/Presentation at Phonon</td>
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<td></td>
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<tr>
<td>Single Axis Compensation</td>
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<tr>
<th>Second Semester</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
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So far our group is on schedule to meet all of the requirements and expectations of the first semester. We have met with our advisor and Phonon contact, written and delivered all of our class reports, and have a good understanding of how compensation can be achieved for shock. Our research on accelerometers and preliminary testing will conclude during this last week of classes, which we expect to see desired results in single axis. We have been provided a single axis accelerometer to test with, and some preliminary testing has already been achieved.

The next objective after compensating in the first axis will be to find a suitable mount for the accelerometer on the VCSO. We would like to solidly contact the two so that each is seeing the same shock, so the accelerometer output can be properly attenuated. Once we have a suitable attachment, we will begin to measure the frequency shifts in the other axis, by turning the VCSO to receive shock in other directions. Once we have seen how the frequency is affected in these new directions, resistive networks will be calculated and tested to achieve compensation.

The final step will be to mount a 3 axis accelerometer and test our compensation circuits in various directions, to verify that our design will in fact compensate in all directions. This will conclude the project objectives given to us by Phonon and we will prepare a final paper and presentation materials by then end of the second semester.

Budget:

Many of the items required for testing have already been provided to us. These items include a National Instruments X series USB-6353 Data Acquisition Card to interface our setup to a computer, NI-DAQmx software for the DAQ, MATLAB 2009, a frequency generator,
Phonon 400MHz VCSOs, a B&K 9130 triple-output power supply for testing purposes, phase-frequency detectors for comparing signals, and the shock tower which was built last year. A budget from Phonon has not been officially proposed, but the company is willing to spend a reasonable amount on the items that are left to purchase. These items include either three single-axis accelerometers or one triple-axis accelerometer which should cost between $10-30, analog circuit components which would cost a max of $50, and vibration-damping supplies which would could reach up to a maximum of $50. Thus, budget is not a huge concern provided that the accelerometer(s) stay within a reasonable price range.

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