Stress sensitivity coefficients of HBAR

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Abstract— **Vibration sensitivity is an important specification for oscillators dedicated to space or airborne systems. Vibration sensitivity can be due to the resonator, the oscillator loop or non-oscillator components like wire, for instance. Commonly, the main source of acceleration sensitivity is due to the resonator. Active compensation can be used to decrease this effect, but such systems are not easily miniaturized. This paper presents computations of the stress sensitivity coefficients of frequency for the high-overtone bulk acoustic resonators and the design of a simple packaging to minimize vibration sensitivity. The final goal is to control vibration sensitivity of the high-overtone bulk acoustic resonators with dedicated packaging. The computed results are compared to experimental ones. The agreement between theoretical and experimental results is about 50%.**

Keywords— High-overtone Bulk Acoustic Resonators (HBAR) component; oscillator; vibration sensitivity; packaging.

I. INTRODUCTION

One of the challenges of frequency sources dedicated to space and airborne systems is the control of the acceleration sensitivity of the oscillator arising from shocks and vibrations. Until now, acoustic resonators such as Bulk Acoustic Wave (BAW) or Surface Acoustic Wave (*SAW*) resonators present a g-sensitivity around 5.10^{-10}/g for *SAW* operating in the 300-600 MHz range and around few 1.10^{-10}/g for *BAW* in the range 10-100 MHz in the best case. As the operating frequency of acoustic wave devices tends to increase, new resonator principles have been investigated recently. Particularly, High-overtone Bulk Acoustic Resonators (HBAR) combining GHz-range operation capabilities with maximum quality factor Q achievable along this principle have been investigated and new (two-port) resonator architectures have been proposed [1]. Intrinsic temperature compensation of such resonators had been demonstrated [2] [3]. A previous work has demonstrated experimentally a low vibration sensitivity of High-overtone Bulk Acoustic Resonators (HBAR) [4]. The corresponding experimental results show a global vibration sensitivity of 3.9×10^{-11}/g for HBAR based on AlN on Sapphire, and 2.6 or 2.9×10^{-9}/g for HBAR based on $LiNbO_3$ piezoelectric layer on Quartz or $LiTaO_3$. To reproduce and improve such results, the resonator design must be supported by accurate computations. However, the calculation of the stress sensitivity of HBAR resonators imposes some theoretical developments and the implementation of an *ad hoc* simulation tool.

This paper describes the theoretical approach used to calculate the HBAR stress sensitivity coefficients of frequency. To validate the approach, we compare the results of computation in the case of HBARs with a quartz substrate, due to the knowledge of non-linear elastic constant. The computation consists of one calculation of the stress sensitivity coefficients of frequency and one computation of stress field taking account the packaging with PCB. The experimental set-up is explained, and finally, a comparison between theoretical and experimental results along each direction of space is done.

II. STRESS SENSITIVITY COEFFICIENTS OF FREQUENCY

HBARs combine the outstanding properties of the strong coupling coefficient of the deposited piezoelectric thin film and of the high intrinsic quality substrates. The piezoelectric film and the two electrodes on opposite sides are used as a transducer whereas the acoustic energy is mainly trapped in the substrate, *Fig. 1*. Resonance frequencies correspond to integer numbers of half wavelengths in the entire thickness. Unlike Film Bulk Acoustic Resonator (*FBAR)* and Solidly Mounted Resonator (*SMR)* in which only odd overtones exist, both odd and even overtones are compatible with resonance mode electrical and mechanical boundary conditions. For more details, the reader can consult [5].

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COMSOL computations have been performed on the supercomputer facilities of the Mésocentre de calcul de Franche-Comté.

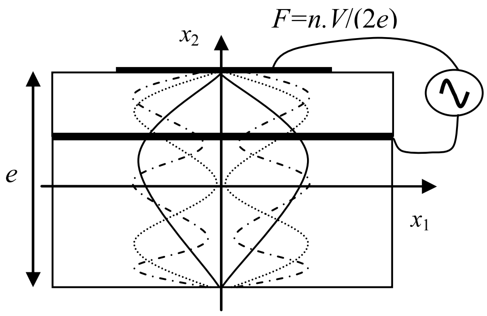

Fig. 1. Principle of a *HBAR*, showing possible harmonics distribution within the stack

A. Theorie

A first attempt to calculate the stress sensitivity coefficients of thin film resonators (FBARs) has been proposed by Masson *et al.* [6] but this approach is not easily adaptable to the treatment of HBARs resonators which are composed of several crystalline materials. In this approach, we consider the effects related to elastic constants. The tridimensional variational formulation for elastic problem can be written in Lagrange coordinate a_i:

$$\int_{\Omega} \left(\frac{\partial \delta u_i^{0*}}{\partial a_j} \bar{A}_{ijkl} \frac{\partial u_l}{\partial a_k} - \rho_0 \omega^2 \delta u_w^{0*} u_w\right) dV = \int_{\Omega} \delta u_i^{0*} F_i \, dV + \int_{\Gamma} \delta u_i^{0*} T_{ij} n_j \, dS \tag{1}$$

Index *0* correspond to the non-perturbed state, while the displacement is denoted by u_i, the surface forces by $T_{ij}.n_j$, the volume forces by F_i, the pulsation by ω, and the mass density by ρ.

