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Review Paper

Quartz Resonators vs Their Environment: Time Base or Sensor?

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This work discusses the effects of temperature, force, and acceleration on the frequency of quartz thickness shear mode resonators. Historically, workers in the frequency control industry have tried to reduce these effects. Some of the physical principles will be discussed. Turning the problem around, sensitivity to these effects can be maximized to develop sensors for temperature and pressure. Advantages of such sensors include inherently digital format, high resolution, high accuracy, and long-term stability. This work reviews the physical principles involved in the operation of some devices used down-hole in the oil and gas service industry.

KEYWORDS: quartz, thickness-shear, resonators, frequency-control, sensors

1. Introduction

Quartz thickness shear mode resonators (TSMR) have been used for decades in oscillators as frequency sources. Modern requirements for stability in mobile phone base stations range from 50 to 0.1 ppb/day. Oven controlled oscillators with precision quartz resonators can now meet this challenge. This work reviews some of the temperature, force, and acceleration effects that have been minimized by researchers to attain these stringent requirements.

Researchers have also found ways to selectively maximize the environmental effects to make sensors. EerNisse, et al.,[1] reviewed quartz bulk resonator sensors in 1988. That paper reviewed several types of bulk acoustic wave (BAW) quartz resonators, such as thickness-shear, torsional, and flexure, for sensing physical parameters. Benes, et al,[2] in 1995, reviewed quartz resonator sensors, including an update of much of the same work, but extended the discussion to surface acoustic wave (SAW) devices. Recently, EerNisse and Wiggins [3] reviewed quartz thickness shear resonator sensors for temperature and pressure.

The purpose of this review is to emphasize that studies of phenomena affecting the frequency of thickness shear resonators can minimize effects for frequency control applications or maximize effects for sensor applications. This work highlights two of the most commercially successful families of TSMR sensors: pressure and temperature.

2. Mode Shape of Thickness Shear Mode Resonator TSMR

The shapes of thickness shear fundamental and overtone vibrational modes are discussed in detail elsewhere[4]. Briefly, a TSMR consists of a plate (often circular) of crystalline quartz with thin-film metal electrodes deposited on the faces. The inverse piezoelectric effect is used to produce vibration in response to alternating voltages. The dimensions, density, and stiffness of the quartz resonator determine the resonant frequency of vibration. By careful control of the thickness contour of the resonator (typically a convex contour on one or both faces), the desired vibration is concentrated in the center of the disc. This "energy trapping" makes it possible to support the resonator without damping the vibration.

The effects of temperature on the frequency of vibration for different crystallographic orientations of quartz are well known. It is possible to select a crystallographic orientation that has a zero slope (turnover) at a given temperature. Placement of a TSMR into an oven constitutes an oven-controlled crystal oscillator, which offers stability, low power, and frequency output essential for frequency control applications.

There are effects from mounting the TSMR that influence the temperature behavior. Typically, the TSMR is mounted to the posts of a metal header using metal clips and conducting adhesive. Figure 1 shows a Finite Element Analysis model of a TSMR in a four-point mount subjected to a temperature change. The deflections in Fig. 1 have been numerically amplified for illustrative purposes. Note in Fig. 1 that the difference in thermal expansion between the header and the quartz causes temperature-dependent diametric forces. Diametric forces cause frequency shift[5,6,7]. Figure 2 shows the force-frequency coefficient for diametric force acting on a resonator disc of diameter d and thickness t. Both the AT-cut and SC-cut are shown. The SC-cut is compensated for the effects of a four-point mount because of the symmetry of the force-frequency coefficient seen in Fig. 2. The AT-cut does not have this symmetry and only a two-point mount can be used to minimize this effect. Temperature changes the force-frequency coefficient [8,9] a fact that must be taken into account when choosing the mounting orientation for a particular oven temperature.

These effects can be minimized by using soft metal clips for mounting the crystals, which allow differences in thermal expansion without significant stress buildup in the TSMR. However, softness of the clips is bounded by the requirement to hold the crystal safely in shock and vibration environments.

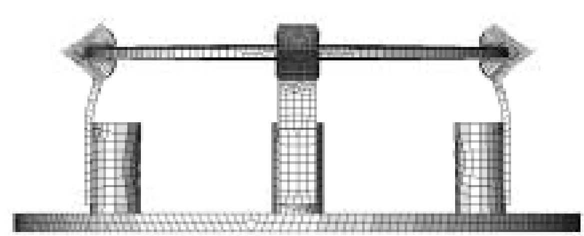

Fig. 1. Finite Element Model showing the deformations caused by differences in thermal expansion between the quartz blank and the mounting structure.

