Dual-mode Oscillators for Clocks and Sensors

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Abstract - Frequency can be measured with far higher accuracy than any other quantity. Dual mode excitation of resonators allows the highly accurate measurement of, and compensation for, the effects of temperature, pressure, etc., by means of frequency measurements alone. In dual mode excitation, the two excited modes occupy the same volume of quartz, thereby eliminating gradients between the resonator and sensor. This paper reviews the dual-mode technique and its applications in oscillators, clocks and sensors.

INTRODUCTION

The interfering effects of environmental changes have been a perennial problem in frequency, time and sensor measurements. For example, when an oscillator's temperature changes, or when a quartz crystal pressure sensor is lowered into an oil well, the effects of temperature changes invariably interfere with the accuracy of measurements. Elaborate temperature control or compensation techniques are often required to achieve sufficient accuracy.

Some of the interfering effects can be greatly reduced by utilizing dual mode excitation of the resonator. For example, in one microbalance technique, the simultaneous excitation of two frequencies, the fundamental mode and third overtone frequencies of an SC-cut resonator, can yield two equations with two unknowns. This allows the separation of mass change effects from temperature change effects.

Large numbers of temperature compensated crystal oscillators (TCXO) and oven controlled crystal oscillators (OCXO) have been manufactured. In such oscillators, temperature is sensed by means of one or more thermistors (or other temperature sensitive components) placed close to the resonator.

Temperature sensors external to the resonator result in inaccuracies due to thermal lag (thermal path differences, and unequal crystal and thermistor thermal time constants), thermal gradients across the crystal and between the crystal and thermistor (due to thermistor location and self-heating), and thermistor instability (e.g., thermistor aging and hysteresis).

Attempts to improve the accuracy of thermometry in oscillators have included the use of a second, "quartz thermometer" crystal [1-5]. The thermal coupling between the temperature compensated crystal and temperature sensing crystal can be improved by placing the two in the same enclosure [1]. However, dual mode excitation can provide superior sensing because the two modes occupy the same volume of quartz, and frequency can be measured with far higher accuracy than any other parameter. The "self-temperature sensing" allows highly accurate compensation over wide temperature ranges.

DUAL MODE RESONATORS AND OSCILLATORS

Modes of motion & doubly rotated cuts

Three thickness modes of motion can be excited in a crystal plate: the "a-mode," "b-mode," and "c-mode" [6,7]. Odd overtones of these modes, as well as spurious modes, may also be excited. Figure 1 illustrates several of the thickness modes for an SC-cut quartz resonator [6]. The normalized frequency of each mode is referenced to the frequency of the fundamental c-mode.

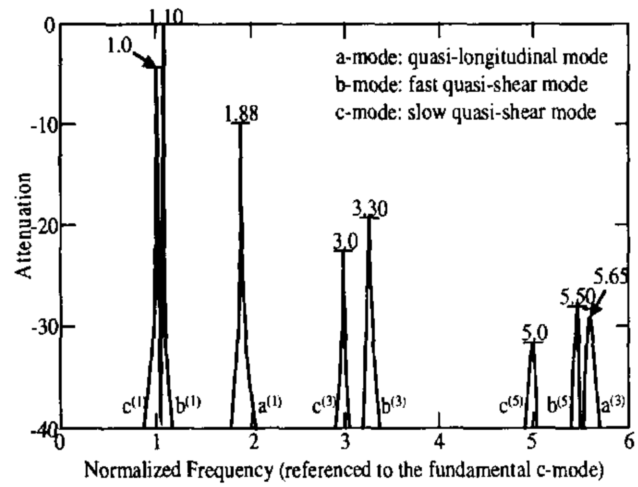


Figure 1 - Mode spectrograph of an SC-cut

In nearly all oscillators, the sustaining circuitry is designed to assure oscillation at a single desired mode only and to prevent the possibility of operation at other modes that may have a lower equivalent series resistance. In oscillators designed for overtone mode of operation of the resonator, for example, fundamental mode suppression circuitry is often included because the resistance of the fundamental mode is often lower than the resistance of the desired overtone mode.

