AXTAL ADVANCED XTAL PRODUCTS

Reduzierung des Phasenrauschens von Ultra-Low Noise Quarzoszillatoren bei Vibrationen

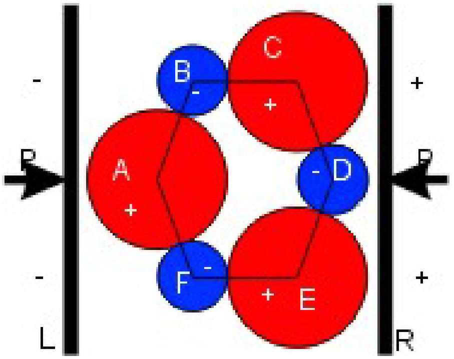
Phase Noise of Crystal Oscillators under Vibration

by Bernd Neubig

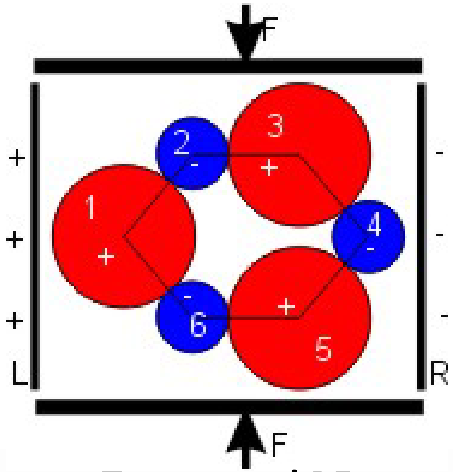
Facility MOS: Römerring 9
74931 Lobbach 74821 Mosbach

