SAW oscillators serve as key components in many military systems, such as IFF equipment on helicopters and tanks, guidance and surveillance systems on UAV's, smart munitions, etc. The timing for military computer systems and high speed bus systems may also be derived from SAW oscillators. The ever-increasing performance demands of these systems combined with the harsh vibration environments in which they operate has led to required acceleration sensitivity of $10^{-12}$ $/g$ for state-of-the-art military applications.

In order to determine how closely commercially available SAW stabilized oscillators approach this requirement, a market survey of both fixed frequency and voltage controlled oscillators (VCO) is being conducted. The results of the complete market survey will lead to a greater understanding of commercial vendors capabilities to satisfy the hostile vibration environment of today's battlefield. The purpose of this paper is to provide a preliminary report on devices tested to date.

**INTRODUCTION**

The harsh operational environments experienced by modern military weapon systems produce a set of demanding system requirements far in excess of commercial requirements. Combinations of environmental effects can degrade weapon system performance at times when maximum performance is needed. Typical mobile military system platforms including fixed wing, rotary wing and wheeled or tracked vehicles produce severe vibration environments for on board electronics. The severe vibration environment not only introduces mechanical failures into equipment due to stress and fatigue, but also introduces degraded electronic performance which is less widely understood.

Among these electronic performance characteristics, the acceleration sensitivity of crystal oscillators has for some time been recognized as one of the limiting factors in the ultimate performance of military systems. The improved system performance which can be achieved by reducing the vibration sensitivity of crystal oscillators can often be dramatic. A 12 dB improvement in oscillator phase noise under vibration will double the range of a radar system for a constant target size, or improve the target detection capability by a factor of 16 for constant range.

Oscillators tested thus far have exhibited acceleration sensitivities ranging from $10^{-9}$/g to $10^{-7}$/g. The range of responses exhibited by the oscillators was as myriad as the number of oscillators tested and several unexpected results were observed in the test data.

**TEST SYSTEM AND PROCEDURE**

In order to test each SAW oscillator, a computer-controlled shake table system is employed, as illustrated in the block diagram, Figure 1, and as seen in the photograph of the test setup, Figure 2. The test fixture used to evaluate each of the oscillators is comprised of two major components, namely, a mounting bracket and a circuit board, as pictured in Figure 3. The mounting bracket, of aluminum construction, is bolted to the shake table and provides a stable platform to mount the circuit board. Each circuit board was fabricated on 0.060" thick pc board, having 2.0 oz. of laminated copper on both sides, in order to insure minimum variation in the test fixture.

U.S. Government work not protected by U.S. copyright.
FIGURE 1  Block Diagram of Shake Table Test System

FIGURE 2  Photograph of Shake Table Test System

FIGURE 3  Photograph of Test Fixture
configuration. The boards, whose dimensions were 4.8 cm x 7.3 cm, were used to mount the SAW oscillator and any necessary external circuitry to the mounting bracket.

After the device under test is powered up and the spectrum analyzer is calibrated, the device is subjected to a sinusoidal acceleration of 2 g's. Two accelerometers are mounted on the fixture. One is used in a feedback loop to maintain a peak acceleration level of 2 g's along the desired test axis while the other is used to measure any unwanted transverse acceleration. The vibration frequency is swept from 90 Hz to 9990 Hz. If the device is a VCO, tuning voltage is also varied. At each vibration frequency (and each tuning voltage, where applicable), measurements are taken of the power levels and frequencies of the carrier, the first upper sideband and the first lower sideband. The acceleration sensitivity is calculated by the computer using the average of the first sideband power levels, the vibration frequency, the peak acceleration along the test axis and the carrier frequency.

Acceleration sensitivity was measured along three orthogonal directions using the axial convention indicated in Figure 4. The three components of the acceleration sensitivity vector \( \Gamma \) are denoted by \( \Gamma_X \), \( \Gamma_Y \) and \( \Gamma_Z \).

For SAW oscillators, the first sideband-to-carrier power level ratio \( \Gamma_V^1(f) \) often exceeds -26 dBc, resulting in a modulation index \( \beta \) which is greater than 0.1. In order to calculate the acceleration sensitivity under these conditions, the "moderate" index approximation is utilized as explained in detail by Kosinski [1]. The procedure is as follows:

1. The first sideband-to-carrier power level ratio is measured in dBc using the spectrum analyzer.
2. The data is converted to decimal format using
   \[
   [\Gamma_V^1(f)/20] = 10^{(E_{\Gamma V^1(f)}/20)}
   \] (1)
3. The modulation index is determined by using the "moderate" modulation index approximation:
   \[
   \beta = \frac{-2 + (4 + 8 \cdot (J_1(B)/J_0(B))^2)^{1/2}}{(J_1(B)/J_0(B))}.
   \] (2)
4. The magnitude of the \( i^{th} \) component of the acceleration sensitivity vector is given by
   \[
   \Gamma_i = \frac{\beta \cdot f_V}{|A| \cdot f_0} \] (3)
   where \( f_V \) is the vibration frequency, \( A \) is the peak acceleration vector and \( f_0 \) is the unperturbed output carrier frequency of the device.

