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Design and Simulation of a Dual-State Quartz Resonator Force Sensor

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ABSTRACT: Quartz crystal is a piezoelectric material which is used as the sensing element in resonator load cells and temperature sensors. In the resonator force sensors, upon force-frequency effect, the resonance frequency of the quartz crystal is changed when the crystal is subjected to external forces. The amount of frequency shift depends on the temperature of the crystal. In this article, a new quartz resonator force sensor is designed and simulated. The sensor is working based on the force-frequency effect and has two working states with different loading conditions. At the first state, the force sensitivity of the sensor is maximum, and at the second loading state, the temperature effect on the force sensitivity may be minimum. The frequency shift of the load sensor is calculated by the combination of the mathematical modelling and finite element method. The simulations are performed at a temperature range of (0-100 °C). The effect of force azimuth angles and the length of flats of the resonator disk on the force sensitivity and temperature error of the sensitivity are evaluated. The designed double state sensor gives us the opportunity to increase the resolution and precision of force measurement at room temperature, and reduce the thermal error at other temperatures.

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1. INTRODUCTION

Ratajski [1] defined the force-frequency coefficient for crystal resonators in 1965 and calculated this coefficient for AT-Cut quartz crystal. Based on the force-frequency effect, researchers developed lots of load sensors and pressure gauges using quartz resonators [2, 3]. The sensitivity of these sensors was determined by the force-frequency coefficient of their resonating crystal. Due to the effect of temperature on the force-frequency coefficients, researchers tried to compensate for the temperature error on the sensitivity of the force and pressure sensors. for this, they used compensating electrical circuits or changed the design parameters of resonating crystal, force azimuth angle, and the electrode geometry and situation, to reduce the thermal error [4, 5]. Also, some researchers have designed resonator load cells which can vibrate in two different vibrating modes with different sensitivities to the temperature. The temperature error compensation was performed by comparing the frequency changes of these modes [6].

In this article, a new force sensor is designed which is capable of working in two different states with different force sensitivities and temperature error. At the first state, the force sensitivity of the sensor is maximum, and at the second loading state, the temperature effect on the force sensitivity may be minimum. The force-frequency effect at the quartz resonator disk with two pair of opposing flats is simulated at a temperature range of 0 to 100°C.

2. DUAL STATE RESONATOR FORCE SENSOR

Resonator force sensors work on the principle of force-frequency effect. Accordingly, the resonance frequency of the quartz crystal changes by the application of diametric forces. The force azimuth angle affects the frequency change. Also, the temperature can change the force-frequency coefficient of the crystal [7]The amount of variation in the force-frequency coefficient, due to the temperature change, depends on the force azimuth angle.

Our design (Fig. 1) includes a circular quartz disk with two pair of flat edges. Each double flat has a predetermined azimuth angle with axis x_1 of the AT-Cut resonator. The force is applied by the upper anvil, and the lower screw pin is fixed during application of the force. To change the loading state, the second anvil and screw pin attach the resonator instead of the previous ones. The azimuth angles of flat pairs are determined in a way that the force sensitivity of the first loading state becomes maximum and for the second state, the temperature error of the force-frequency coefficient becomes minimum.

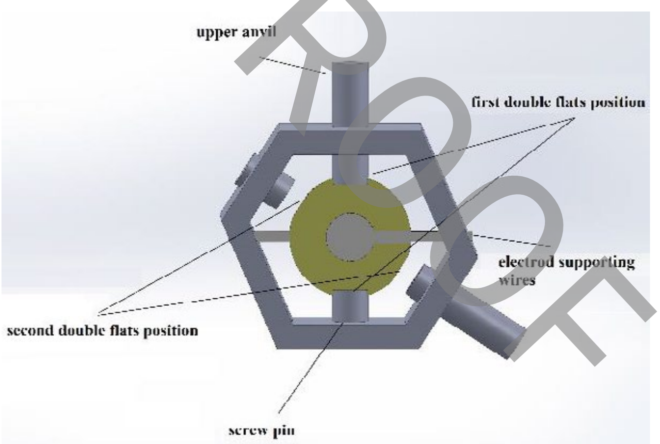

Fig. 1: Schematic model of a dual-state quartz sensor

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A mathematical model has been developed previously for calculation of the frequency shift of an AT-Cut resonator, subjected to diametric forces at different temperatures [7] Accordingly, the frequency shift is calculated by Eq. (1):

$$\frac{\Delta f}{f_0} = (U_{1,1}{}^{(0)})_m + \frac{1}{2C_{66}^{\theta}} C_{661}^{\theta}(E_1^{(0)})_m + C_{662}^{\theta}(E_2^{(0)})_m + C_{663}^{\theta}(E_3^{(0)})_m + C_{664}^{\theta}(E_4^{(0)})_m \quad (1)$$

where is the variation of the fundamental thickness shear frequency and f_0 is the fundamental cutoff frequency of AT-Cut quartz, $(U_{1,1}{}^{(0)})_m$ is the zero-order component of the initial displacement, $(E_i^{(0)})_m$ is the mechanical part of zero-order initial strains, C_{66}^{θ} and C_{66i}^{θ} are second- and third-order elastic constants of AT-Cut quartz crystal, respectively. Superscript θ shows the dependence of the parameters on the temperature, and subscript m shows the mechanical source of the parameter. The initial strains in the Eq. (1) may be determined numerically by Finite Element Method (FEM) [7]

In this paper, the zero order strain components were evaluated for the double state force sensor. Accordingly, the frequency shift and force-frequency coefficient were determined for the sensor. For validation of the force-frequency model, the force-frequency coefficients were evaluated for AT-Cut quartz disks at 25 and 78°C. The results were in close accordance with the experimental results published in the literature [8].