www.axtal.com
info@axtal.com
fon: +49 6261 939834

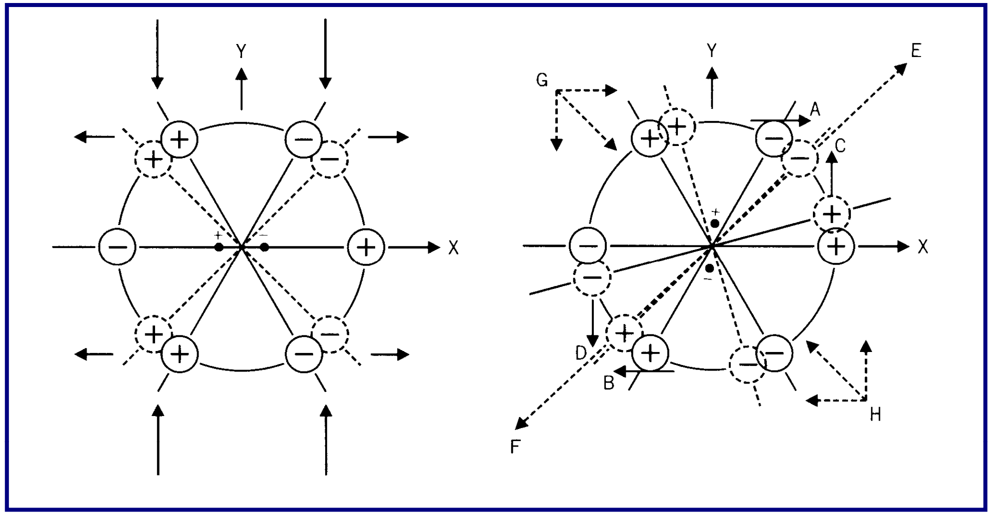
Piezo-electrial Effect



Longitudinal PE



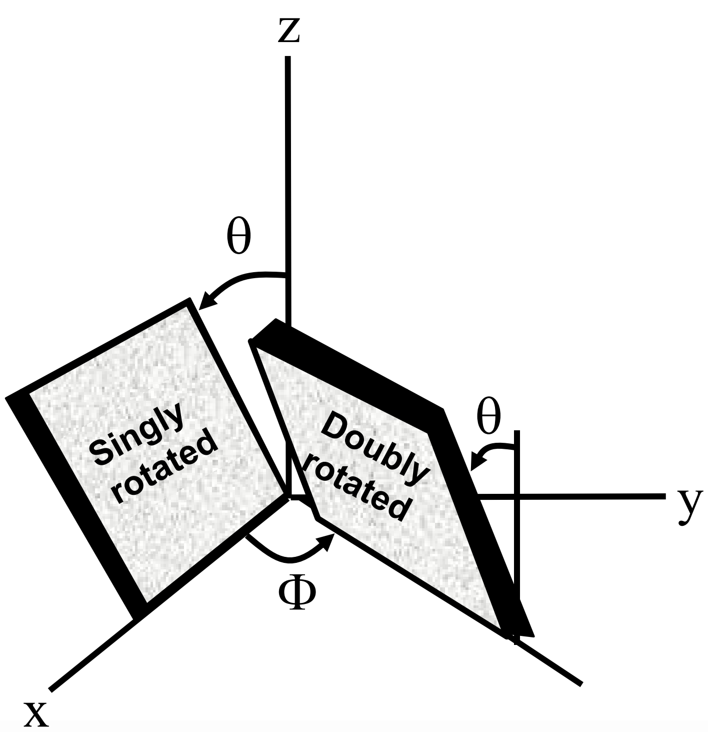
Transversal PE

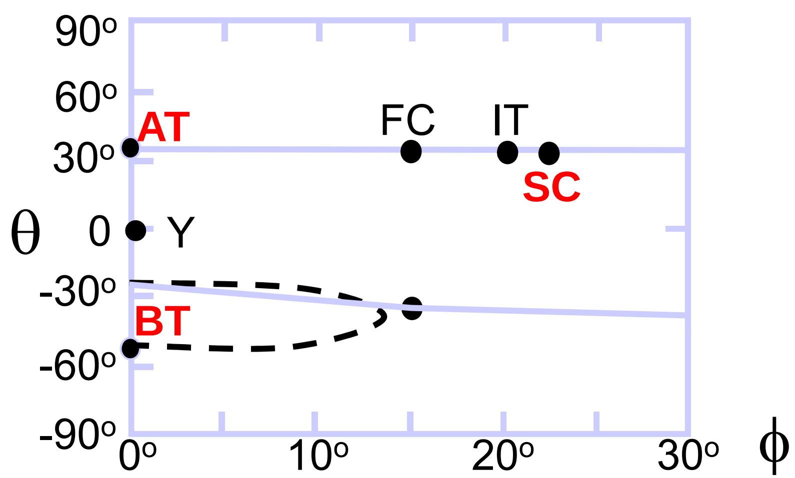


Mechanical force (pressure) creates electrical charge (voltage) and vice versa

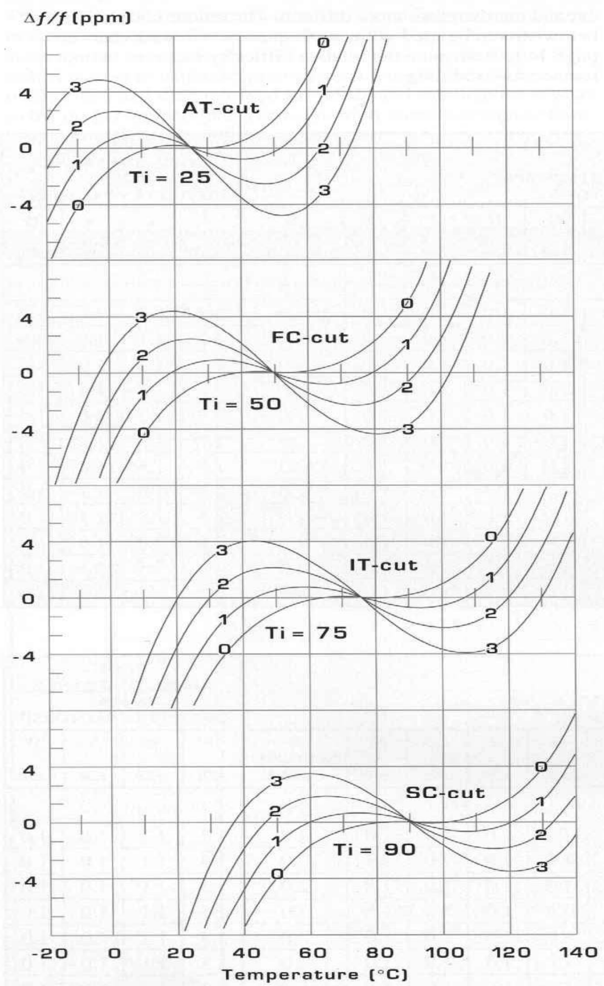
=> Quartz crystal = „microphone“ by nature

Cuts with zero Temperature Coefficient (Thickness shear mode)





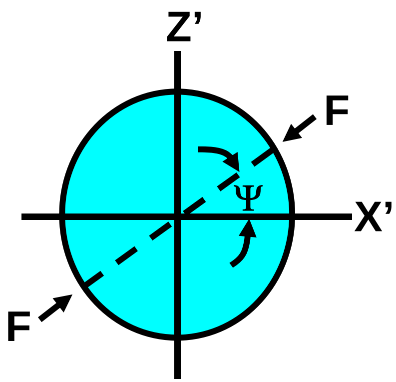
f(T) for doubly rotated cuts



The inflection temperature moves up with increasing 2nd rotation angle Φ.

For Φ ≈ 22° (T_{inv} ≈ 90°C), the so-called SC cut („Stress Compensated) the impact of mechanical stresses on the resonance frequency compensate

Influence of lateral forces

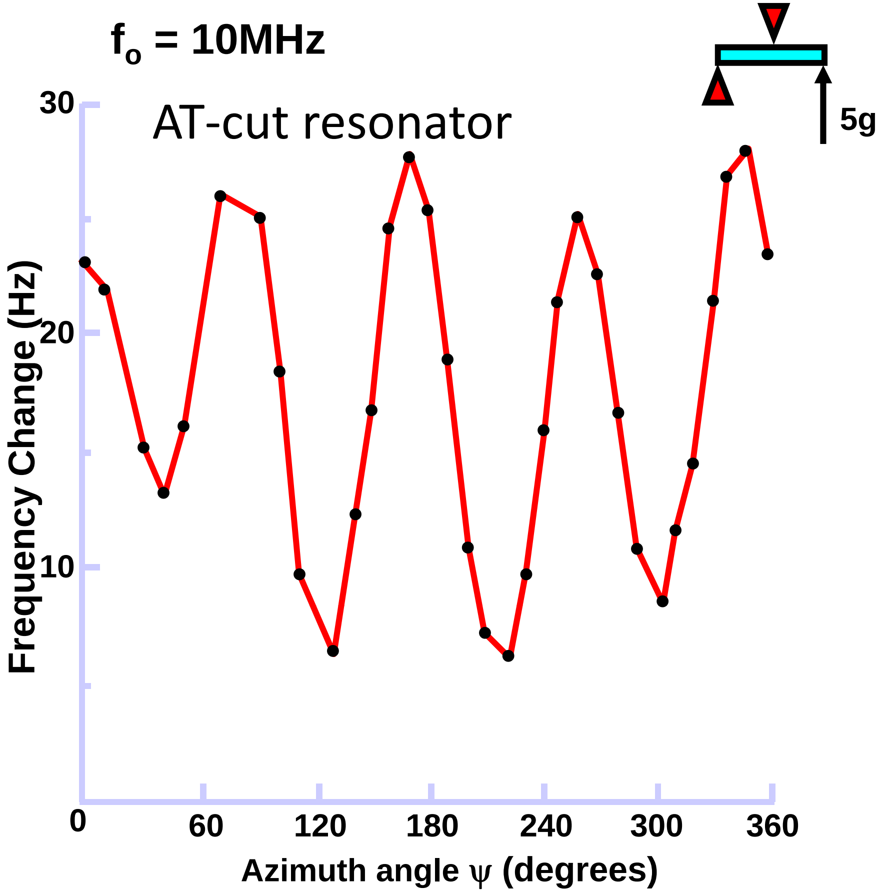


Example:

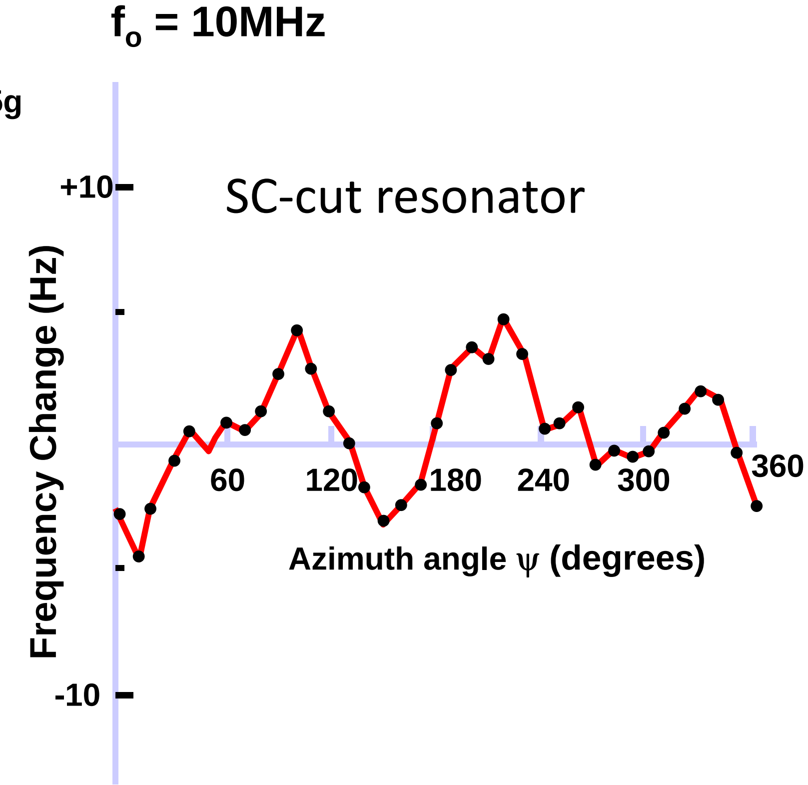
Resonator 5 MHz 3rd overtone, 14 mm diameter