In principle, a single crystal may be excited simultaneously at multiple modes of vibration, without the modes interfering with each other. Because each mode has a different frequency vs. temperature, as well as a different set of other characteristics, the simultaneous excitation of N frequencies can yield N equations with N unknowns, thereby allowing simultaneous determination of a variety of parameters. In practice, only two simultaneous modes of excitation have been employed so far.

Multiple modes can be excited simultaneously by means of multiple oscillator circuits sharing a common crystal. A single gain loop may also excite multiple modes, however, that trades off fewer parts for the ability to optimize the oscillation characteristics of the modes (such as the drive level) [8-25].

Resonator designs aimed at controlling the relative resistances of the b and c-modes, by means fundamental mode resonator designs [12], lateral field excitation [13], rectangular plate geometry [14] and excitation by means of cross-connected half-electrodes [15], have been explored.

Oscillator Compensation Applications

Temperature compensated crystal oscillators

"Dual mode" operation of an SC-cut resonator on one c-mode and one b-mode has been used for the temperature compensation of oscillators [8-11]. In this method, the b-mode frequency, or the difference frequency between the b-mode and c-mode frequencies, is a "thermometer" frequency that is a measure of the internal temperature of the resonator, and the c-mode is a frequency that has a relatively small temperature sensitivity. Figure 2 illustrates the b-mode and c-mode frequency vs. temperature (f vs. T) characteristics of an SC-cut resonator [8].

The b-mode frequency is utilized by a compensation circuit as a thermometer frequency. The temperature induced frequency changes of the c-mode frequency were compensated to 10^{-8} in a slowly varying (< 3°C per minute) temperature environment, and to 10^{-7} in a rapidly changing environment (15°C per minute) [8,10].

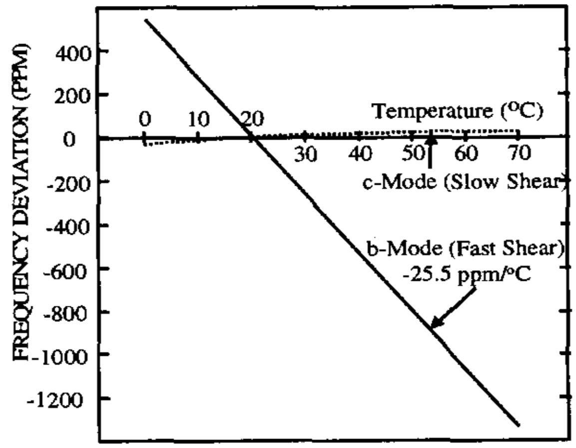


Figure 2 - SC-cut f vs. T for b-mode and c-mode

This method's limitations are due primarily to the b-mode's sensitivity to thermal transients, and to the b-mode's greater susceptibility to activity dips than the c-mode's. These limitations were overcome by dual c-mode excitation of an SC-cut resonator. The fundamental mode and third overtone frequencies are excited simultaneously, and the beat frequency, f_β, between three times the fundamental mode frequency (f_{c1}) and the third overtone frequency (f_{c3}) is used as a precise measure of the internal temperature of the resonator [20,21,29-37]. Figures 3 and 4 illustrate the f vs. T characteristics of the fundamental mode, third overtone, and the beat frequency. Figure 5 illustrates how the beat frequency is generated. A major advantage of the dual c-mode technique is illustrated in Figure 6. During a rapid (2K/minute) temperature cycle from –50°C to +80°C to –50°C, the f vs. T using an external temperature sensor is compared with the f vs. f_β. The f vs. T shows a large hysteresis due to the temperature gradient between the sensor and the resonator. The f vs. f_β curves show no hysteresis (on the scale shown).

The dual-c-mode method has been utilized for the microcomputer compensated crystal oscillator (MCXO) [20,21,29-36]. The method makes use of the fact that the normalized f vs. T of the fundamental mode is different from that of the third overtone, and that the difference is due almost entirely to the first order *temperature coefficients*. The beat frequency f_β is, therefore, a nearly linear function of temperature.