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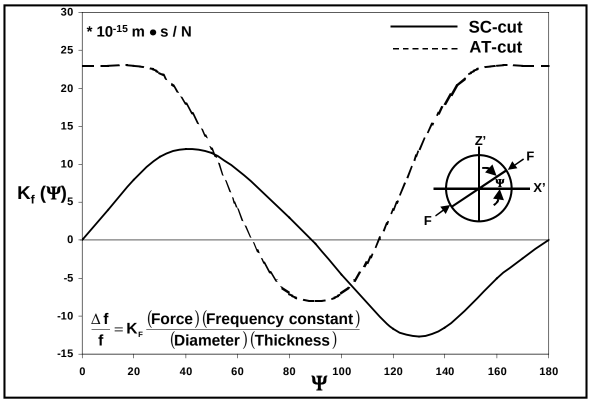

Fig. 2. Force frequency coefficient for the AT-cut and SC-cut.

Acceleration is a body force. As such, it does not inherently alter the frequency of the TSMR. However, since the TSMR must be mounted, there are stresses arising from the interaction of the TSMR with the mounting structure. Figure 3 shows the distortion, numerically amplified for illustrative purposes, for a sideways acceleration of a four-point mounted TSMR. Figure 4 shows the distortion for an acceleration normal to the TSMR, again, numerically amplified for illustrative purposes. The stresses from these accelerations are difficult to reduce in practice. Stresses cause a frequency shift through nonlinear elastic effects. Finite Element Analysis provides a design tool to minimize the effects[10]. However, theoretical modeling only covers the exact geometry modeled. Figure 5 shows one simple problem that occurs in processing: The operator has used less adhesive on one clip. The net result is a loss of symmetry that creates a stress pattern shifted to one side. When this occurs, the effect of acceleration changes and modeling assumptions of a symmetric situation do not apply. It is not practical to model all the possibilities of processing and structural variations. Typically, the acceleration sensitivity of the frequency of a TSMR is represented by the magnitude of the gamma vector in ppb/g, where g is the acceleration of gravity. The gamma vector of commercially available TSMR's is typically 1 ppb/g. With careful design and processing controls, gamma vectors can be reduced to around 0.4 ppb/g.

An example of the problem of acceleration is increased noise floor of an oscillator output. One modern requirement for frequency stability in telecommunications ranges from 0.1 to 50 ppb/day. A gamma vector of 1 ppb/g can cause problems if a background vibration as low as 0.1 g is present. This level of vibration can be present in a variety of environments. Besides the ambient vibration level, one has to be aware of resonant modes in the circuit boards and mechanical support structures of the equipment. A resonant mode can amplify an apparently negligible vibration level to troublesome levels.

3. Temperature Sensors

Attempts to find TSMR cuts (crystallographic orientations) with minimal temperature sensitivity for frequency control applications revealed cuts with large temperature sensitivities, which were recognized in the 1960s as useful for temperature sensing. Wade and Slutsky [11] determined that a TSMR temperature sensor would provide good resolution and low

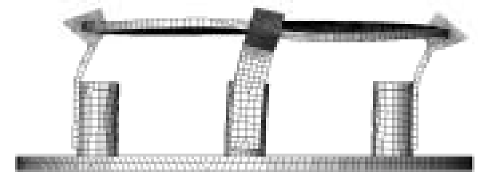

Fig.3. Finite Element Model showing the deformations caused by acceleration in the plane of the quartz blank.

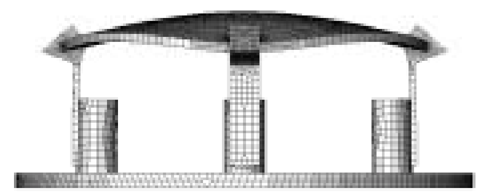

Fig. 4. Finite Element Model showing the deformations caused by acceleration normal to the plane of the quartz blank.

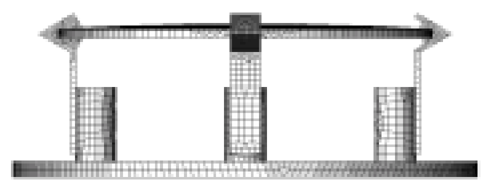

Fig.5. Finite Element Model of a typical reason why perfect mounting symmetry is difficult to attain in production.

power dissipation (thermometer self-heating). This sensor demonstrated resolution of 0.0001C, using direct frequency measurement with a 10 second gate time. Smith and Spencer [12] also studied a temperature sensor. They claimed $4x10^{-4}$°C resolution with a crystal sensitivity of 80 ppm/°C. Neither of these developments led to a commercial product.

