Experimental procedure to design stressed HBAR devices when the third-order elastic constants are not known

Baron Thomas, Bebon Ludovic, Petrini Valérie, Martin Gilles, Dulmet Bernard
Time & Frequency department,
FEMTO-ST, UMR CNRS-UFC-ENSMM-UTBM 6174,
26 Chemin de l'Epitaphe,
25030 Besançon Cedex, France
E-mail: thomas.baron@femto-st.fr

Lesage Jean-Marc
DGA – Information Superiority,
DGA, French MoD,
Bruz, France

***Abstract*— Vibration sensitivity is an important specification for oscillators dedicated to space or airborne systems. For some crystallographic material, some physical constant are not yet measured. So, computation of stress coefficients of frequency is not possible. This paper presents a simple experimentation which allows the determination of the six stress coefficients of frequency for each high-overtone bulk acoustic resonators configuration. The first three coefficient are $^{s}\alpha_{mn}$ are -2.9×10^{-12}/Pa, 4.3×10^{-10}/Pa and 9.4×10^{-11}/Pa. The relative standard deviation can be high due to experimental uncertainty.**

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 vibration sensitivity. Vibration sensitivity can be due to the resonator, the oscillator loop or non-oscillator components like wires, for instance. Commonly, the main source of acceleration sensitivity comes from the resonator. Active compensation can be used to decrease this effect, but such systems are not easily miniaturized.

Past papers at the EFTF conferences have focused on vibration sensitivity of High-overtone Bulk Acoustic Resonators (HBAR). Initial works have focused on the experimental results on HBAR with quartz or sapphire substrates [1] which present few 10^{-11}/G sensitivity. Further investigations focus on the implementation of theoretical aspects on modeling tools. These works were validated by comparison between the results of design and experimentation [2] in the case of quartz material. The agreement is around 50%.

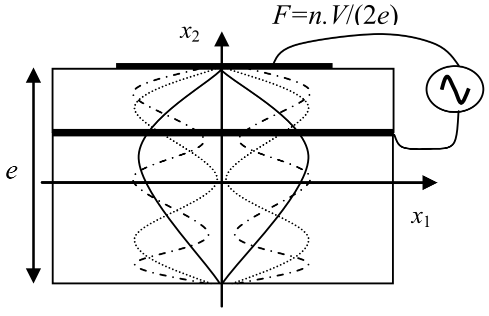
Third-order elastic constants are mandatory requirements to compute stress sensitivity of HBAR. Thereby, most materials are not suitable to design low vibration sensitivity HBAR oscillator or pressure sensor. This work presents a new way to design such components when third-order elastic constants are not known. This approach is based on experimental measurements of stress sensitivity coefficients of HBAR. We use $LiNbO_3$ (YX*l*)/163 piezoelectric layer on $LiTaO_3$ Z-cut substrate as example of this approach.

This paper described experimental approach to estimate the stress sensitivity coefficients of frequency of specific HBARs. Combined with the distinguishing features of HBAR resonator such as *Q.f* product and temperature coefficient of frequency [3], a complete oscillator design optimization can be done thanks to the six stress sensitivity coefficients. Similarly, it is possible to design a pressure sensor although the involved nonlinear elastic constants have not been determined yet.

II. HBAR

A. HBAR principle

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 modes satisfying the electrical and mechanical boundary conditions. For more details, the reader can look at [4].



This work was partly supported by the RAPID project ORAGE under grant #092906659#.

This work was partly supported by the French RENATECH network and its FEMTO-ST technological facility.

This project has been performed in cooperation with the Labex ACTION program (contract ANR-11-LABX-0001-01).

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

978-1-5090-0720-2/16/$31.00 ©2016 IEEE

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

B. HBAR features

For the experimentation, we use HBAR constituted by $LiNbO_3$ (YX*l*)/163 piezoelectric layer on $LiTaO_3$ Z-cut substrate. $LiTaO_3$ material presents low acoustic attenuation, so the *Q.f* product can be high, as shown with the result presented in Fig. 2.