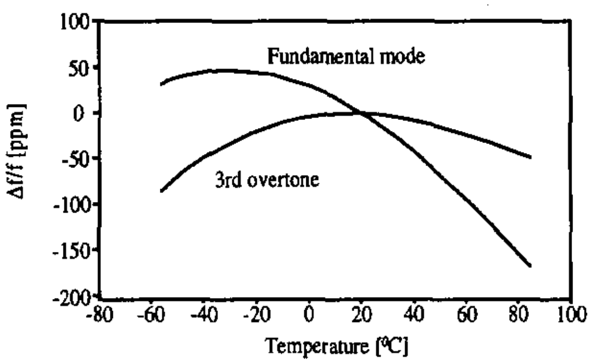


Figure 3 - SC-cut resonator's fundamental mode and 3rd overtone f vs. T

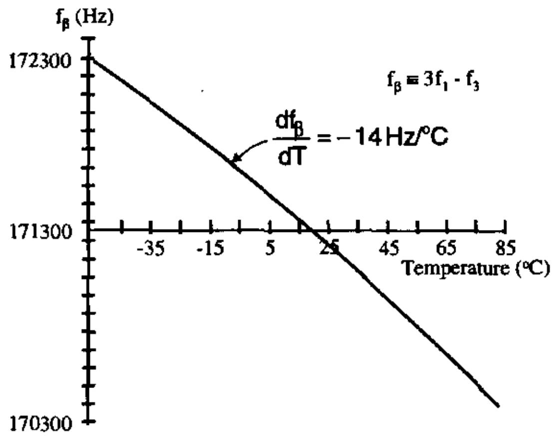


Figure 4 - Beat frequency vs. temperature

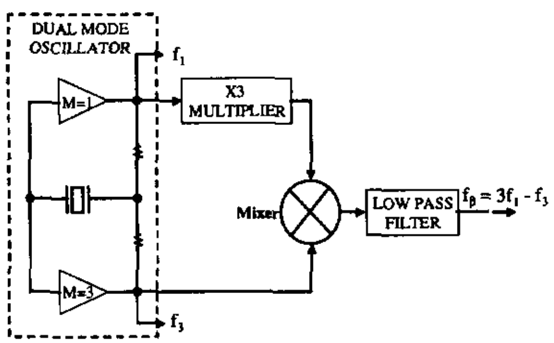


Figure 5 - Thermometric beat frequency generation

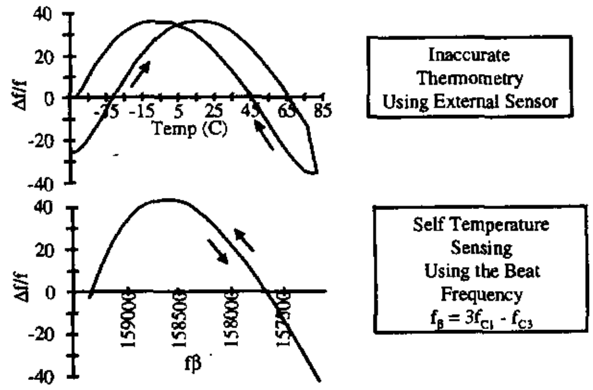


Figure 6 – Comparison of f vs. T and f vs. f_β during a rapid temperature cycle

This self-temperature-sensing technique eliminates the need for an external thermometer, it eliminates thermometry related errors, and it makes temperature control unnecessary. Instead of an f vs. T calibration, one uses an f vs. f_β calibration. This is advantageous because: 1) frequency, in general, can be measured with much higher accuracy than temperature, 2) the beat frequency is a measure of temperature at the exact location where the resonator is vibrating, thus *eliminating temperature gradients* between the resonator and temperature sensor, and 3) frequency measurements are inherently digital. Another important aspect for both sensor and clock applications is the ability to operate over a wide temperature range without f vs. T and resistance vs. temperature anomalies, i.e., without activity dips.