**Figure 4 AXIAL CONVENTION FOR VIBRATION STUDY**

**TEST VALIDITY AND VERIFICATION**

In the majority of the SAW oscillators, the component of acceleration sensitivity in the Y-direction, \( |\Gamma_Y| \), was an order of magnitude higher than the other components of the acceleration sensitivity vector. Due to the construction of the test fixture, this presented a problem in the form of unwanted transverse acceleration when measuring \( |\Gamma_X| \) and \( |\Gamma_Z| \). As explained by Kosinski [1], when \( |\Gamma_Y| \) is substantially greater than \( |\Gamma_X| \) and \( |\Gamma_Z| \), a small transverse motion in the test fixture can...
cause a greater effect on the oscillator than the substantially larger motion along the desired axis. In order to assess the extent to which the data were affected, the values of \(|f_V|\) were used to calculate the transverse motion induced power levels for the x-axis and z-axis tests. The transverse motion sideband levels were plotted together with and compared to the measured sideband levels in order to determine the validity range for the x-axis and z-axis data. Examples of such plots are illustrated in Figure 5. Whenever the transverse motion induced sideband levels were equal to or greater than the measured sideband levels, the data can only be interpreted as representing the upper bound for the acceleration vector component in question. A superior test fixture is under construction in order to reduce the problem of transverse acceleration.

Most of the tests resulted in mechanical resonances in the part of the test system consisting of the SAW resonator, the SAW oscillator, the test fixture and the shake table. The vibration frequencies at which the resonances occurred varied from one device to another and from one mounting to another.

Limitations in the measurement system have been discussed by Kosinski [2]. Errors in measuring the vibration frequency during acceleration contribute to the error in the calculation of \(\Gamma\) via the following equation:

\[
\delta \Gamma = \frac{\epsilon}{\Gamma f_v},
\]

where \(\epsilon\) is the error in \(f_v\).

Errors \(\epsilon\) in measuring either the peak acceleration or the carrier frequency contribute

\[
\delta \Gamma = -\frac{\epsilon}{\Gamma \phi + \epsilon},
\]

where \(\phi\) is the measurand.

Errors in measuring the sideband levels contribute

\[
\delta \Gamma = 10(\epsilon/20) - 1.
\]

where \(\epsilon\) is the error in measuring the sideband-to-carrier power level ratio in dBc. The dominant source of error is the sideband power ratio measurement, which introduces an error in \(|\Gamma|\) ranging from +19\% to -16\% [2].
Vender A - 500 MHz SAW oscillator with a sinusoidal output,

Vender B1 - 225 MHz SAW oscillator with a complementary ECL output,

Vender B2 - 357 MHz SAW oscillator with a complementary ECL output,

Vender E - 250 MHz SAW oscillator with two pairs of differential ECL outputs.

The 3 dimensional plots seen in Figures 10-13 show data from the four types of voltage controlled SAW oscillators (VCSOs) examined in the survey. The device descriptions are as follows:

Vender B3 - VCSO with two sinusoidal outputs, one at 701 MHz, and the other at 1403 MHz,

Vender C1 - VCSO with a 240 MHz sinusoidal output,

Vender C2 - VCSO with a 400 MHz sinusoidal output,

Vender D - VCSO with a 622 MHz sinusoidal output.

The information provided by the shake table test results is much more comprehensive than the information which is usually available from industry. For example, for a single-frequency SAW oscillator, acceleration sensitivity is often given at only one vibration frequency. However, the two dimensional plots displayed in this report indicate that acceleration sensitivity may vary significantly with vibration frequency. For VCO's, industry often provides acceleration sensitivity at only one tuning voltage. While Figure 11 indicates that for some VCO's \( \Gamma \) may be relatively constant with tuning voltage, it turns out to be unwise to assume that all VCO's follow the same behavior. For example, Figure 12 displays a large dependence of \(|\Gamma_x|\) and \(|\Gamma_z|\) on tuning voltage at the lower vibration frequencies.