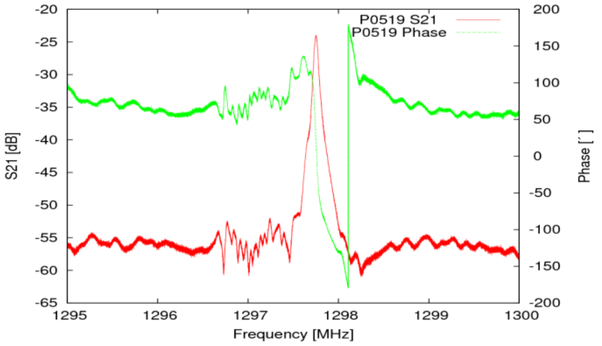


Fig. 2. Electrical response of *HBAR* with $LiNbO_3$ (YXl)/163° as piezoelectric layer and $LiTaO_3$ (YX*l*)/90° as substrate. This overtone exhibits *Q.f* product around 3.7×10^{13} Hz.

Moreover, $LiTaO_3$ Z-cut is a cut orientation exhibiting a near zero frequency drift w.r.t. [5]. A turn-over point is found around 55°C and fifteenth consecutive overtones present the same behavior with the temperature. The figure 3 shows this result.

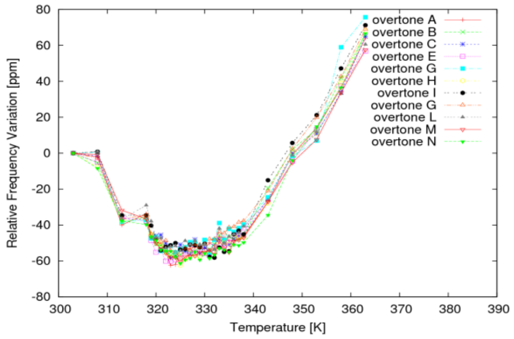


Fig. 3. Relative frequency variation versus temperature of several consecutive overtones of *HBAR* constituted by 150 nm of Aluminum, 1.8 µm of $LiNbO_3$ (YX*l*)/163°, 400 nm of Gold layer and 550 µm of $LiTaO_3$ (YX*l*)/90° substrate.

III. STRESS SENSITIVITY COEFFICIENTS OF FREQUENCY OF HBAR

A. Stress sensitivity coefficients of frequency

According to the following equations (1-3), introduced by Filler in [6], the measurement and the computation of vibration sensitivity of the acoustic resonator inside an oscillator loop is possible. Computation with the knowledge of the 14 non-linear coefficients for *(3m)* crystallographic material allows the determination of vibration sensitivity of the system in all-space directions (2-3). On the contrary, the measurement of different sensitivity in all-space direction (1) combined with the computation of stress tensor $\sigma_{ij,xi}$ is not sufficient to determine the 14 non-linear coefficients.

$$\Gamma_{x_i} = 10^{\left(L_f/20\right)} \frac{2\nu}{\nu_0\sqrt{\gamma_{rms}^2/BW}} \qquad (1)$$

$$\Gamma = \sqrt{\Gamma_X^{\,2} + \Gamma_Y^{\,2} + \Gamma_Z^{\,2}} \quad ,x_i = X,Y,Z \qquad (2)$$

$$\Gamma_{x_i} = {}^S\alpha_{ij} \bullet \sigma_{ij,x_i} \qquad (3)$$

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, ${}^s\alpha_{ij}$ is the stress sensitivity coefficients of HBAR.

B. Experimental principle

From the knowledge of nonlinear elastic constants, it is possible to calculate the HBAR stress sensitivity coefficients of frequency (${}^s\alpha_{mn}$) [2]. With the equation (3) above, the measurement of vibration sensitivity of HBAR oscillators in all-space direction allows to establish three equations. The six unknown coefficients ${}^s\alpha_{mn}$ oblige to determine three other equations from another package configuration.

Four package configurations were realized to determine the six stress sensitivity coefficients of HBAR. The configurations include two PCB configurations with hinges in two axis directions: vertical and horizontal. HBAR is glued on the PCB along vertical or horizontal orientations. Fig. 2 shows the configuration with vertical hinge and horizontal HBAR orientation. To prevent deterioration of acoustic wave inside the HBAR, the HBAR is glued on the alumina with hole. These four different configurations are realized twice to improve the accuracy of the coefficients determination.