The MCXO based on the dual c-mode SC-cut resonator has achieved a stability of 10^{-8} over a –55° C to 85°C temperature range [30-36], which is nearly 100x better than the stability achievable with temperature compensated crystal oscillators (TCXO) that generally employ AT-cut resonators and *temperature sensors that are external to the resonator.*

A dual-mode temperature compensated AT-cut oscillator has also been described [38]. In this, a temperature sensitive "low frequency mode," probably a flexure mode, is used to compensate an AT-cut resonator. Using an 810 kHz low frequency mode, a 3 MHz AT-cut resonator was compensated to ~2×10^{-7}.

Temperature compensation by means of dual-mode excitation of a quartz tuning fork resonator seems also possible [39] (although no such oscillator description could be found in the literature). The first overtone (flexure mode) frequency of a tuning fork is six times higher than the frequency of the fundamental mode, and, for example, when the fundamental mode's turning point is at 20°C, first overtone's is at 74°C [40].

Oven-controlled oscillators

The f vs. T stability of an OCXO depends on the static and dynamic f vs. T characteristics of the resonator, the design temperature range of the OCXO, the stability of the oven and of the components in the sustaining circuitry, and the accuracy with which the oven is set to the turnover temperature of the resonator [41]. In a conventional OCXO, the accuracy with which the oven is set to turnover temperature is limited by the thermal transient effect, the thermal time constant of the oven, and the location of the temperature sensor outside the resonator which can result in temperature gradients between the resonator and the sensor. The use of a dual mode SC-cut oscillator can minimize these effects because the SC-cut is thermal transient compensated, and the temperature sensing frequency is a measure of the temperature of the vibrating volume [8,41,42].

A dual-mode OCXO used infrared radiation to heat the resonator, and simultaneous excitation of the fundamental mode and third overtone of an AT-cut resonator to sense and control the resonator's temperature [43].

An OCXO in which simultaneous excitation of three modes is used has also been proposed [44]. One mode would be a temperature stable mode that would be driven at a constant drive level, a second mode of variable drive level would be used to heat the resonator, and a third mode would be the temperature sensor. The frequency of the temperature-sensing mode would be used to control the drive level (i.e., power dissipation) of the second mode so as to maintain the temperature of the resonator at the turnover temperature of the first mode.

SAW oscillator compensation

A surface acoustic wave oscillator's temperature sensitivity can be reduced by using quasi-dual-mode excitation along two delay paths on the same substrate [45-47]. In this case, the two modes propagate on the same wafer, but not in the same volume, hence the "quasi-dual-mode". The first path is along a SAW orientation having low temperature sensitivity, such as one that might be used for a clock oscillator. The second delay path is aligned at an appropriate angle to the first delay path so that it has a SAW orientation that results in a high temperature coefficient of frequency, as illustrated in Figures 7 and 8. The frequency of oscillation along the second path is used in a compensation circuit that compensates for the temperature induced variations along the first path.

Figure 8 shows the uncompensated and compensated f vs. T characteristics of one such SAW oscillator. The clock propagation path was along the X-axis; the thermometer delay path was at a 34.8° angle.