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

Influence of bending forces

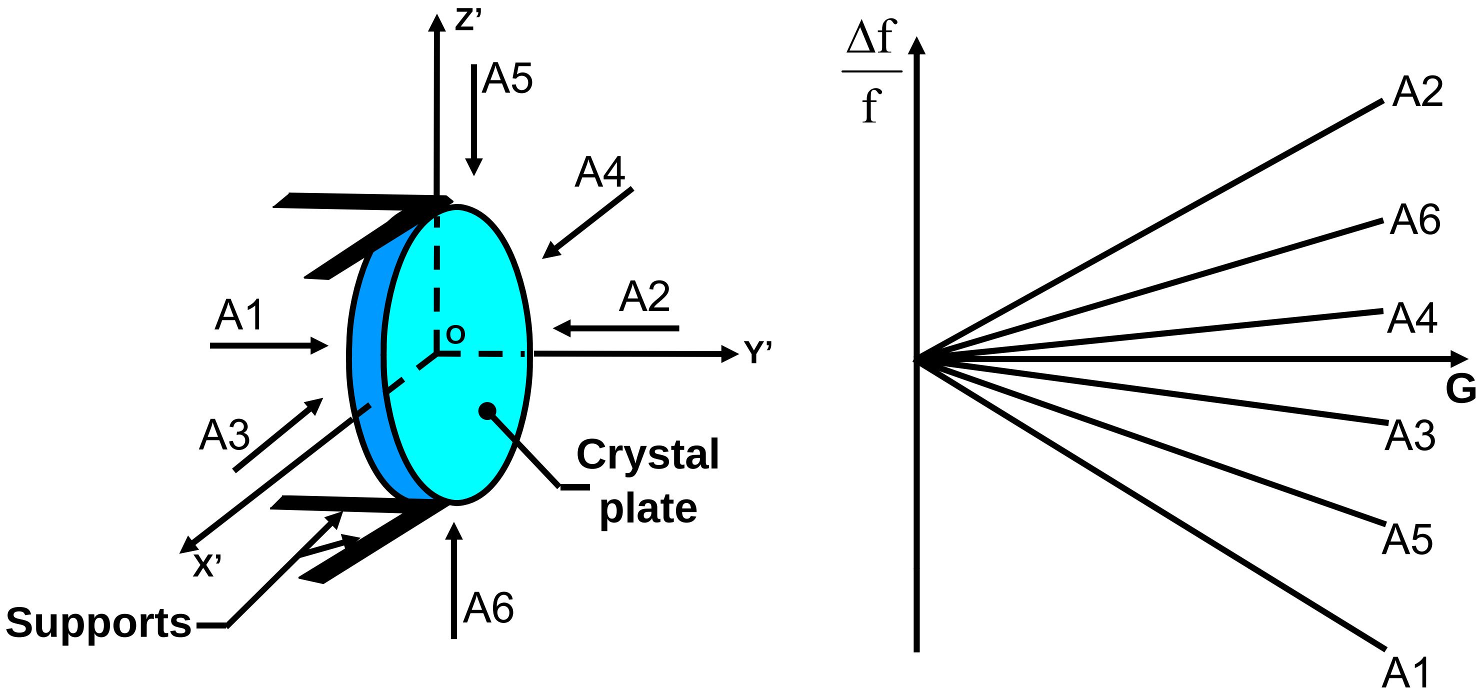


Frequency change for symmetrical bending, AT-cut crystal.



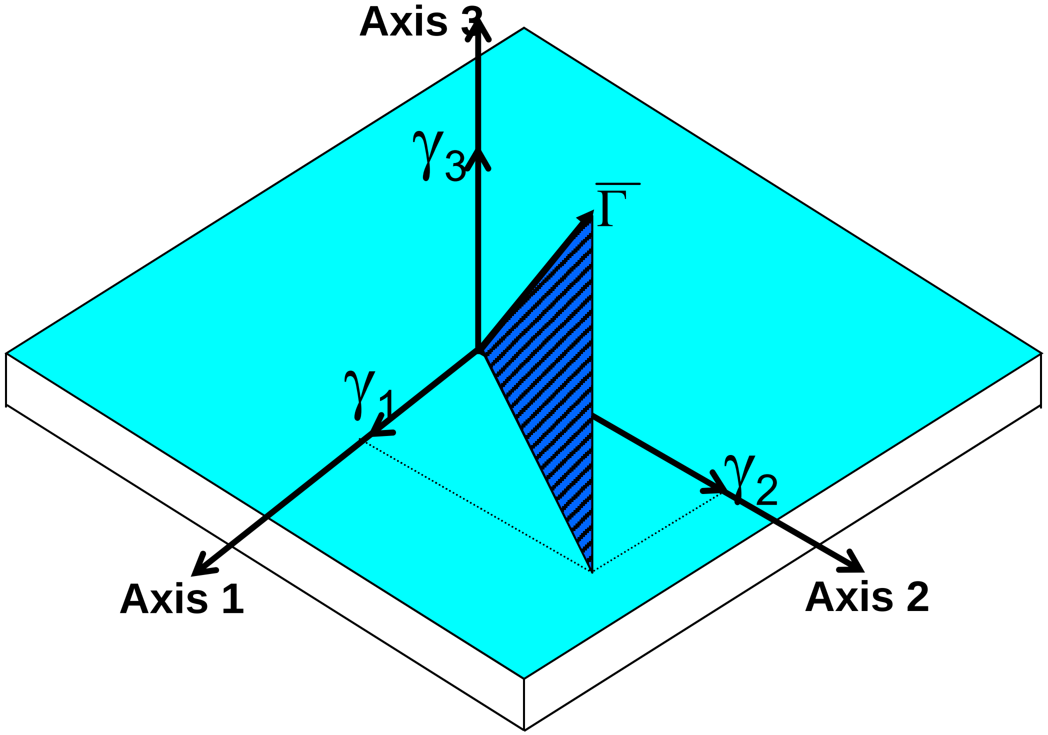
Frequency change for symmetrical bending, SC-cut crystal.