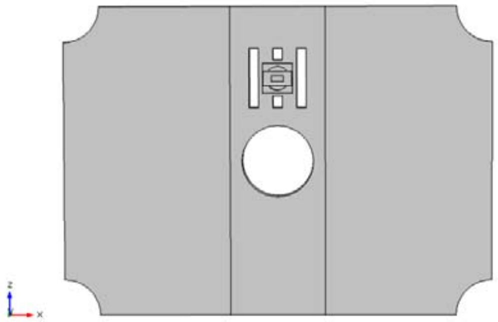


Fig. 4. Schematic view of HBAR of one the PCB one of the PCB of this paper. The orientation of HBAR or the hinges can be rotated of 90°.

The computation of the six stress sensitivity coefficients of frequency (${}^s\alpha_{mn}$) is possible due to the computation of the six stress coefficients in each configuration. The following table shows the six stress coefficients calculated with COMSOL for the configuration of Fig. 2 and for all three orientations. The stress coefficients were calculated in the active volume of the HBAR.

TABLE I. STRESS TENSOR APPLIED ON THE HBAR BASED ON (ZX) LITAO$_3$ SUBSTRATE (THICKNESS EQUAL TO 500μM) WITH (YX*L*)/163° LINBO$_3$ LAYER OF 3 μM THICKNESS WITH 1G IN ALL-SPACE DIRECTION

	X	*Y*	*Z*
σ_x	-57,811	-306,39	-175,4
σ_y	3,8604	29,081	6,0777
σ_z	-96,219	-628,36	-477,2
σ_{xy}	-2,4774	-6,3219	4,3319
σ_{xz}	-40,214	-130,24	-55,234
σ_{yz}	-3,1395	-18,372	-13,871

C. *Experimental measurment*

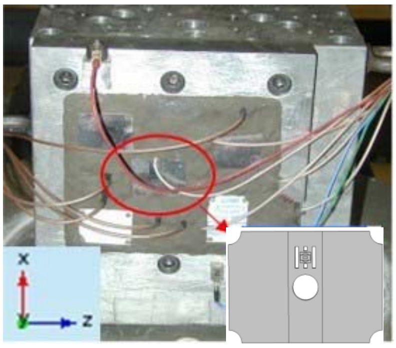


Fig. 5. Set-up for g sensitivity measurement. Rotation of 90° is done to measure along Z axis, and resonators are put on the top of the bench to measure g sensitivity along Y axis.

The measurements of g-sensitivity have been achieved in all space directions on a test bench, shown in figure 5, applying random vibrations in the 10–2000 Hz frequency range with 20 G rms intensity levels respectively. Random vibrations are applied vertically, and the oscillators were rotated in different positions to achieve the three directions.

Even if the configuration is not done to realize low G–sensitivity oscillators, The figure 3 shows the PSD results provided by one oscillator exhibiting a sensitivity of 4.5×10-^{11}/G.

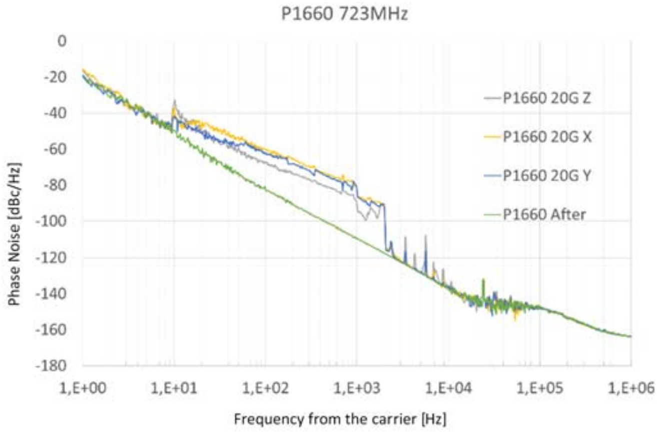


Fig. 6. Experimental phase noise density of an HBAR oscillator under vibration.