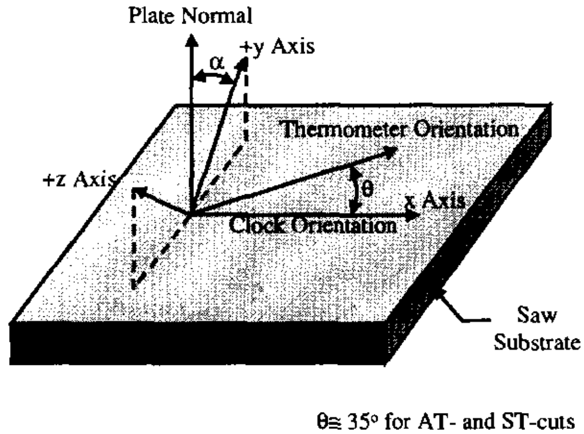


Figure 7 - Temperature compensated SAW oscillator

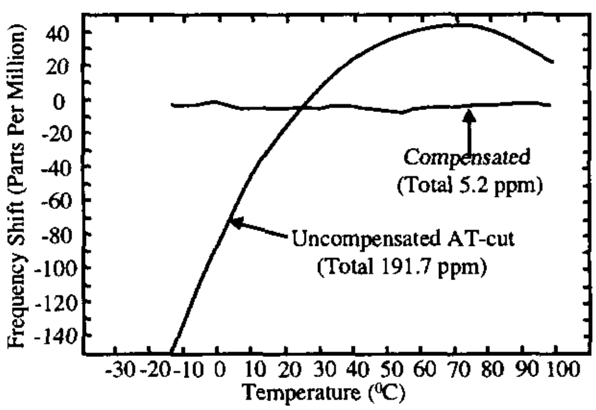


Figure 8 - Temperature sensitivity of a temperature compensated SAW oscillator

SENSOR APPLICATIONS

Pressure and force sensors

High precision pressure sensors employ quartz thickness shear resonators. The frequencies of these vary not only with pressure, but also with temperature. Temperature control, or compensation is used to minimize the errors due to temperature effects. Some pressure sensors have used a temperature sensor that is external, but in close proximity, to the pressure sensing resonator, and shielded from the applied pressure [48-50]. However, when a temperature gradient exists between the pressure and temperature sensors, such as may occur under pressure and temperature transients, the accuracy of pressure measurement is degraded.

Dual-mode pressure sensors have been proposed in which the b-mode is stress compensated and the c-mode is temperature compensated [51-54]. In such a sensor, the b-mode indicates primarily the temperature of the sensing resonator, and the c-mode indicates the applied pressure. As the b-mode's frequency depends on the temperature of the resonator's vibrating volume, the effects of temperature gradients are greatly reduced. Under pressure transients, especially, dual-mode pressure sensors allow for superior temperature sensing and compensation accuracy, and superior pressure sensing accuracy. Figure 9 shows such a dual mode pressure sensor [55].

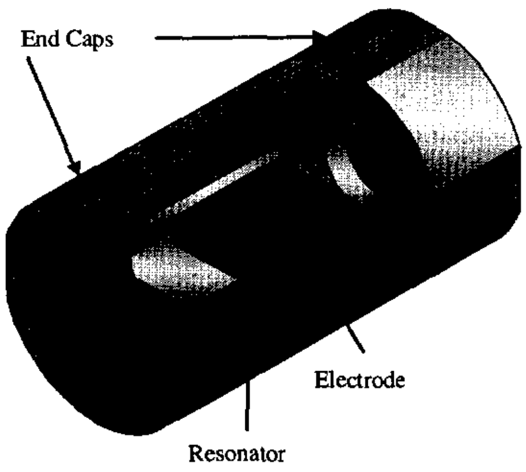


Figure 9 - Dual-mode pressure sensor

A dual-mode SC-cut force sensor utilized simultaneous excitation of anharmonic modes to reduce the temperature sensitivity of the sensor [56]

Temperature sensing and IR imaging

The possibilities of using quartz resonators as precision thermometers have been known since at least 1962 [1,2,57]. The frequencies of resonators made of some cuts of quartz vary with temperature monotonically, with a slope of about 10^{-4}/K. Due to the low noise capabilities of crystal oscillators, the frequency noise limitation for resolving temperature changes is, for example, $\leq 10^{-12}$ for a low-noise 10 MHz resonator. Therefore, the noise of such a resonator corresponds to temperature fluctuations of ~10 nanokelvins.

Because SC-cut resonators are thermal transient compensated, dual-mode SC-cut resonators have the potential for high-accuracy temperature sensing, especially in a rapidly changing temperature environment [8,21].

Quartz microresonators have been proposed for high-performance IR sensing and imaging [58,59]. Using dual mode SC-cut microresonators was one of the proposed implementations.