Figure 14 summarizes the results of all the SAW oscillators tested. Figures 14a, 14b and 14c show the magnitudes of the various components for all of the outputs of the units tested. Figure 15 shows the magnitude of the total acceleration sensitivity vector \(|\Gamma|\) for each device output measured, i.e., it is the root-sum-squared of the three orthogonal components. Table 1 serves as a key of the various vendors and oscillator types represented in Figure 14. Typical values of acceleration sensitivity components range from \(10^{-10}/g\) to slightly above \(4.0\times10^{-8}/g\). Notice the similarity of \(|\Gamma_\text{y}|\) and \(|\Gamma|\). As mentioned earlier, this illustrates that \(|\Gamma_\text{y}|\) is usually the most dominant component of acceleration sensitivity, \(|\Gamma|\) ranges from \(1.4\times10^{-9}/g\) to \(4.4\times10^{-8}/g\). Clearly, the Army's requirement of \(10^{-12}/g\) is three orders of magnitude better than the best oscillator tested to date in the survey.

Table 2 provides the acceleration sensitivity result summary for each output of the 16 devices tested. The data presented in this table includes the device number where A, B, C and D after the device number denote the different outputs of the device. Column 2 identifies the vendor of a particular device. The next three columns provide the magnitude of the acceleration sensitivity for the three vector components. Column 6 gives the magnitude of the total acceleration sensitivity vector. The relatively small data sample represented in this market survey shows a large degree of variability, not only from manufacturer to manufacturer and device to device as one might expect, but also from one output to another for devices with more than one output. For example, in one device with two outputs, there was a difference of a factor of four in the acceleration sensitivity between the two outputs. In the continuation of this study, combined with the measurements of acceleration sensitivity of the oscillators, there will be an empirical study of the physical construction of the oscillators. Notably, during the evaluation of the physical construction of the oscillator, emphasis will be placed on the aspect ratio of the SAW device, the mounting of the SAW, type of components used (i.e., discrete & chip versus thin film & microstrip), etc. The combination of the acceleration sensitivity data with the observations of the physical construction of the devices should provide an excellent tool for the design and development of a state-of-the-art vibration insensitive SAW based oscillators.
ACKNOWLEDGEMENT

The authors would like to thank the CECOM Center for EW/RSTA for its support in this effort.

REFERENCES


FIGURE 6 ACCELERATION SENSITIVITY FOR VENDOR A IN THREE ORTHOGONAL DIRECTIONS

854
Figure 7  Acceleration Sensitivity for VENDER B1 in three orthogonal directions

Test Conditions:
Nom. Carrier = 357 MHz
Mult. Factor = 1
Nom. G Level = 2 g
Tune Voltage = 0 V

Figure 8  Acceleration Sensitivity for VENDER B2 in three orthogonal directions

Test Conditions:
Nom. Carrier = 357 MHz
Mult. Factor = 1
Nom. G Level = 2 g
Tune Voltage = 0 V
FIGURE 9 ACCELERATION SENSITIVITY FOR VENDER E IN THREE ORTHOGONAL DIRECTIONS

FIGURE 10 ACCELERATION SENSITIVITY FOR VENDER B3 IN THREE ORTHOGONAL DIRECTIONS
FIGURE 11 ACCELERATION SENSITIVITY FOR VENDOR C1 IN THREE ORTHOGONAL DIRECTIONS

FIGURE 12 ACCELERATION SENSITIVITY FOR VENDOR C2 IN THREE ORTHOGONAL DIRECTIONS
VCO X-Axis Acceleration Sensitivity

A. X-AXIS

VCO Y-Axis Acceleration Sensitivity

B. Y-AXIS

VCO Z-Axis Acceleration Sensitivity

C. Z-AXIS

FIGURE 13 ACCELERATION SENSITIVITY FOR VENDER D IN THREE ORTHOGONAL DIRECTIONS

FIGURE 14 ACCELERATION SENSITIVITY SUMMARIES FOR THE THREE VECTOR COMPONENTS
FIGURE 15  SUMMARY OF THE TOTAL ACCELERATION SENSITIVITY VECTOR
**Table 1** Vender Key