D. *Determination of six stress sensitivity coefficient of HBAR*

The four configurations are double, and each configuration is measured for all-space directions. So, the 24 linear equations (3) allow us to make several systems of six equations of six unknown variables. The redundancy of the equations, increase the accuracy of the coefficient estimation. Some mistakes are possible due to the inaccuracy of the stress coefficients, the parasitic vibrations, and the inaccuracy of the HBAR position on the PCB and on the position of oscillators on the test bench.

The six stress sensitivity coefficients of this specific configuration of HBAR have been computed. The following table summarizes the three first *s*tress sensitivity coefficients of frequency of HBAR with an estimation of the relative standard deviation.

TABLE II. STRESS SENSITIVITY COEFFICIENTS OF FREQUENCY OF HBAR BASED ON (ZX) LITAO$_3$ SUBSTRATE (THICKNESS EQUAL TO 500μM) WITH (YX*L*)/163° LINBO$_3$ LAYER OF 3 μM THICKNESS WITH THE RELATIVE STANDARD DEVIATION

	Stress sensitivity coefficients of frequency (/Pa)	Relative standard deviation
$^s\alpha_x$	-2.9×10^{-12}	56.8
$^s\alpha_y$	4.3×10^{-10}	204.1
$^s\alpha_z$	9.4×10^{-11}	47.7

The knowledge of the six stress sensitivity coefficients of frequency allows us to design different components like an optimized low vibration sensitivity oscillator or a pressure sensor. Moreover, the present work can be completed by all future measurements of components sensitive to stress, easily computed, to increase the accuracy of the coefficient.

IV. DISCUSSION

The knowledge of the non-linear coefficients allows the computation of the six stress coefficient sensitivity for all HBAR configurations. In the case of materials with not known non-linear coefficients, the determination of the six stress coefficients have to be done for each HBAR configuration. Moreover, this work allows the computation of different systems using the HBAR. It is possible to design an optimize oscillator presenting a low-G-sensitivity or a HBAR pressure sensor.

A. *Oscillator design optimization procedure*

The goal of this part is to propose a procedure to minimize the vibration sensitivity of HBAR oscillator realize on a PCB. The stress tensor on the PCB is easily computed by finite element software. From the equation (3), it is possible to calculate the effective vibration sensitivity of a virtual HBAR placed on each point of the PCB. The sum of these results time the six stress coefficients give us the optimal position of the HBAR.

The rotation of the HBAR on the PCB can also influence the vibration sensitivity. Fig. 5 shows this evolution; the orientations of 0° and 180° present the best configuration to minimize the vibration sensitivity and the technological drift.

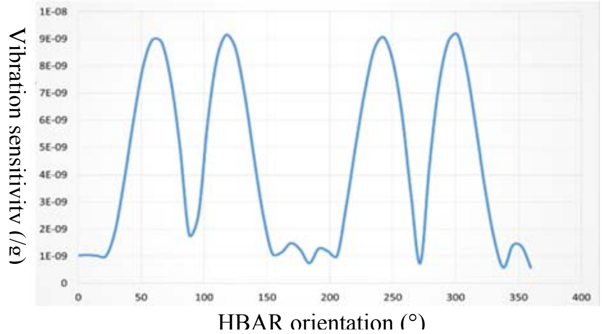


Fig. 7. Vibration sensitivity of HBAR with quartz substrate (/G) in function of its orientation.

Based on the stress sensitivity coefficients of frequency of the HBAR, it is possible to optimize the position of the HBAR in the oscillator to minimize the vibration sensitivity. To improve this sensitivity, it is possible to either pattern the PCB, as was done in the first part of this paper or to use active compensation.

B. HBAR pressure sensor

This part deals with the issue of pressure sensors based on HBAR. Previous works [7,8] presented the principle of HBAR pressure sensors and showed first experimental results. These first pressure sensors had not been designed due to lack of a software tool. The implementation of model allows us such design. So, the goal of this section is to give realistic dimensions of a HBAR pressure sensor based on quartz substrate. The dimension is determined based on the stress sensitivity coefficients of frequency of the HBAR.