Then, let us consider the Sinha-Tiersten perturbation method [7] [8] [9] which involves the computation of static U_{ijkl} and dynamic $\bar{H}_{ijkl}$ terms.

$$\frac{\Delta\omega}{\omega_0} = U_{ijkl} \bar{H}_{ijkl} \tag{2}$$

$$\bar{H}_{ijkl} = (\delta_{ik}\delta_{jm}\delta_{ln} + C_{ijkluv} s_{uvmn} + C_{pjkl} s_{ipmn} + C_{ijql} s_{kqmn}) \bar{T}_{mn} \tag{3}$$

$$U_{ijkl} = \frac{\int_{\Omega} \left(\frac{\partial u_i^{0*}}{\partial a_j} \frac{\partial u_l^{0}}{\partial a_k}\right) dV}{2\rho_0 \omega_0^2 \int_{\Omega} u_w^{0*} u_w^{0} \, dV} \tag{4}$$

We adapt the method to carry all necessary integrations across the different layers of the stacked HBARs structures. Assumption of constant stress in the various layers is done allowing the derivation of HBAR stress sensitivity coefficients of frequency (${}^{s}\alpha_{mn}$). It is possible to consider vertically–inhomogeneous stresses in our model by increasing artificially the number of layer of the HBAR stack. Only mechanical terms are taken into account and the contribution of the piezoelectric constants were deliberately omitted in the perturbation equations since the electromechanical coupling rarely approaches the percent in HBARs.

B. HBAR stress sensitivity coefficients of frequency computation

All non-linear constants of material were found in **Error! Reference source not found.**. The knowledge of $LiNbO_3$ and quartz non-linear constants will allow us to validate the computation of the stress–sensitivity coefficients of frequency of HBARs. We firstly compute these coefficients and with the separate computation of stress field, we will obtain computational results suitable for comparison with experimental results.

Fig. 2 shows the evolution of stress sensitivity coefficients for the case of HBAR based on (YX*l*)/163° $LiNbO_3$ piezoelectric layer and (YX*lt*)/35°/90° quartz substrate. The stress sensitivity coefficients are slowly changing along the overtone number but we note a maximum variation near the piezoelectric layer fundamental resonance. For other overtones, stress sensitivity coefficients are almost constant and remain close to the coefficient of the single substrate plate. Since the stress coefficients obtained using the proposed calculation are very close to those obtained with the calculation of BAW ${}^{s}\alpha_{mn}$ on single-crystal substrates, usual low sensitivity cuts for BAW can be used also for HBAR.

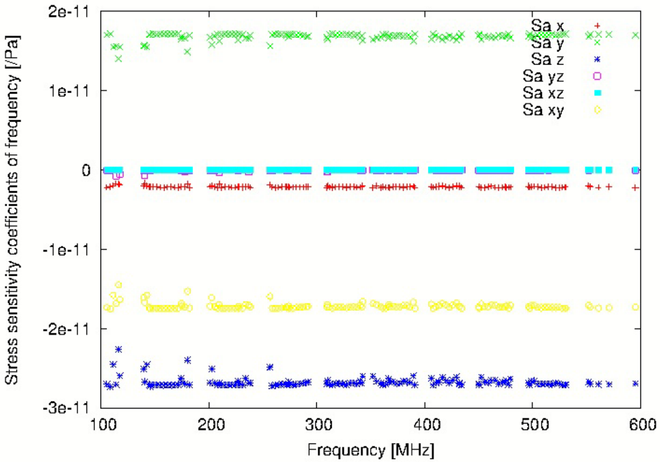

Fig. 2. HBAR Sensitivity coefficient for HBAR based on (YX*lt*)/35°/90° quartz substrate (thickness equal to 350µm) with (YX*l*)/163° $LiNbO_3$ layer of 15 µm thickness.

For the computation of vibration sensitivity, we used values of table I, which correspond to the high frequency on the *Fig. 2*.

