Phase Noise under Vibration
Theory and Test Results

Bernd Neubig
AXTAL GmbH & Co. KG
Wasemweg 5
D-74821 Mosbach
www.axtal.com
Content

- Theoretical Background
  - Sensitivity to forces and acceleration
  - Sensitivity to vibrations

- Experimental Results
  - AXIOM75-16-60 MHz with AT-cut (HC-43/U)
  - AXIOM75-16A-60 MHz with SC-cut (HC-35/U)
  - AXIOM35-14A-100 MHz with SC-cut (HC-43/U)
  - 100 MHz with SC-cut (HC-43/U) other supplier
Content

Theoretical Background
- Sensitivity to forces and acceleration
- Sensitivity to vibrations

Experimental Results
- AXIOM75-16-60 MHz with AT-cut (HC-43/U)
- AXIOM75-16A-60 MHz with SC-cut (HC-35/U)
- AXIOM35-14A-100 MHz with SC-cut (HC-43/U)
- 100 MHz with SC-cut (HC-43/U) other supplier
Piezo-electrical Effect

Mechanical force (pressure) creates electrical charge (voltage) and vice versa
Most popular cuts

Fig. 2.2-6 Principal cuts of right-hand alpha quartz.
Influence of lateral forces

Example:
Resonator 5 MHz 3rd overtone, 14 mm diameter

\[
\left( \frac{\Delta f}{f} \right)_{\text{Max}} = \begin{cases} 
3 \text{ ppm/N for AT-cut resonator} \\
1.7 \text{ ppm/N for SC-cut resonator}
\end{cases}
\]
Influence of bending forces

Frequency change for symmetrical bending, AT-cut crystal.

AT-cut resonator

\[ f_0 = 10 \text{MHz} \]

Frequency change for symmetrical bending, SC-cut crystal.

SC-cut resonator

\[ f_0 = 10 \text{MHz} \]

Azimuth angle \( \psi \) (degrees)

Frequency Change (Hz)
Frequency change with acceleration

Strains due to acceleration cause frequency changes. Under vibration, the time varying strains cause time dependent frequency changes, i.e. frequency modulation.
Acceleration Sensitivity Vector

\[ \overline{\Gamma} = \gamma_1 \hat{i} + \gamma_2 \hat{j} + \gamma_3 \hat{k} \]

\[ \Gamma = \sqrt{\gamma_1^2 + \gamma_2^2 + \gamma_3^2} \]
Sine Vibration Induced Sidebands

Example:
Vibration 10 G @ 100 Hz
Acceleration sensitivity vector
$|\Gamma| = 1.4 \times 10^{-9} / G$

Sinusoidal vibration with vibration frequency $f_v$ produces spectral lines at $\pm f_v$ from the carrier.
Frequency Multiplication

Each frequency multiplication by 10 increases the sidebands by 20 dB

$$\Delta a = 20 \cdot \log(N)$$
Sine Vibration Induced Sidebands

Sinusoidal vibration produces spectral lines at ±f_v from the carrier, where f_v is the vibration frequency.

\[ \mathcal{L}(f_v) = 20 \log \left( \frac{\Gamma \cdot A_{f_0}}{2f_v} \right) \]

e.g., if |Γ| = 1 × 10^{-9}/G and f_0 = 10 MHz, then even if the oscillator is completely noise free at rest, the spectral lines due solely to a sine vibration level of 1G are:

<table>
<thead>
<tr>
<th>Vibr. freq., f_v [Hz]</th>
<th>( \mathcal{L}(f_v) ) [dBc]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-46</td>
</tr>
<tr>
<td>10</td>
<td>-66</td>
</tr>
<tr>
<td>100</td>
<td>-86</td>
</tr>
<tr>
<td>1,000</td>
<td>-106</td>
</tr>
<tr>
<td>10,000</td>
<td>-126</td>
</tr>
</tbody>
</table>
Random Vibration Induced Phase Noise

