Sensitivity of SAW devices to Temperature and Mechanical Stresses, application to Physical Sensors

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Abstract

Applications of SAW devices to physical sensors have already reached industrial maturity in the field of passive physical sensors (e.g. wireless torque sensors) the last development being related to the capability of SAW devices to offer remote readout by a radio-frequency link.

A review of existing simulation methods is used to derive the sensitivity of SAW devices to temperature or mechanical stress is presented. The emphasis is put on perturbation methods based on Tiersten and Sinha theory. Applications including current commercially available SAW physical sensors will be discussed.

Introduction

Starting from the very high performance of oscillators based on Bulk Acoustic Wave (BAW) and Surface Acoustic Wave devices (SAW), the idea to apply an external physical parameter to the piezoelectric resonator was investigated first in order to minimise environment effects on high stability clocks ; quartz and now some new piezoelectric materials offer naturally compensated crystalline orientations for which the sensitivity of the device to temperature effects is minimised. Stress sensitivity was also addressed to minimise the sensitivity of high performance quartz oscillators to accelerations in airborne applications. Table 1 shows the present performance of BAW and SAW oscillators as a results of minimising the effects of temperature and mechanical stresses.

f_0	short term stability	day drift	g-sensitivity
BAW 5-10 MHz	$\frac{\Delta f}{f} < 10^{-13}$	10^{-10}/d	10^{-10}/g
SAW $\simeq$ 500 MHz	$\frac{\Delta f}{f} < 10^{-11}$	10^{-9}/d	10^{-9}/g

Table 1: State of the art BAW and SAW oscillators

It should be noted that such a high level of performance is achieved only when the crystal is perfectly mounted and isolated from the environment and not as a sensing element. However the very high resolution potentially achievable with BAW or SAW-based sensors for which the output parameter is a change in resonant frequency are easily understood.

Modeling temperature effects for bulk and surface wave devices

The intuitive approach for modeling temperature sensitivity in BAW and SAW devices is explained on fig.1

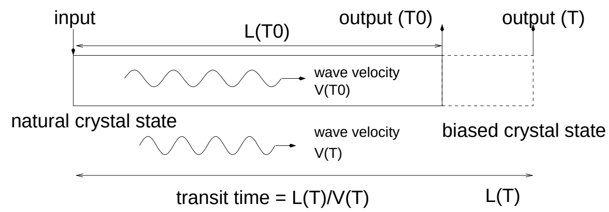

Figure 1: An intuitive approach for temperature effects

If $\tau = \dfrac{L(T)}{V(T)}$ denotes the *transit time* between input and output for wave propagation, velocity V, propagation length L, the *Temperature Coefficient of transit Time* (TCT) is defined as: $TCT = \dfrac{\tau(T) - \tau(T_0)}{\tau(T)}$. If the device is resonant and included in the electronic closed loop of an oscillator, it can be shown that the contribution of environmental effects on the resonator to the oscillator frequency, the *Temperature Coefficient of Frequency*, TCF, is given by : $TCF = -TCT$. The usual approach to predict these effects and derive temperature-compensated orientations of the crystal is based on the variation of effective elastic constants vs. temperature (hence : V(T)) combined with thermal expansion effects (L(T). This classical approach [1] was very successful to find the so-called AT-cuts for BAWs in quartz and the ST-cut for SAWs.

A polynomial expansion for temperature effects

Usually the temperature dependence of frequency in a BAW or SAW device is expressed under a polynomial expansion to the 3-rd order vs. temperature shifts, denoted now as θ to avoid possible confusion with stress effects:

$$\frac{\Delta f}{f_0} = {}^{\theta}\!\alpha(\theta - \theta_0) + {}^{\theta}\!\alpha^{(2)}(\theta - \theta_0)^2 + {}^{\theta}\!\alpha^{(3)}(\theta - \theta_0)^3 \quad (1)$$

For AT cuts of BAWs in quartz, both coefficients ${}^{\theta}\!\alpha$ and ${}^{\theta}\!\alpha^{(2)}$ vanish (cubic temperature dependence), whereas for SAWs on quartz, the second-order coefficient is always non zero. It is possible however to find for SAWs on quartz a particular cut for which both ${}^{\theta}\!\alpha^{(2)}$ and ${}^{\theta}\!\alpha^{(3)}$ vanish, yielding an extremely linear *LST-cut quartz SAW temperature sensor* [2]. The residual parabolic temperature effect for the classical ST cut of quartz is ${}^{\theta}\!\alpha^{(2)} = -34 \times 10^{-9}/K^2$.