The HBAR pressure sensor consists of a membrane with a cavity under the HBAR to confine the acoustic wave. For the specification of the sensor, we impose a maximum pressure of 5 bar and a resolution of 500 Hz at 434 MHz.

The size limitation of the membrane comes from the maximum stress admitted by the material. So, an experimental measurement to determine this maximal stress supported by the $\mathrm{LiTaO_3}$ (ZX) cut material was done, and a value around 260MPa was found. Finally, the micro-fabrication based on bonding/lapping process gives us an acceptable thickness of 300µm for the membrane. A comparison between HBARs based on quartz and HBARs based on LiTaO3 is done. Table III summarizes the results.

TABLE III. RESULTS OF HBAR PRESSURE SENSORS BASED ON (ZX) $\mathrm{LiTaO_3}$ SUBSTRATE OR QUARTZ SUBSTRATE WITH (YXl)/163° $\mathrm{LiNbO_3}$ AS PIEZOELCTRIC LAYER

Substrate of HBAR	*Quartz*	*LiTaO3*
Diameter (mm)	9000	3000
Sensitivity (Hz/Pa)	5.1×10^{-10}	1.5×10^{-9}
Resolution (Pa/Hz)	2.2×10^{3}	7.3×10^{2}

V. CONCLUSION

This paper presents an experimental procedure to determine the stress sensitivity coefficients of frequency of HBARs when the non–linear coefficients of material are not known. The first three coefficients are ${}^{s}\alpha_{mn}$ are -2.9×10^{-12}/Pa, 4.3×10^{-10}/Pa and 9.4×10^{-11}/Pa. From these stress sensitivity coefficients of frequency, a simple static study of the packaging allows us to determine the best position of each HBAR on the same PCB to minimize the vibration sensitivity.

REFERENCES

[1] T. Baron, G. Martin, F. Bassignot, N. Chrétien, A. Reinhardt, P. Lassagne, J. Lesage, D. Rabus, L. Chommeloux, and S. Ballandras, "Low-G Sensitivity of HBAR Oscillator," *28th Eur. Freq. Time Forum*, pp. 431–434, 2014.

[2] B. Thomas, P. Valerie, M. Gilles, C. Guillaume, C. Alexandre, D. Bernard, L. Jean-marc, L. Thierry, and B. Sylvain, "Stress sensitivity coefficients of HBAR," *Freq. Control Symp. Eur. Freq. Time Forum (FCS), 2015 Jt. Conf. IEEE Int.*, pp. 214–217, 2015.

[3] B. Thomas, M. Gilles, C. Nicolas, P. Valérie, C. Guillaume, H. Fabien, B. Florent, R. David, C. Luc, R. Alexandre, L. Pierre-patrick, L. Jean-Marc, and B. Sylvain, "High-Q and low TCF HBAR based on LiTaO3 substrate," *Freq. Control Symp.*, pp. 1–4, 2014.

[4] T. Baron, E. Lebrasseur, F. Bassignot, G. Martin, V. Pétrini, and S. Ballandras, *Chapter 13 High-Overtone Bulk Acoustic Resonator. Modeling And Measurement Methods For Acoustic Waves And For Acoustic Microdevices*. 2013.

[5] S. V. Krishnaswamy, B. R. McAvoy, J. H. L. Salvo, and R. A. Moore, "Temperature Frequency Characteristics of Selected high Q acoustic Materials," *Ultrason. Symp.*, pp. 421–423, 1984.

[6] R. L. Filler, "The acceleration sensitivity of quartz crystal oscillators: a review.," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 35, pp. 297–305, 1988.

[7] T. Baron, J. Masson, J. P. Romand, L. Catherinot, M. Chatras, and S. Ballandras, "BAW pressure sensor on LiNbO membrane lapping .," *EFTF*, no. 1, 2010.

[8] T. Baron, D. Gachon, J. P. Romand, S. Alzuaga, S. Ballandras, J. Masson, L. Catherinot, and L. Chatras, "A pressure Sensor based on a HBAR micromachined structure," *IFCS*, 2010.