TABLE I. STRESS SENSITIVITY COEFFICIENTS OF FREQUENCY OF HBAR BASED ON (YX*LT*)/35°/90° QUARTZ SUBSTRATE (THICKNESS EQUAL TO 350µM) WITH (YX*L*)/163° LINBO$_3$ LAYER OF 15 µM THICKNESS

Component of stress sensitivity coefficients of frequency (/Pa)					
X	Y	Z	YZ	XZ	XY
$-2.15e^{-12}$	$1.71e^{-11}$	$-2.70e^{-11}$	$-7.80e^{-15}$	$3.52e^{-16}$	$-1.74e^{-11}$

C. HBAR vibration sensitivity computation

Firstly, we compute stress field applied in quartz substrate with COMSOL, as shown in *Fig. 3*. We take into account PCB of FR-4 with fixed boundary all around the PCB, the rectangular alumina which used to decreased stress field into the resonator and only the substrate of the HBAR for this computation. We take into account the cut orientation of the quartz substrate.

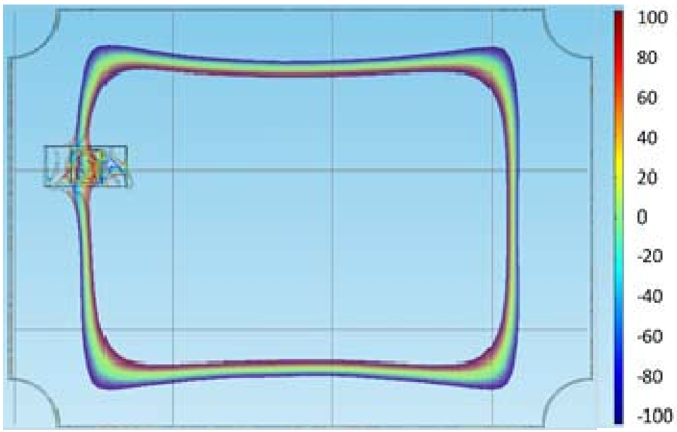

Fig. 3. Computation of stress field with COMSOL, example of the surface stress tensor z component (N/m²).

Due to the assumption of the computation of stress coefficient sensitivity, we assume a homogenous stress in all HBAR. Table II synthetized values of stress field calculate with COMSOL on the active volume of HBAR. The active volume of HBAR corresponds to the volume under the electrodes due to energy confinement at high frequency [11].

TABLE II. STRESS TENSOR ALONG THE THREE COORDINATES OF SPACE FOR SOLICITATION OF 1G

Stress tensor (Pa)	**Component of stress tensor**					
	X	**Y**	**Z**	**YZ**	**XZ**	**XY**
X axis	2.72	0.05	5.50	-0.56	44.59	-2.65
Y axis	-111.6	0.51	143.9	5.21	-581.7	2.29
Z axis	-34.01	0.13	45.3	-3.92	-14.75	0.31

Based on the computed results of stress tensor and of the stress−sensitivity coefficients of frequency, we easily calculate the vibration sensitivity of our oscillator by multiplying the stress tensor with the stress−sensitivity coefficient of frequency. The results are on table III.

TABLE III. VIBRATION SENSIBILITY OF PACKAGED HBAR CONSTITUTED BY (YX*lt*)/35°/90° QUARTZ SUBSTRATE AND (YX*l*)/163° $LiNbO_3$ LAYER TRANSDUCER

X axis	**Y axis**	**Z axis**	**Total**
$-1.08e^{-10}$/g	$-3.68e^{-9}$/g	$1.15e^{-9}$/g	$3.86e^{-9}$/g

III. *HBAR* RESONATOR CHARACTERIZATION

A. *HBAR oscillator*

We used a Quartz/$LiNbO_3$ HBAR resonator to realize an oscillator. A filter is inserted in the oscillator loop to select a specific overtone among the many ones accessible. The oscillator loop is also made with a low noise RF amplifier and the output is extracted by a coupler. *HBAR* oscillator has been built in a package 3×4 cm², as shown in *Fig. 4*. The HBAR resonator was conditioned onto a dedicated PCB and alumina.

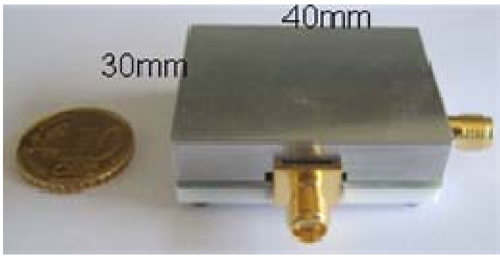

Fig. 4. HBAR oscillator tested

B. *HBAR vibration sensitivity measurement*

Typical frequency shifts in oscillators due to vibration are on the order of 10^{-8} to 10^{-10} per g (acceleration of gravity near the earth's surface) [12]. The acceleration sensitivity of an oscillator was explained in detail by Filler, [13]. Two main equations can help us to determine the vibration sensitivity of our oscillator:

$$\Gamma_{x_i} = 10^{\left(L_f/20\right)} \frac{2\nu}{\nu_0\sqrt{\gamma_{rms}^2/BW}} \tag{5}$$

$$\Gamma = \sqrt{\Gamma_x^2 + \Gamma_y^2 + \Gamma_z^2}.\ x_i = X, Y, Z \tag{6}$$

γ_{rms} is the root-mean-square value of vibration, Γ_{xi} is the component of acceleration sensitivity vector in the i (i=X,Y and Z) direction, ν and ν_0 are respectively the Fourier frequency and the frequency of the oscillator, BW is the bandwidth of vibration and L_f is the phase noise.