<table>
<thead>
<tr>
<th>UNIT</th>
<th>VENDER</th>
<th>OSCILLATOR DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>A</td>
<td>Fixed Frequency: 500 MHz</td>
</tr>
<tr>
<td>3a</td>
<td>B</td>
<td>VC50: 780 MHz; 1x Output</td>
</tr>
<tr>
<td>3b</td>
<td>B</td>
<td>VC50: 1400 MHz; 2x Output</td>
</tr>
<tr>
<td>4-5</td>
<td>B</td>
<td>Fixed Frequency: 225 MHz Complementary ECL Output</td>
</tr>
<tr>
<td>6-7</td>
<td>B</td>
<td>Fixed Frequency: 357 MHz Complementary ECL Output</td>
</tr>
<tr>
<td>8-9</td>
<td>C</td>
<td>VC50: 240 MHz</td>
</tr>
<tr>
<td>10-11</td>
<td>C</td>
<td>VC50: 400 MHz</td>
</tr>
<tr>
<td>12-15</td>
<td>D</td>
<td>VC50: 422 MHz</td>
</tr>
<tr>
<td>16</td>
<td>E</td>
<td>Fixed Frequency: 250 MHz The Pairs of Differential ECL Outputs</td>
</tr>
</tbody>
</table>

**Table 2** Summary of Acceleration Sensitivity

| OUT | VENDER | | | | |
|-----|--------|--------|--------|--------|
| 1   | A      | \( | r_x | \) | \( | r_y | \) | \( | r_z | \) |
| 2   | A      | \( | \leq 2.00 | \) | \( | \leq 0.60 | \) | \( | \leq 6.00 | \) | \( | \leq 6.30 | \) |
| 3a  | B      | \( | 0.20 | \) | \( | 0.20^* | \) | \( | 4.80 | \) | \( | 4.80 | \) |
| 3b  | B      | \( | 0.50 | \) | \( | 0.10^* | \) | \( | 5.00 | \) | \( | 5.00 | \) |
| 4a  | B      | \( | 2.10 | \) | \( | 1.00 | \) | \( | 6.30 | \) | \( | 6.70 | \) |
| 4b  | B      | \( | 1.90 | \) | \( | 1.00 | \) | \( | 6.30 | \) | \( | 6.70 | \) |
| 5a  | B      | \( | 3.30 | \) | \( | 3.20 | \) | \( | 9.00 | \) | \( | 9.70 | \) |
| 5b  | B      | \( | 3.10 | \) | \( | 1.30 | \) | \( | 7.90 | \) | \( | 8.60 | \) |
| 6a  | B      | \( | 3.30 | \) | \( | 2.30 | \) | \( | 3.70 | \) | \( | 5.20 | \) |
| 6b  | B      | \( | 3.60 | \) | \( | 0.87 | \) | \( | 2.90 | \) | \( | 4.80 | \) |
| 7a  | B      | \( | 1.10 | \) | \( | 0.61 | \) | \( | 0.66 | \) | \( | 1.40 | \) |
| 7b  | B      | \( | 1.20 | \) | \( | 0.44 | \) | \( | 0.57 | \) | \( | 1.50 | \) |
| 8   | C      | \( | \leq 25.4 | \) | \( | \leq 7.97 | \) | \( | 39.2 | \) | \( | \leq 44.1 | \) |
| 9   | C      | \( | 1.31 | \) | \( | \leq 2.44 | \) | \( | 22.7 | \) | \( | \leq 22.9 | \) |
| 10  | C      | \( | \leq 9.31 | \) | \( | \leq 3.60^* | \) | \( | \leq 29.3^* | \) | \( | \leq 29.8 | \) |
| 11  | C      | \( | \leq 5.99^* | \) | \( | \leq 14.9^* | \) | \( | \leq 7.00^* | \) | \( | \leq 17.5 | \) |
| 12  | D      | \( | \leq 6.62 | \) | \( | \leq 1.38^* | \) | \( | 39.5 | \) | \( | \leq 40.0 | \) |
| 13  | D      | \( | \leq 7.51 | \) | \( | \leq 10.9 | \) | \( | \leq 39.8^* | \) | \( | \leq 43.9 | \) |
| 14  | D      | \( | \leq 15.5 | \) | \( | \leq 16.0 | \) | \( | \leq 37.3^* | \) | \( | \leq 44.0 | \) |
| 15  | D      | \( | \leq 9.25 | \) | \( | 2.23 | \) | \( | 31.0 | \) | \( | \leq 32.4 | \) |
| 16a | E      | \( | 5.37 | \) | \( | 5.12 | \) | \( | 30.2 | \) | \( | 30.5 | \) |
| 16b | E      | \( | 2.26 | \) | \( | \leq 2.01 | \) | \( | 28.3 | \) | \( | 28.5 | \) |
| 16c | E      | \( | 1.77 | \) | \( | \leq 1.36 | \) | \( | 22.6 | \) | \( | 22.7 | \) |
| 16d | E      | \( | 2.03 | \) | \( | \leq 1.00 | \) | \( | 23.3 | \) | \( | 32.3 | \) |

* Varied substantially with tuning voltage.