Hammond, et. al, [13, 14] at Hewlett Packard found the substantially-linear LC cut. Linearity from 0 to 200°C was 0.002% ($9.2x10^{-3}$°C). They demonstrated stability of 0.01°C with repeated thermal cycling. (The Benes review [15] provides a good summary of the HP development.) The HP thermometer was commercial from the late 60s to the mid 90's. It occupied a small niche in the overall temperature sensor market. It provided a high resolution digital output, showed good stability, and was easy to use (including the HPIB version of IEEE-488 interface). Eventually, the commercial demise of the HP Thermometer was not due to improvements in the resistive sensors, but because of other advances in electronics. Cheap digital circuits enabled linearized, high resolution digital outputs from resistive sensors with acceptable stability and faster thermal response, all at low cost.

4. Pressure Sensors

When a resonator disc is squeezed uniformly around the perimeter, frequency changes[16]. Karrer and Leach [17] and Hammond and Benjaminson [18] at Hewlett Packard, HP, used this effect with the geometry shown in Fig. 6a to develop a pressure sensor. Their design incorporated an integral shell to move the joint far enough away from the resonator to minimize effects of joint instability. The structure is closed with two end caps as seen in Fig. 6a. The joining of the three parts is done with devitrifying glass. Electrical contacts to the electrodes on the resonator disc are made via metal tabs that pass through the glass joints. As pressure outside the structure compresses the cylindrical shell, a uniform radial stress 2 to 3 times the applied pressure occurs in the resonator disc.

This HP device uses a BT-cut resonator, which exhibits a scale factor of frequency vs. pressure relatively independent of temperature. This was an important feature because the data processing electronics of that period lacked the microprocessor power to correct for this effect. Static temperature effects on the frequency are compensated by mixing the output signal of the pressure oscillator with a BT-cut resonator oscillator matched in terms of static frequency vs. temperature. The resulting system had no independent temperature measurement.

In the early 1990's, Quartzdyne, Inc. recognized the need for a quartz resonator pressure sensor for oil and gas exploration and production that was both cheaper to manufacture and smaller in size to speed up response to thermal transient conditions (see Ward and Wiggins[19]. Microprocessors were readily available by this timeframe, so an independent temperature measurement could be used for temperature compensation. EerNisse and Ward[20] chose a simpler geometry to reduce manufacturing costs.

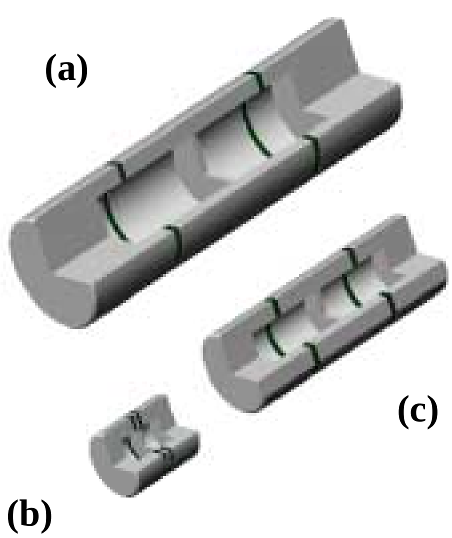

Fig. 6. Structures where external hydrostatic pressure applies planar stress patterns in a TSMR disc via a cylindrical shell. (a) Hewlett Packard device. (b) Quartzdyne device. (c) Halliburton device.

As seen in Fig. 6b, the geometry is simply a resonator disc with end caps attached to both major surfaces. Fabrication techniques are similar to the HP device. The cost of manufacturing dropped dramatically with only a small sacrifice in long-term drift performance. The device uses an AT-cut resonator[21]. The AT-cut can maintain a high Q with a relatively small diameter to thickness ratio, so the size of this device is only 1.46 cm outside diameter. The smaller size improves the response time to transient pressure and temperature situations and allows use of bellows to isolate the pressure sensor from the corrosive gases and liquids in oil and gas wells.