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

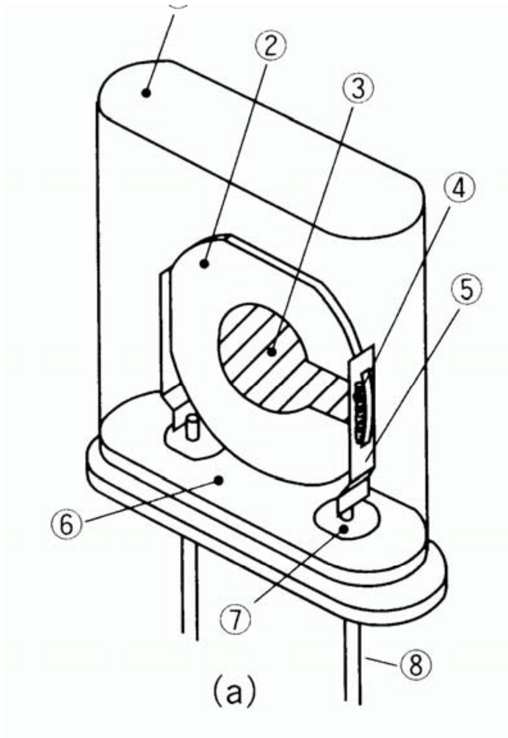
Acceleration Sensitivity Vector

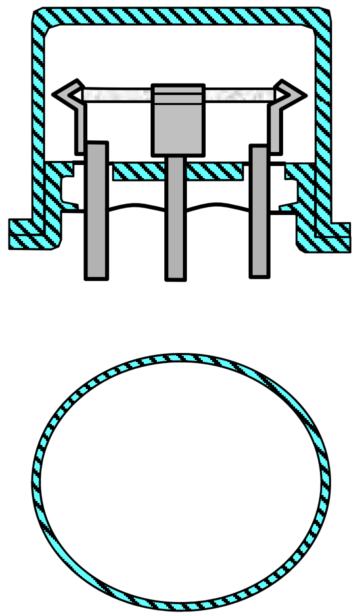


$$\overline{\Gamma} = \gamma_1 \hat{i} + \gamma_2 \hat{j} + \gamma_3 \hat{k}$$

$$\Gamma = \sqrt{\gamma_1^2 + \gamma_2^2 + \gamma_3^2}$$

Comparison of Crystal packages



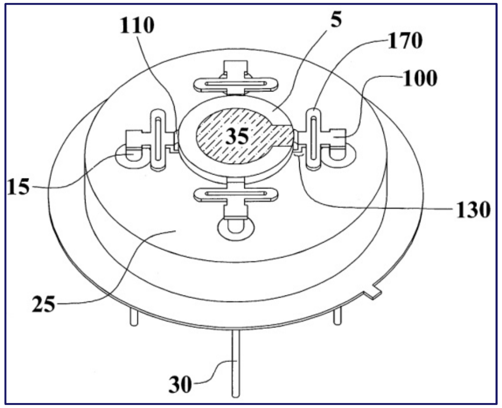


Two-point Mount Package
e.g. HC-43/U or HC-45/U

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

Factors determining Acceleration Sensitivity

- Crystal cut
- Crystal holder
- Crystal design, e.g. ➡
- Oscillator mounting structure
  - rigid mounting
  - vibration „isolation“
  - mechanical structural resonances
- G-sensitivity of other components



US-Patent 6,984,925

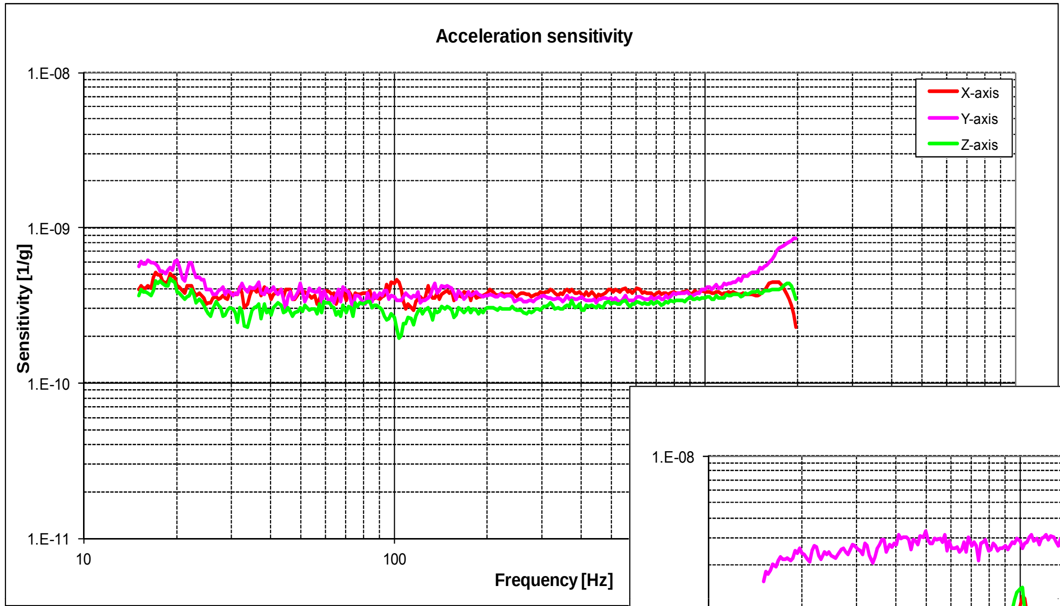
Typical values of G-sensitivity

Example: 100 MHz 5th overtone crystals
(in ppb/G for worst axis)

Cut	Package	Typical	Better	Best
AT-cut	HC-43/U	3.0	2.0	1.5
AT-cut	HC-35/U	1.5	1.0	0.5
SC-cut	HC-43/U	2.0	1.5	1.0
SC-cut	HC-35/U	1.0	0.5	0.15

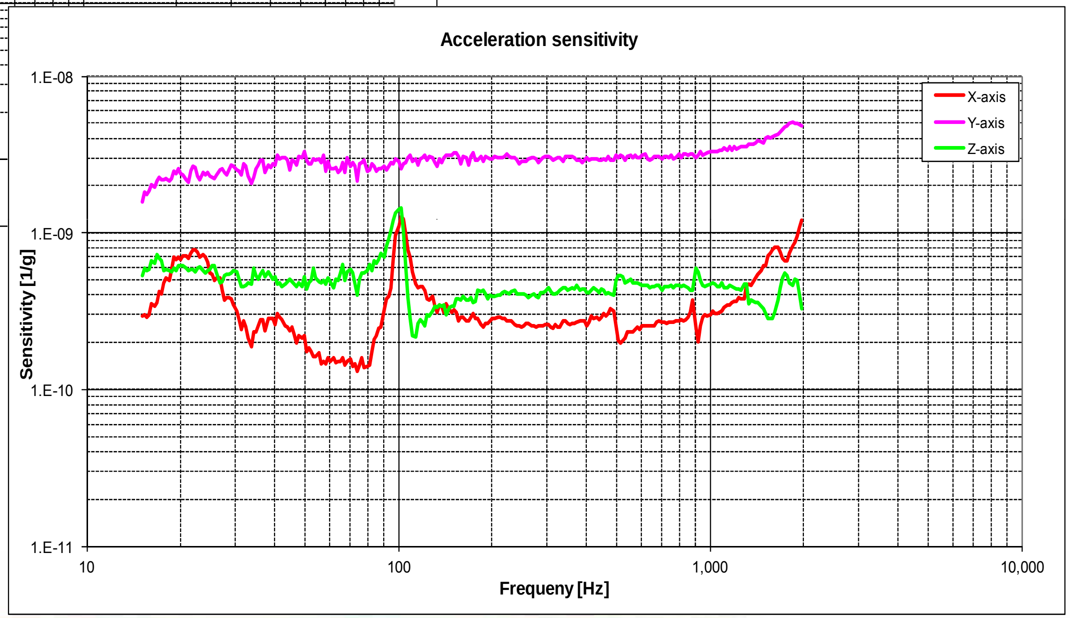
Note:
G-sensitivity may differ strongly in the different axes!