Chemical Sensor

A chemical sensor consisting of an array of quartz microresonators has been proposed [60]. A microresonator can simultaneously act as a mass sensor (microbalance) and a calorimeter because resonators can be highly sensitive to both mass and temperature changes. Dual mode excitation allows the separation of temperature change effects from the mass change effects (due to adsorption or reaction). The possibility of detecting and identifying a variety of chemical and biological agents was suggested via applying a variety of thin-film adsorbers to the different resonators in an array and observing the pattern of frequency changes due to an unknown admitted into the array enclosure.

Microbalance and film thickness monitor

AT-cut resonators have been the most extensively used resonators in mass sensing applications such as in microbalances and film thickness monitors. The AT-cut, however, has serious limitations due to its temperature and stress sensitivities. As the temperature deviates from the turnover temperature, the temperature coefficient of frequency increases, which makes the temperature fluctuation induced mass sensing errors also increase. Transient temperature changes can also produce significant degradation in performance.

Mass deposition onto a microbalance is often accompanied by a temperature change (e.g., due to the energy of condensation and the heat emitted by the evaporation source). By measuring a single frequency only, it is not possible to separate the frequency change due to mass change from that due to temperature change. In the temperature insensitive microbalance technique, measurements of two frequencies, the fundamental mode and third overtone frequencies of an SC-cut resonator, yield two equations with two unknowns. This allows the separation of mass change effects from temperature change effects.

The dual mode microbalance is capable of high accuracy determination of film mass changes, over wide temperature ranges; it requires no temperature control, and it can be used in rapidly changing thermal environments [61-63]. Figure 10 shows the results of an experiment during which the temperature rose by about 40°C while a thick film of polymethyl methacrylate was removed from the surfaces of a quartz resonator. The various frequency changes are shown as a function of time of mass removal.

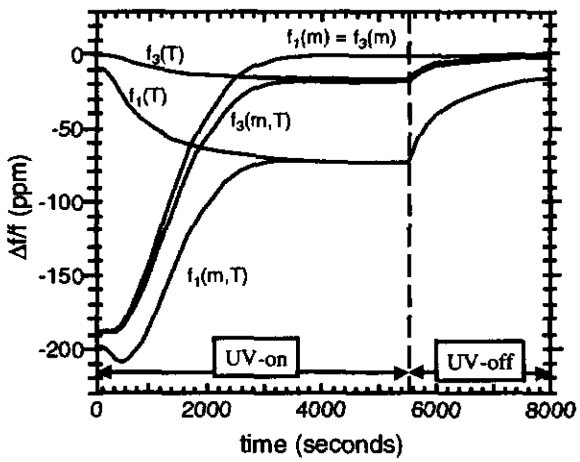
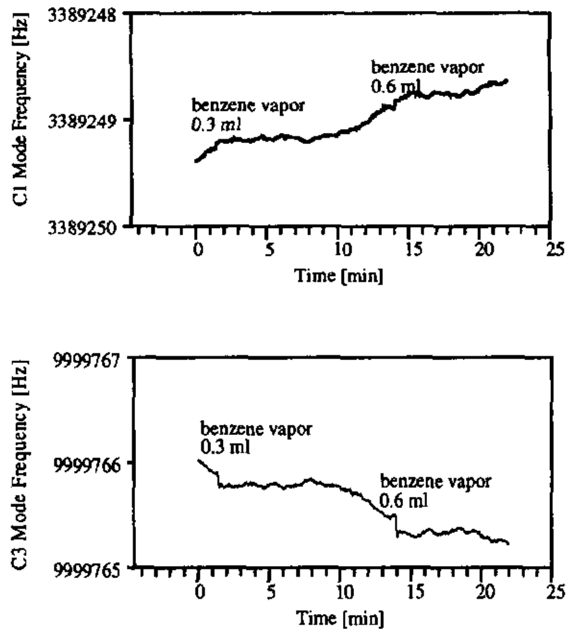


Figure 10 - Frequency changes during cleaning

The measured (normalized) fundamental and third overtone frequencies are $f_{c1}(m,T)$ and $f_{c3}(m,T)$, respectively. Shown are the results of solving two equations for the two unknowns, i.e., the temperature induced components and the mass change components of the frequency changes, $f_{c1}(T)$ and $f_{c3}(T)$, and $f_{c1}(m)$ and $f_{c3}(m)$, respectively.
By measuring a single frequency only, the temperature change induced frequency change would have caused a large error. With the dual mode technique, the frequency changes due to mass changes could be accurately determined, independently of the frequency changes due to temperature changes.