Random vibration’s contribution to phase noise is given by:

$$\mathcal{L}(f) = 20 \log \left( \frac{\Gamma \cdot A_{f_0}}{2f} \right), \quad \text{where} \quad |A| = \left[ \frac{1}{2} \langle \text{PSD} \rangle \right]^{1/2}$$

e.g., if $|\Gamma| = 1 \times 10^{-9}/\text{G}$ and $f_0 = 10 \text{ MHz}$, then even if the oscillator is completely noise free at rest, the phase “noise” i.e., the spectral lines, due solely to a vibration of power spectral density, PSD = 0.1 $\text{g}^2/\text{Hz}$ will be:

<table>
<thead>
<tr>
<th>Offset freq. f [Hz]</th>
<th>$\mathcal{L}'(f)$ [dBc/Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-53</td>
</tr>
<tr>
<td>10</td>
<td>-73</td>
</tr>
<tr>
<td>100</td>
<td>-93</td>
</tr>
<tr>
<td>1,000</td>
<td>-113</td>
</tr>
<tr>
<td>10,000</td>
<td>-133</td>
</tr>
</tbody>
</table>
Random Vibration Induced Phase Noise

Random Vibration for a Crystal with Vibration Sensitivity of $|\Gamma| = 1 \times 10^{-9}/G$
Osc frequency $f_0 = 10$ MHz

Vibration profile (aircraft):

- $\angle(f)$ without vibration
- $\angle(f)$ under the random vibration shown

$\angle(f)$ in dBc at different frequencies:
- 45 dB at 5 Hz

PSD (g^2/Hz) at different frequencies:
- 0.04 at 5 Hz
- 0.07 at 300 Hz
- 0.10 at 1K Hz
- 0.07 at 2K Hz
In an ideal oscillator, $\Gamma(f_v)$ would be constant, but real oscillators exhibit resonances which increase the $\Gamma$ in the relevant frequency band.
Factors determining Acceleration Sensitivity

- Crystal cut
- Crystal holder
- Mounting structure
- Crystal design
  - symmetrical shape of crystal blank (contour), electrodes and mounting structure
- G-Sensitivity of other components
Cuts with zero TC (Thickness shear)

\[ \Theta \approx 35^\circ: \quad \text{AT cut: } TC = 0 \text{ ppm/K at } \approx 25^\circ\text{C} \]

\[ \text{SC cut*: } TC = 0 \text{ ppm/K bei } \approx 95^\circ\text{C} \]

*SC = Stress Compensated
f(T) for doubly rotated cuts

The inflection temperature moves up with increasing 2nd rotation angle $\Phi$.

For $\Phi \approx 22^\circ$ ($T_{\text{inv}} \approx 95^\circ$C), the so-called SC cut („Stress Compensated) the impact of mechanical stresses on the Resonance frequency compensate.
Comparison of Crystal packages

Two-point Mount Package
  e.g. HC-43/U or HC-45/U

Three- and Four-point Mount Package
  e.g. HC-35/U or HC-37/U
Testing of Vibration Sensitivity

Test Setup

PN Test Systems:
- Phase Quadrature Method
- Cross Correlation
Phase Noise Test

The signal under test and a signal of same frequency from a reference oscillator are combined in a phase detector. The frequency of oscillator #2 is locked to oscillator #1 by a PLL. The DC output signal of the phase detector is proportional to the phase difference of the two signals. All noise spectral components, which are „faster“ than the loop filter will be measured by the spectrum analyzer or FFT.

If the reference oscillator has very low phase noise, the measured noise is dominated by the noise of the oscillator under test.

If both oscillators have the same noise, the noise of one oscillator is -3 dB lower than the noise measured with the spectrum analyzer.

Example: Aeroflex PN9000
Phase Noise Test

The signal is fed into two phase detectors and both channels are mixed with an internal low-noise reference signal. Both channels are locked to the test signal through a PLL. The noise content of the identical channels is evaluated by mathematical cross-correlation technique. Examples: Agilent Signal Source Analyzer E5052B, Rohde & Schwarz FSUP.