Temperature compensation is accomplished with a TSMR temperature sensor. In fact, the Quartzdyne Pressure Transducer, as described by Ward and Wiggins[22], specifies three TSMR crystals: a pressure sensor in the pressure fluid, accompanied by temperature and reference crystals not in the pressure fluid. The temperature and reference crystals are packaged in typical TO-5 cans, which are thermally coupled to the pressure crystal by the metalwork of the assembly. Preferred orientations are AT- or BT-cut for pressure, AC- or BC-cut for temperature sensing, and SC-cut for reference

A structure used by Halliburton in oil and gas exploration and production today is shown in Fig. 6c. Flats are added to break up the symmetry of the shell surrounding the resonator disc. The structure is closed with two end caps as seen in Fig. 6c. Fabrication techniques are similar to the HP device. The result of applying pressure to this structure is a non-uniform stress in the resonator disc. The major stress in the resonator is along the flat axis where the walls of the shell are thinnest. The minor stress (still compressive) is orthogonal to the flat axis where the walls of the shell are thickest. The net result is an additional degree of freedom by choosing the crystallographic orientation of the flat axis.

The parameter chosen for optimization was the temperature dependence of scale factor. The effect is defined as the fractional change in scale factor with temperature. This parameter is as large as 1,000 ppm/ºC for the AT-cut with uniform stress[23]. This parameter was intentionally minimized in the uniform stress sensors of HP by using the BT-cut device, as mentioned above. In the present case, the ratio of stress along the flat axis to stress orthogonal to the flat axis can be increased by increasing the flat depth. The fractional change in scale factor with temperature could be reduced to 250 ppm/ºC[24]. Temperature compensation for this sensor is accomplished with a separate resonator for temperature measurement.

Another choice for a stress pattern is uniaxial. This stress pattern is generated in a sensor used extensively in oil and gas exploration and production by Schlumberger. The structure, proposed by Besson, et al.,[25] is shown in Fig. 7. The resonator plate is rectangular and is contoured for energy trapping. The resonator plate is formed integral to, and suspended across a diameter of a cylindrical shell[26,27,28], but the normal of the plate is orthogonal to the axis of the cylinder. The shell is closed with endcaps as seen in Fig. 7. Fabrication techniques are similar to the HP device. Temperature compensation is accomplished by operating the TSMR in two thickness shear modes simultaneously. One mode is primarily sensitive to pressure, the other temperature. The use of two modes is modeled theoretically by Sinha[29].

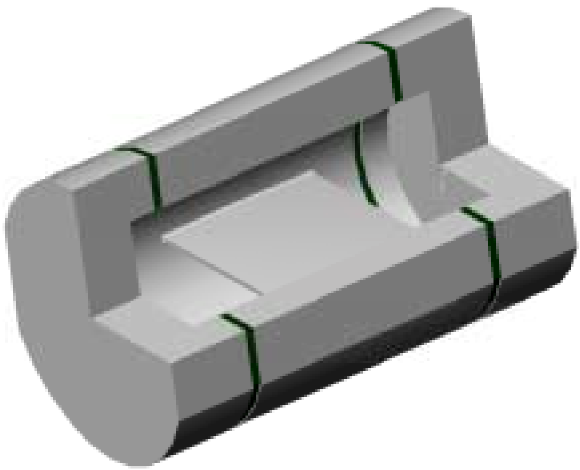

Fig. 7. Structure used by Schlumberger for unaxial stress and dual-mode operation.

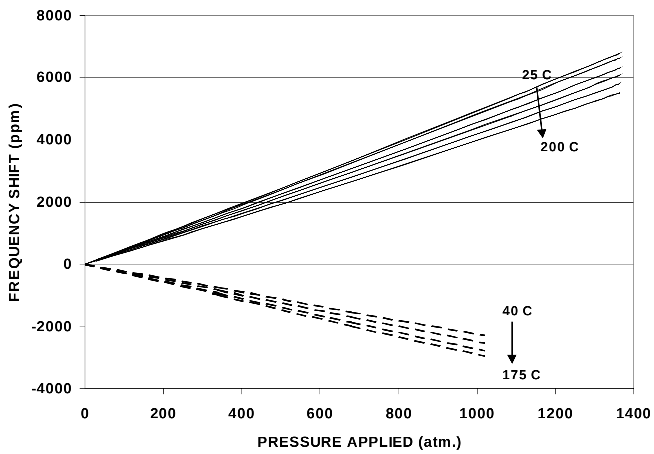

Fig. 8. Frequency vs pressure at various temperatures for the Quartzdyne device (solid lines) and published data for the Schlumberger device (dashed lines).