Figure 11 shows another example of the dual mode technique. It was not possible to detect the adsorption of benzene by measuring the change in the C1 (or C3) frequency alone, as can be seen in Figures 11a and 11b. With the dual mode technique, the adsorption of the benzene vapor and the temperature changes are clearly detected, as can be seen Figures 11c and 11d, respectively.



Figures 11a & b– Measured frequency changes during adsorption of benzene vapor

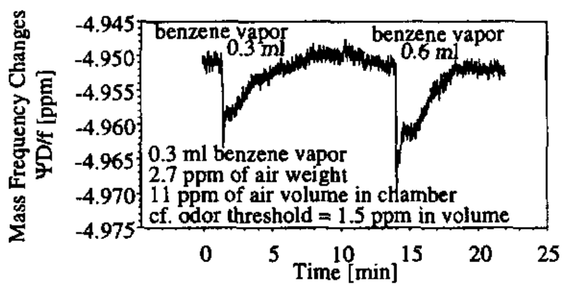


Figure 11c – Frequency change due to mass change alone

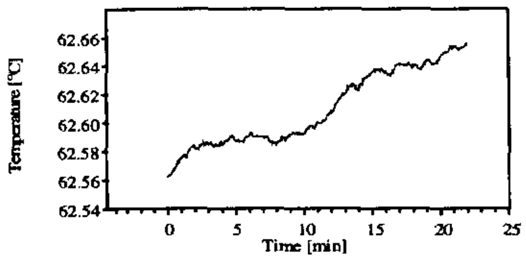


Figure 11d – Frequency change due to temperature change.

Fluid density and viscosity sensor

In a vibrating doubly rotated resonator ($\theta \approx 35^\circ$ and $\phi > 0^\circ$), the displacement is partly out of the plane of the plate, as is illustrated in Figure 12. By controlling the ϕ angle, one may control the ratio of in-plane to out-of-plane displacements. In a fluid, the out-of-plane component of the displacement propagates a damped compressional wave, while the in-plane component propagates a damped shear wave. The frequency changes of doubly rotated resonators have been measured in glycerol solutions of a variety of concentrations. At each concentration, the frequency change was found to increase with increasing ϕ angle.

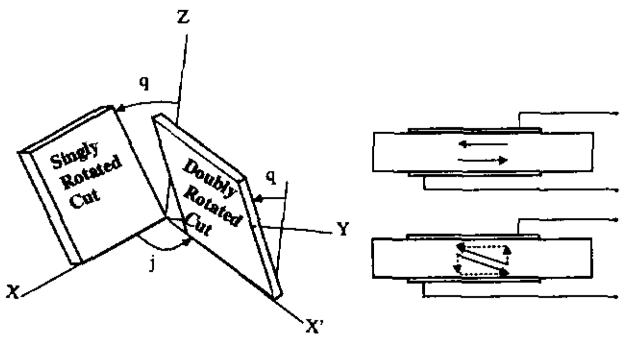


Figure 12 - Singly rotated (upper resonator) and doubly rotated cuts' displacements

A method using doubly rotated resonators has been proposed for the determination of a fluid's density, viscosity and acoustic wave velocity [64]. If such a technique is used to sense the properties of, for example, engine oil, frequency changes will be caused by both the degradation of the oil and the change in the oil's temperature. Dual mode excitation of a doubly rotated resonator sensor can allow the separation of these effects.

SUMMARY AND CONCLUSIONS

Dual mode excitation of resonators allows the highly accurate measurement of, and compensation for, the effects of temperature, pressure, etc., by means of frequency measurements alone. The method has been applied to improving the accuracy of sensors and temperature compensated oscillators.

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