A better approach, a perturbation method by Tiersten and Sinha

There is a fundamental objection to the use of effective elastic constants varying with temperature. Although the approach was successful to derive temperature-compensated quartz cuts, the models fails to accurately represent the crystal behaviour vs. its anisotropy because the effective coefficients are not *true tensors* and do intermix some non linear higher-order effects. A more rigorous approach proposed by Tiersten and Sinha [3] based on a perturbation method and a better definition of temperature derivatives of fundamental elastic constants has been developed and applied to find temperature effects to the first order in a formalism using Lagrangian coordinates of the crystal in its natural state. This approach has been extended by Dulmet *et al.* [4] to precisely re-derive temperature effects for BAWs ans SAWs up to higher orders.

Stress sensitivity

Stress sensitivity of BAW and SAW devices can be defined using a similar perturbation method [5]. In eq.(2), T_{ij} is the stress tensor, and the stress sensitivity coefficients are a tensor ${}^{S}\alpha_{ij}$ and the contribution of stress components is additive:

$$\frac{\Delta f}{f_0} = \sum_{i,j} {}^{S}\alpha_{ij}\, T_{ij} \qquad (2)$$

$${}^{S}\alpha_{ln} = \sum_{i,k,j,m} H_{ikjmln}\, U_{ikjm} \qquad (3)$$

where f_0 refers to the Lagrangian coordinates and H_{ikjmln} is a a mixture of linear elastic constants, non linear elastic constants (stiffnesses), linear elastic compliances. U_{ikjm} is a combination of acoustic mode parameters in the natural state. Sensitivity coefficients for quartz are tabulated in [5].

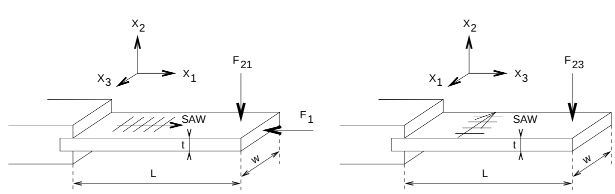

Figure 2: Force-frequency effect on a SAW structure

Stress sensitivity of SAW devices

The model was applied to find SAW quartz cuts both insensitive to temperature and planar isotropic stress effects [5]. It can be applied to find the sensitivity of a SAW structure to any combination of stresses. For example, figure 2 gives the magnitude of the force-frequency effect for a cantilever built on a ST cut of quartz. Table 2 shows the experimental values of the force-frequency effect in a SAW cantilever structure [2], ST cut, L=20 mm, w = 10 mm, t=0.5 mm, f= 100 MHz

SF_{21}	SF_{23}/SF_{21}	SF_1/SF_{21}
$5.3 \times 10^5 Hz/N$	2.4×10^{-6}	5.8×10^{-3}

Table 2: Stress sensitivity, ST quartz, SAW cantilever

Application to wireless sensors

Many SAW sensors were developed in the 1980's but did not find their way to the market except SAW gas sensors. A renewed interest in physical SAW sensors is based on their ability of wireless and power-less operation as a radio-frequency coded reflector (fig.3). Examples of such devices are : pressure sensors for monitoring tyre pressure in rotation, torque sensors for non-contact probing of stresses in rotating shafts [6].

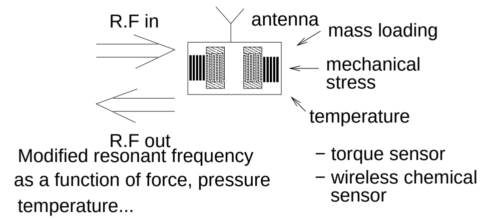

Figure 3: SAW wireless SAW sensors

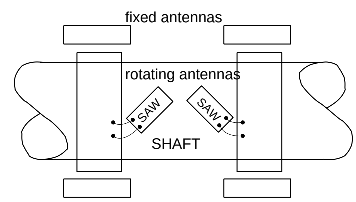

Figure 4: A wireless SAW torque sensor

Conclusion

Perturbation methods allow a precise modeling of SAW sensitivity for physical sensors, industrial applications exist now, new piezoelectric materials exist but their non linear elastic constants are not known. Also, there will always be a competition with BAW devices, for example, Who would have expected to see thin film BAW filters at 2 GHz for mobile phones ?

References

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