Examples of frequency shifts with pressure are shown in Fig. 8. Note that the slope changes with temperature for both sensor concepts shown, as mentioned previously. Figure 9 shows representative temperature behavior of the frequency for different pressures for the Quartzdyne Pressure Transducer. The curves have been shifted for viewing purposes. Temperature compensation is accomplished by monitoring the frequencies of the temperature sensing crystal and the pressure sensing crystal at a variety of temperatures and pressures. A least-squared fit of polynomials (typically 3rd or 4th order) in temperature and pressure are used to calculate calibration coefficients. Figure 10 shows the residual from a typical calibration run at Quartzdyne. Note that the performance is better than 0.01 % of full scale, even for a full scale pressure of 1,700 atm (25,000 psi) and a temperature maximum of 200° C.

These pressure sensors are used in several stages of the oil and gas service industry. For instance, measurement while drilling allows adjustment of the drilling mud pressure-head to avoid injection of drilling mud into the formation (underbalanced drilling). Open-hole logging, before the hole is cased, allows pressure transient measurements of selected portions of the bore hole to ascertain permeability of the formation. Memory gauges with battery packs are placed at the bottom of the producing zone

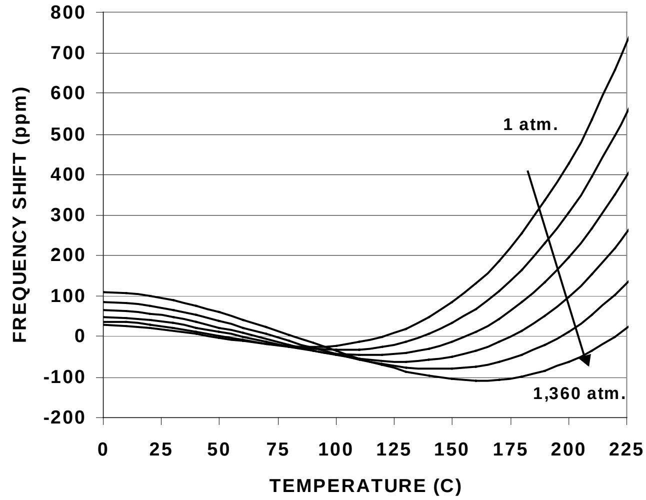

Fig. 9. Frequency vs temperature at various pressures for the Quartzdyne device (curves displaced for viewing purposes).

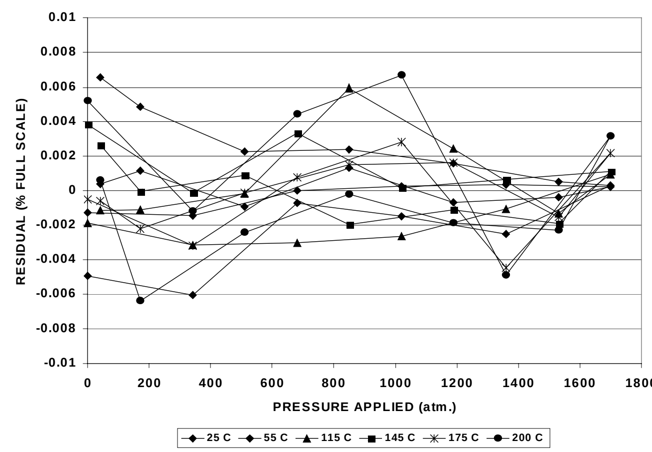

Fig. 10. Typical calibration residuals for the Quartzdyne device.

to accumulate pressure vs. time data while a well is producing. Finally, permanent installation of a pressure transducer in the annulus between the production tubing and the casing with a port into the production tubing allows continuous monitoring. These latter two applications provide pressure vs. time data that can be analyzed to determine both formation permeability and total oil or gas estimates.

5. Summary

This review covered the use of TSMR as frequency control devices and as sensors for temperature and pressure. Some of the physical principles affecting the frequency of a TSMR were discussed. Workers in the frequency control field have had some success minimizing the effects of temperature and acceleration. Oven-controlled crystal oscillators now satisfy stability requirements of modern telecommunications.

Other workers have maximized the effects for sensor applications. Stand-alone temperature sensors have had mixed commercial success even though they exhibit high resolution and accuracy.

Pressure sensors have been highly successful in oil and gas exploration and production because of their high resolution and accuracy and because of their ability to withstand the high pressures and temperatures in oil and gas wells. Temperature compensation is accomplished by either a separate temperature sensing TSMR or by dual-mode operation.

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