Acceleration Sensitivity with Resonances

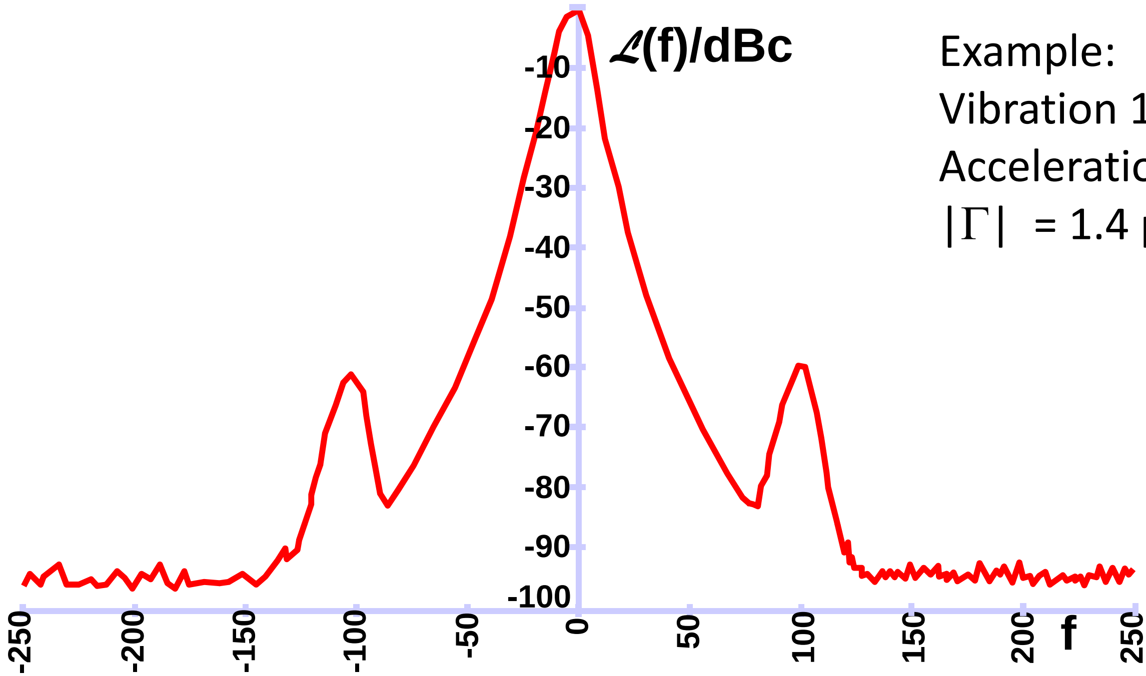


„good“ crystal

Crystal with resonances



Sine Vibration Induced Sidebands



Example:
Vibration 10 G @ 100 Hz
Acceleration sensitivity vector
$|\Gamma|$ = 1.4 ppb/ G

Sinusoidal vibration with vibration frequency fv produces spectral lines at $\pm$ fv from the carrier

Sine Vibration Induced Sidebands

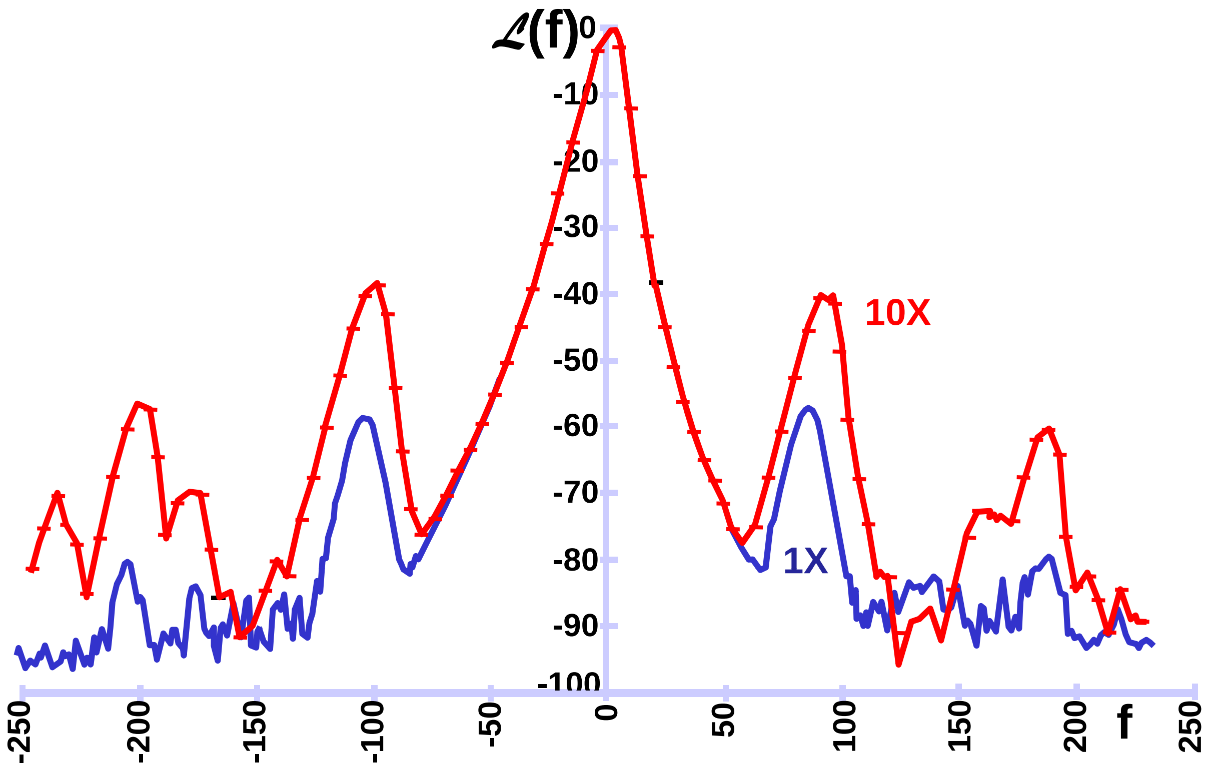
Sinusoidal vibration produces spectral lines at $\pm f_v$ from the carrier, where f_v is the vibration frequency.

$$\mathcal{L}'(f_v) = 20 \log \left(\frac{\overline{\Gamma} \cdot a \cdot f_0}{2 f_v} \right)$$

e.g., if $|\Gamma|$ = 1 ppb/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 a = 1 G are:

Vibr. freq., f_v [Hz]	$\mathcal{L}'(f_v)$ [dBc]
1	-46
10	-66
100	-86
1,000	-106
10,000	-126

Frequency Multiplication



Each frequency multiplication by 10 increases the sidebands by 20 dB

$$\Delta a = 20 \cdot \log(N)$$

Random Vibration Induced Phase Noise

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

$$\mathcal{L}(f) = 20\log\left(\frac{\bar{\Gamma}\bullet\bar{A}f_0}{2F}\right), \quad where\ |\bar{A}| = [(2)(PSD)]^{1/2}$$

PSD = Power Spectral Density (or ASD = Acceleration Spectral Density) in G^2/Hz

For $|\Gamma|$ = 1 ppb/G, the phase "noise", due solely to a vibration of PSD = 0.1 G^2/Hz - **even if the oscillator is completely noise free at rest -** will be:

Offset F	f_0 = 10 MHz	f_0 =100MHz
1 Hz	-53 dBc/Hz	-33 dBc/Hz
10 Hz	-73 dBc/Hz	-53 dBc/Hz
100 Hz	-93 dBc/Hz	-73 dBc/Hz
1 kHz	-113 dBc/Hz	-93 dBc/Hz
10 kHz	-133 dBc/Hz	-113 dBc/Hz

Rules:

- Noise increases with $20\cdot\log_{10}(f/f_0)$
  $f/f_0 = 10$ → PN + 20 dB
- Noise decreases with $20\cdot\log_{10}(F/F_0)$
  $F/F_0 = 10$ → PN - 20 dB
- Noise increases with $10\cdot\log_{10}(PSD/PSD_0)$
  $PSD/PSD_0 = 10$ → PN + 10 dB

Random Vibration Induced Phase Noise

Impact of vibration on phase noise may not be negligible even at low levels

$$\mathcal{L}(f) = 20\log\left(\frac{\overline{\Gamma}\bullet\overline{A}f_0}{2F}\right), \quad where\ l\overline{A}l = [(2)(PSD)]^{1/2}$$