3. RESULTS AND DISCUSSION

The design parameters of the dual-state sensor, are the azimuth angle of double flats, and the edge length of flats. For determining the azimuth angle of the first loading state (ψ), the azimuth angle of the second flats pair (φ), was kept constant. Then, the force-frequency constants were evaluated as a function of the azimuth angle (ψ). Fig. 2 represents the results.

As shown in Fig. 2, the force-frequency coefficients are maximum when ψ is between -20° and 9°. At the angle 9°, the flat pairs contact with each other and the force-frequency

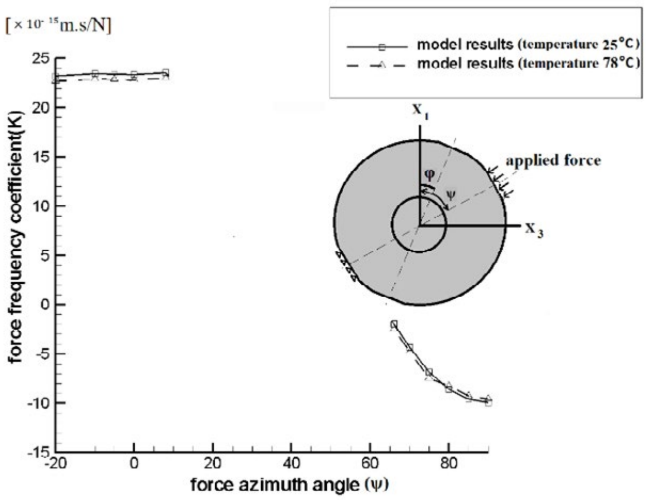

Fig. 2: Force-frequency coefficients of the sensor at the first working state at 25°C and 78°C

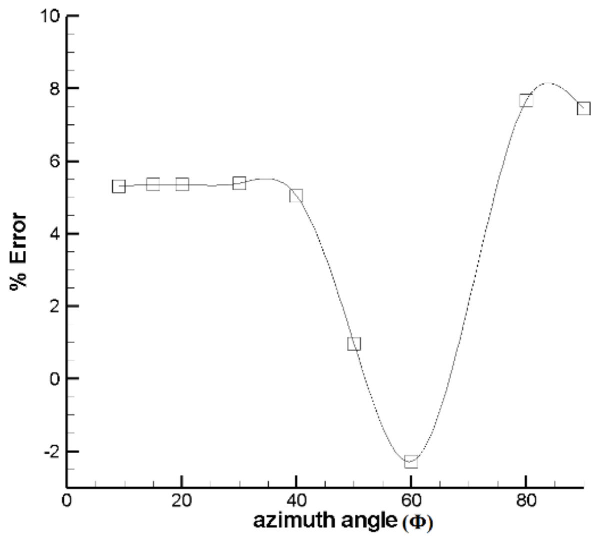

Fig. 3: The temperature error of force frequency coefficients between 25°C and 100°C

constant were not evaluated in the contact region. To have the maximum distance between the flat pairs, the angle $\psi = -20°$ was chosen for the first working state of the sensor.

For determining the second azimuth angle (φ), the first azimuth angle was considered to be $-20°$, and the temperature error on force frequency coefficients was evaluated at the temperature range of 0°C -100°C. The results have presented in Fig. 3.

Upon the error curve in Fig. 3, the temperature error of the sensitivity at $\varphi = 53°$ is almost zero. The force-frequency coefficient at this angle is 7.43×10^{-15}m.s/N . This angle may be chosen for the double flats of the second working state of the sensor Also, higher sensitivities may be achieved if a definite temperature error would be acceptable for the second working state. For example, at angle $\varphi = 50°$ the temperature error is 1% and the force-frequency coefficient is 9×10^{-15}m.s/N .

In addition to the azimuth angle analysis, the effect of flats length on the force-frequency coefficients was evaluated in the manuscript. Simulations showed that by decreasing the edge length, the force-frequency coefficients may increase.

4. CONCLUSIONS

The dependency of the force-frequency coefficient in quartz resonators to temperature and force azimuth angle gives us the opportunity of designing double state force sensors. This sensor may work at two different working state. At the first state, the force sensitivity of the sensor is maximum, and at the second loading state, the temperature effect on the force sensitivity may be minimum. By analyzing the variation of force frequency coefficient at different azimuth angles and temperatures, the force azimuth angles for these states were determined. Also, the effect of flats length on force frequency coefficients was evaluated.

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