Cross Correlation Method

\[
S_p(f)_{\text{Meas}} = S_p(f)_{\text{DUT}} + \frac{S_e(f)_{\text{LO1}} + S_e(f)_{\text{LO2}} + S_e(f)_{\text{System1}} + S_e(f)_{\text{System2}}}{\sqrt{N_{\text{Correlation}}}}
\]

© Agilent
Testing of Vibration Sensitivity

Cables and mounting

- (1) flex coax w/ vib
- (2) semi-rigid coax w/ vib
- (3) PM noise floor w/o vib

Graph showing frequency response with different cables and mounting conditions.
Content

Theoretical Background
- Sensitivity to forces and acceleration
- Sensitivity to vibrations

Experimental Results
- AXIOM75-16-60 MHz with AT-cut (HC-43/U)
- AXIOM75-16A-60 MHz with SC-cut (HC-35/U)
- AXIOM35-14A-100 MHz with SC-cut (HC-43/U)
- 60 MHz with SC-cut (HC-43/U) other vendor
Vibration Spectrum

$W_1 = 0.01g^2/Hz$, $W_2 = 0.06g^2/Hz$

$f_1 = 500Hz$, $f_2 = 1500Hz$

Customer spec Tested profile
AXIOM75-16-60 MHz AT-cut (HC-43/U) Output Spectrum

AXIOM75-15 (AT - Cut HC-43/U)

Power (dBm)

Frequency Offset (Hz)

X-Axis
Y-Axis
Z-Axis
AXIOM75-16-60 MHz AT-cut (HC-43/U) Phase Noise

![Phase Noise Graph]

Axion 75-16-60 MHz AT-cut (HC-43/U) phase noise graph showing the noise levels at different offset frequencies.
AXIOM75-16-60 MHz AT-cut (HC-43/U)  
G - Sensitivity

![Graph showing acceleration sensitivity vs. offset frequency for X, Y, and Z axes. The x-axis represents offset frequency (10 Hz to 10 kHz), and the y-axis represents acceleration sensitivity (1/G) ranging from 1E-10 to 1E-7. There are plots for X-Axis, Y-Axis, and Z-Axis, each with distinct peaks and troughs across the frequency range.](image-url)
AXIOM75-16A-60 MHz SC-cut (HC-35/U)
Test fixture

Orientation

Z

Y
AXIOM75-16A-60 MHz SC-cut (HC-35/U)
Output Spectrum
AXIOM75-16A-60 MHz SC-cut (HC-35/U) Phase Noise

AXIOM75-16A-60 MHz SC-cut (HC-35/U) Phase Noise

Phase Noise (dBc/Hz)

Offset Frequency

1 Hz 10 Hz 100 Hz 1 kHz 10 kHz 100 kHz 1 MHz 10 MHz

AXIOM75-16A-60 MHz SC-cut (HC-35/U)  
G - Sensitivity

![Graph showing sensitivity of AXIOM75-15A HC-35/U 60MHz](image)
AXIOM35-14A-100 MHz SC-cut (HC-43/U)
Test fixture
AXIOM35-14A-100 MHz SC-cut (HC-43/U)
Output Spectrum

![Graph showing output spectrum of AXIOM35-14A-100 MHz SC-cut (HC-43/U)]
AXIOM35-14A-100 MHz SC-cut (HC-43/U)

Phase noise
AXIOM35-14A-100 MHz SC-cut (HC-43/U)
G-Sensitivity
60 MHz SC-cut (HC-43/U) other vendor
Test fixture
60 MHz SC-cut (HC-43/U) other vendor
Output Spectrum

![Chart showing output spectrum of HC-43/U 60 MHz SC-cut](chart.png)
60 MHz SC-cut (HC-43/U) other vendor
Phase noise
60 MHz SC-cut (HC-43/U) other vendor
G-Sensitivity