<u>Example:</u>

Good Low-Noise 10 MHz OCXO has (at rest):

$\mathcal{L}$(f) ≤ -100 dBc/Hz @ 1 Hz

$\mathcal{L}$(f) ≤ -130 dBc/Hz @ 10 Hz

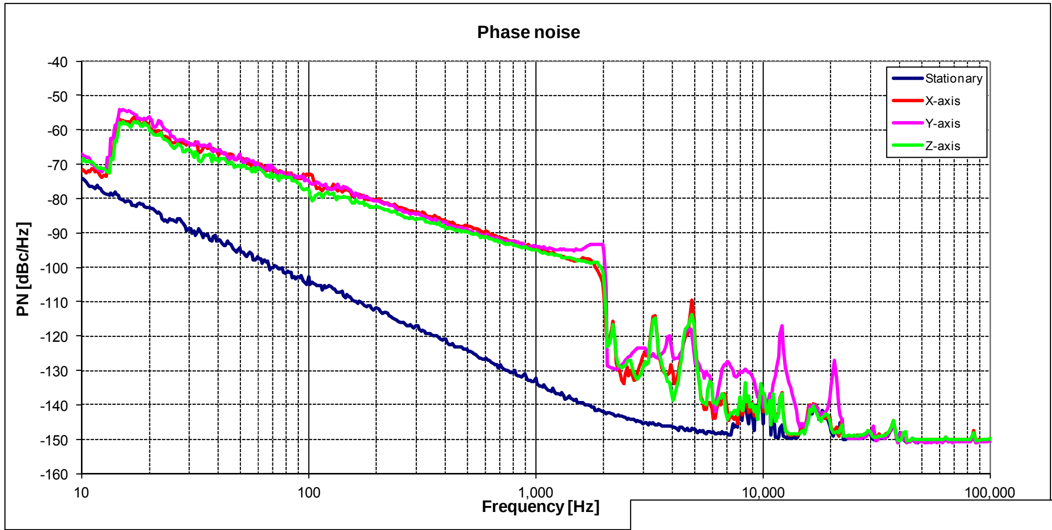
$\mathcal{L}$(f) ≤ -150 dBc/Hz @ 100 Hz

With a G-sensitivity of 1 ppb/G, the same level of noise is created by a random vibration PSD of

$2\cdot10^{-6}$ G^2/Hz @ 1 Hz

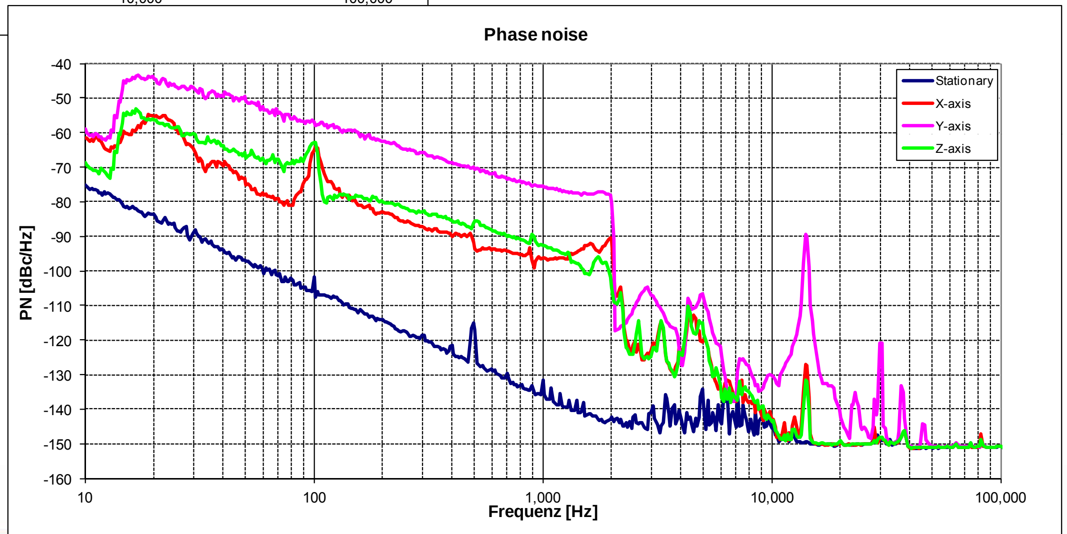
$2\cdot10^{-7}$ G^2/Hz @ 10 Hz and 100 Hz

Phase Noise



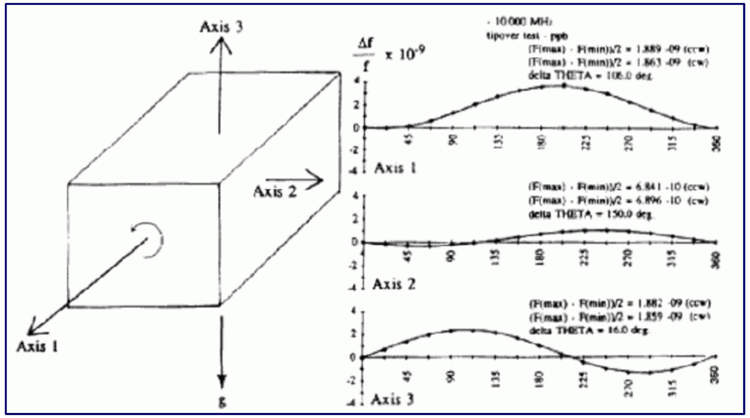
with „good“ crystal

Crystal with resonances



Measurement of G-Sensitivity Γ

- 2G-Flip-over Test
  - No information about frequency dependance
  - High impact of thermal effects (OCXO)



- Calculation from Phase Noise $\mathscr{L}(f)$ under Vibration from equation page 16:
  - Use flat PSD profile, low G_{eff}
  - Lienarity test: Increase of PSD by factor of 10 yields 10 dB increase of phase noise