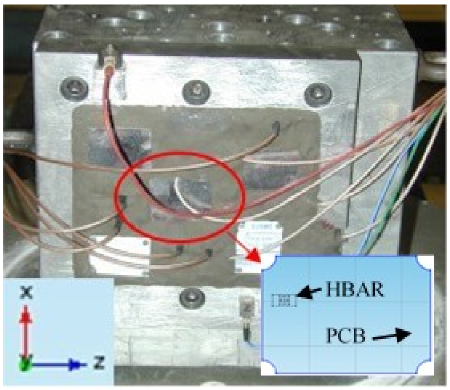

Fig. 5. Set-up for g sensitivity measurement. Rotation of 90° is done to measure along Z axis, and resonators are put on the top of the bench to measure g sensitivity along Y axis.

The measurements of g-sensitivity have been achieved in all space directions on a test bench applying random vibrations in the 10 - 2000 Hz frequency range with 5 and 7 g rms intensity levels respectively. Random vibrations are applied vertically, and the oscillators were rotated in different position to achieve three directions. In *Fig. 5*, the position for X axis is shown.

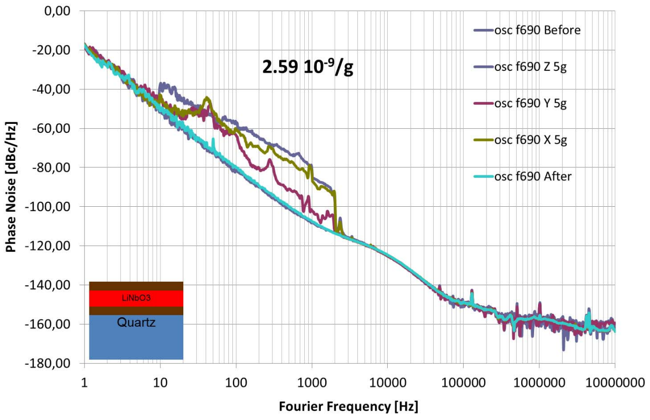

Fig. 6. Phase noise of LiNbO3/Quartz HBAR oscillator before and under vibration test.

The impact of acceleration on the phase noise of the HBAR-stabilized oscillator is illustrated in *Fig. 6* showing the evolution of the phase noise when submitted to the above-mentioned perturbation. LiNbO$_3$/Quartz HBAR oscillators operating at 690 MHz experience a g-sensitivity of 2.59×10^{-9}/g. The g sensitivity along X axis is 4.03×10^{-10}/g, along Y axis is 2.2×10^{-9}/g, and along Z axis is 1.28×10^{-9}/g.

IV. *DISCUSSION*

The ratio between theoretical and experimental vibration sensitivity is 1.5. This result validates our approach to design HBAR integrated with the electronics of the oscillator to minimize the vibration sensitivity of the system. Indeed, some assumptions are done to calculate the stress sensitivity coefficients of frequency of the HBAR. One assumption consists in considering homogenous stresses in the device. It is possible to improve the accuracy of the computation by splitting the substrate into different layers, but the first result shows enough accuracy, and the control of the vibration sensitivity can be done only with the improvement of the stress induced by the packaging on the resonator.

The knowledge of the stress sensitivity coefficients of frequency allows us to work on the static stress induced by the approach of the packaging. Thus, it is possible to minimize some stress tensor components in function of the stress sensitivity coefficients of frequency of the HBAR. In the case of this paper, the HBAR presents negligible stress sensitivity coefficients of frequency for the yz and xz components, but high values for the y, z and xy components. So, some attention needs to be drawn on this stress tensor component for the design of the integration. Moreover, the y component of the stress−sensitivity coefficients of frequency is opposite to the xy component of the stress sensitivity coefficients of frequency. An approach to compensate both stress tensor components can be used to minimize the vibration sensitivity.

V. CONCLUSION

This paper presents the computation of the stress sensitivity coefficients of frequency of high-overtone bulk acoustic resonators. From these stress sensitivity coefficients of frequency, a simple static study of the packaging of the oscillator allows us to compute the vibration sensitivity of the system. The results are compared to experimental results. The theoretical and experimental results show an agreement of 50%.

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