$$\Gamma = 10^{\frac{L(F)}{20}} \cdot \frac{2F}{f_0 \cdot \sqrt{2 \cdot PSD}}$$

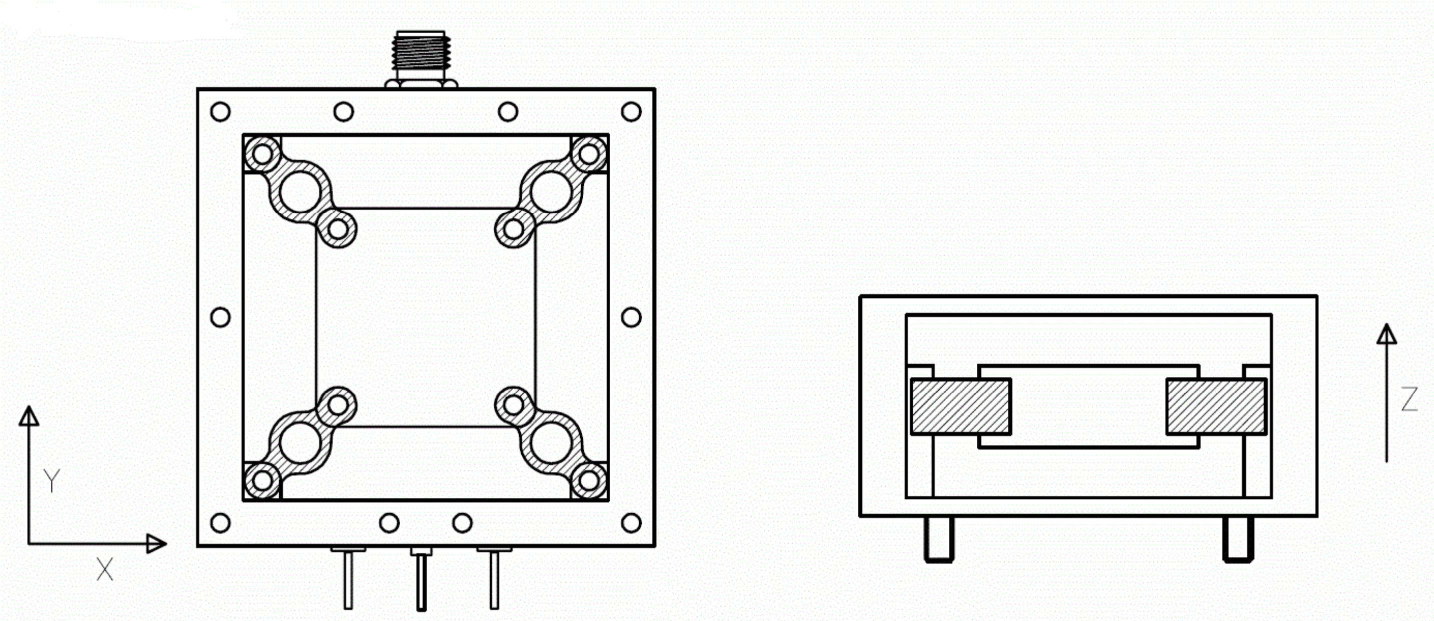
Vibration Isolation

Shock absorbers outside the package (AXIOM260)

Disadvantages: Headroom required
Cable mounts (solder joints) are subject to vibration

Vibration Isolation

Shock absorbers in the package (AXIOM200)



Advantages: No headroom required

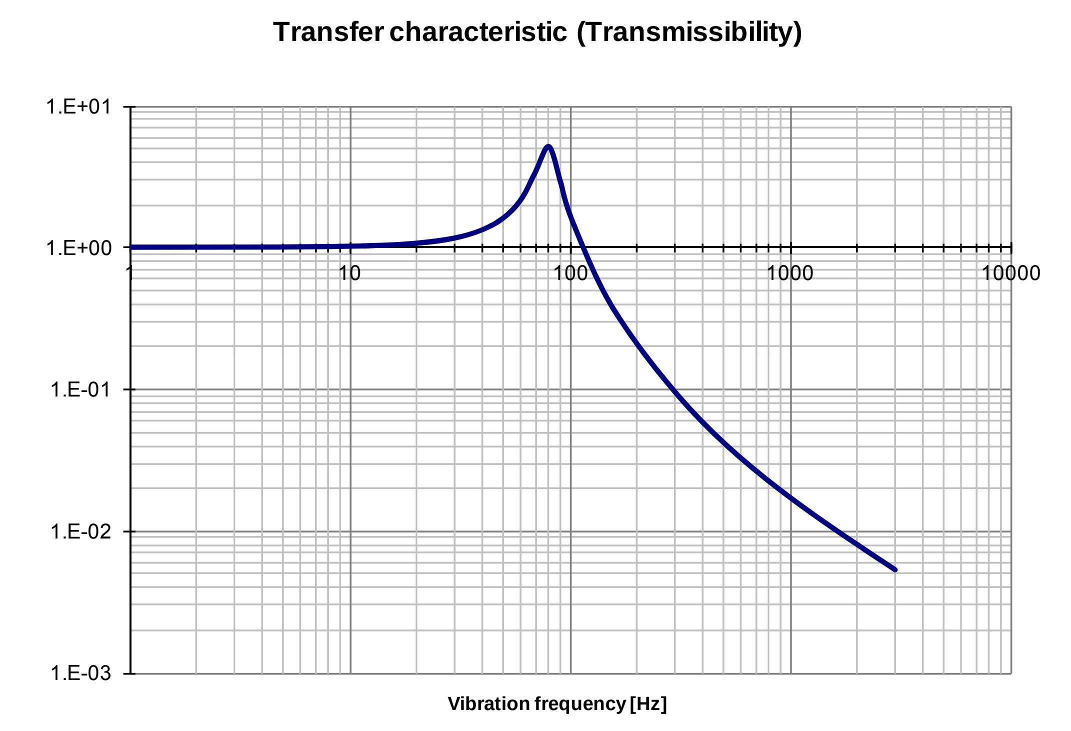
Cable mounts (solder joints and connector) are fixed

Shock Absorbers

Many different shapes, sizes, stiffnesses and damping are in use.
Stiffness, damping, and maximum deflection depend on direction

Frequency Response

Mechanical transfer characteristic



$$T = \sqrt{\frac{1+\left(2\cdot\xi\cdot\frac{f}{f_{nat}}\right)^2}{\left(1-\left(\frac{f}{f_{nat}}\right)^2\right)^2+\left(2\cdot\xi\cdot\frac{f}{f_{nat}}\right)^2}}$$

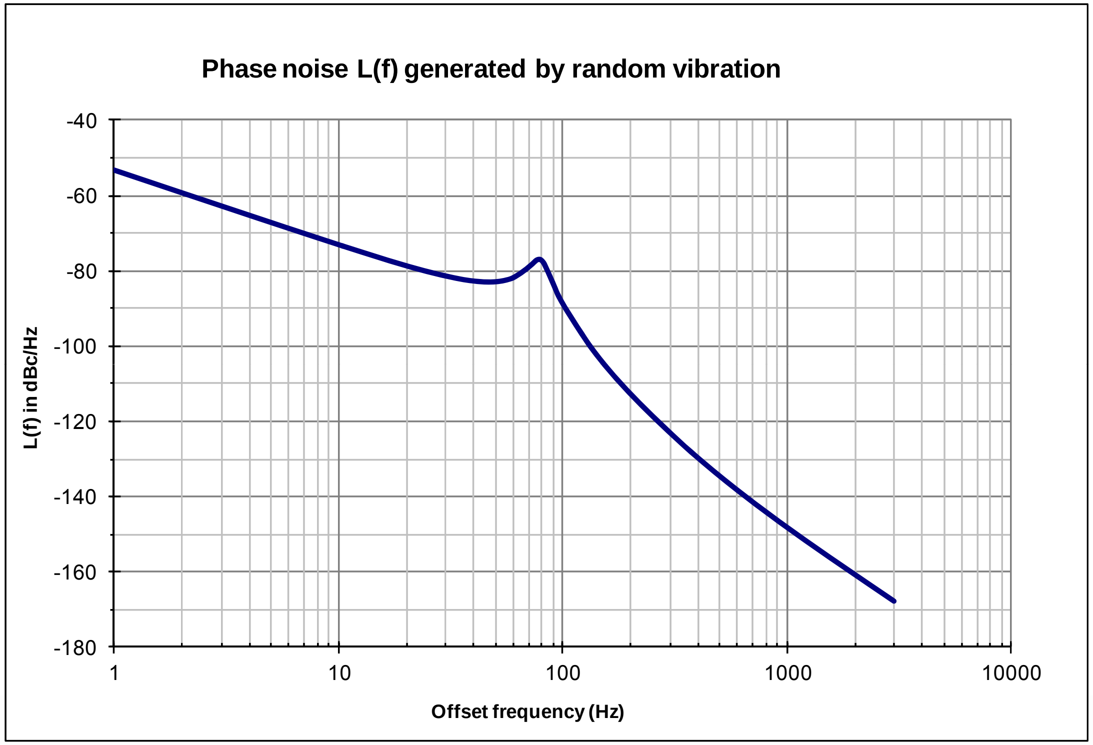
Simple model with
- Natural frequency
f_{nat} = 80 Hz
- Damping factor
ξ = 0.1

f_{nat} determined by:
- vibrating mass
- shore hardness (shock absorber)
- shape of shock absorber

ξ determined by:
- absorber Q, material and shape

Frequency Response

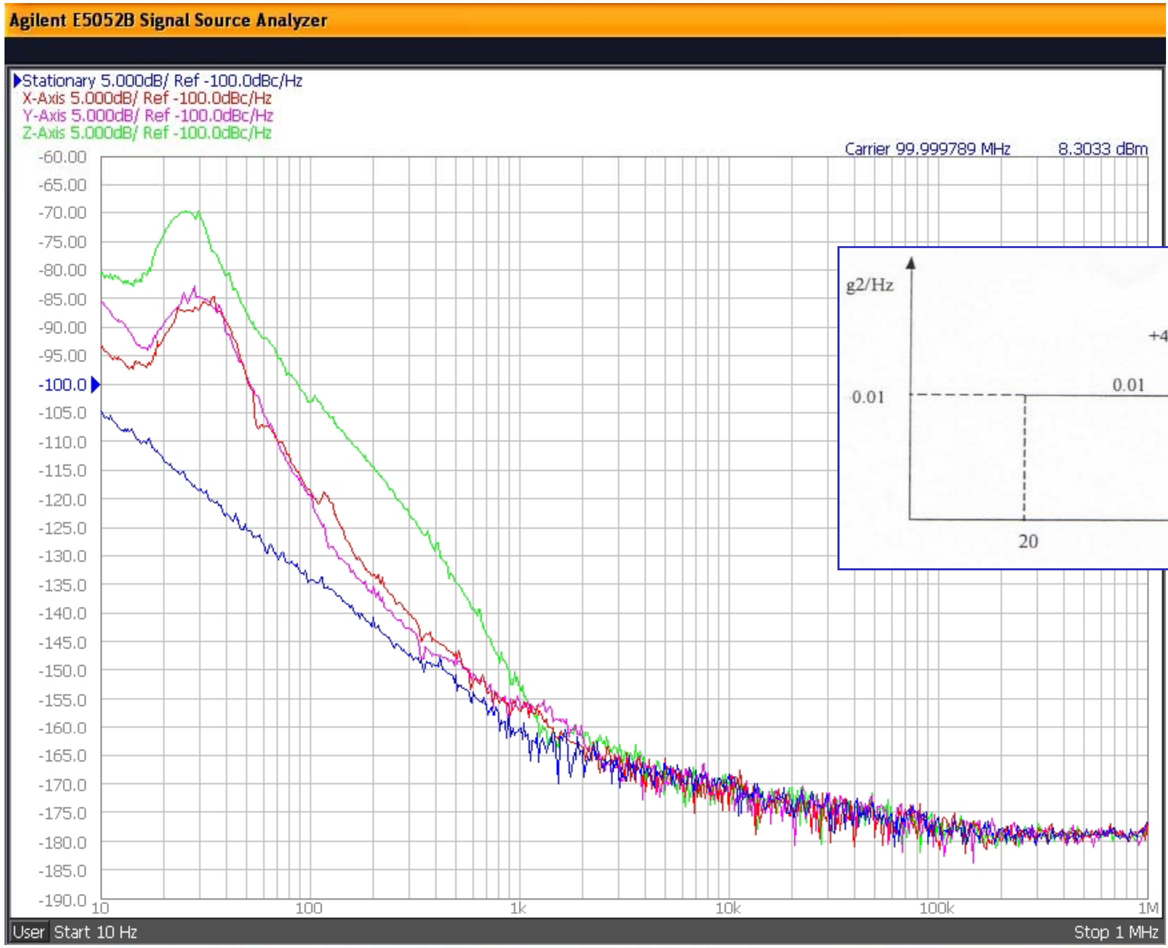
Resulting phase noise



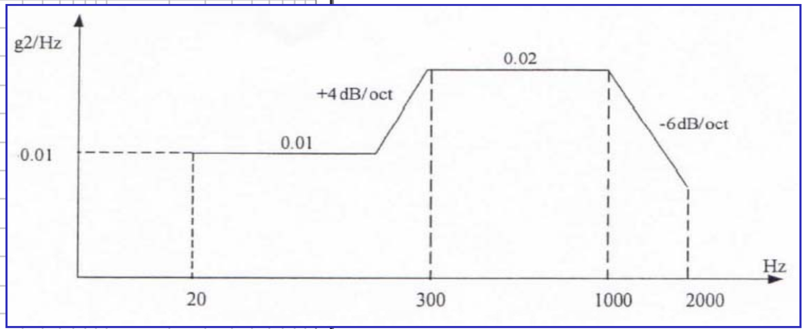
Phase noise determined by:

- Effective Vibration level
  = PSD [in G^2/Hz] weighted by Transmissibility
- G – Sensitivity of crystal
- Oscillator frequency

Practical Result



Vibration profile

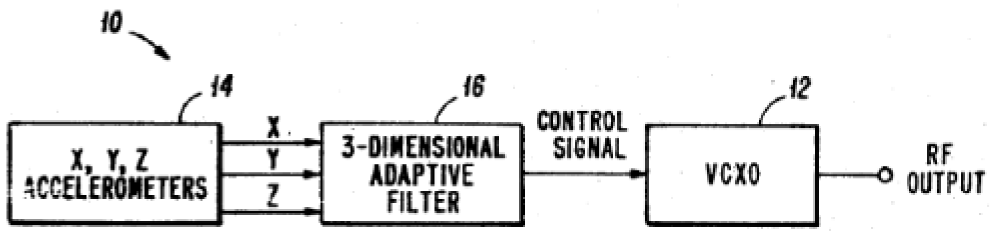


AXIOM200 - 100 MHz

Vibration Compensation

Vibration Compensation

- Multiple Crystal Arrangement
  3 or 6 crystals in orthogonal arrangement driving one oscillator
- Accelerometer compensation (US-Patent 4 891 611 and others)
  Generates control signal for equal amplitude but opposite phase



- Active Compensation Technique
  Accelerometers driving electromechanical actors

Conclusions

- Vibration sensitivity can be improved by
  - optimized crystal design (SC-cut, HC-35/U)
  - orientation of crystal: direction of smallest G-sensitivity => direction of strongest vibration
  - Use of shock absorbers for vibration isolation
    - outside oscillator package
    - inside of package
  - Vibration compensation
    - Multiple-crystal arrangement in 3 axes
    - Accelerometer technique
    - active compensation technique (actors)

Conclusions

- Vibration isolation with shock absorbers
  - Larger package size
  - Higher mass
    - OCXO: higher current consumption
    - OCXO: slower warm-up
  - Lower Shore hardness limits max. vibration level
  - Low-pass response
    - no attenuation at low frequencies
    - degradation in the vicinity of the natural frequency worse with lower damping factor
    - less attenuation with higher damping factor

Vielen Dank für Ihr Interesse
Thank you for your attention