Analysis of Mechanism of Dew Point Measurement Using a Colpitts Oscillation Circuit

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Abstract. In this paper, based on the phenomenon that Colpitts oscillation circuit is hard to work when condensation occurs on the surface of the quartz crystal, a new dew point measurement device is developed, and it is mainly composed of a quartz crystal and a Peltier module. This measurement way is both rapid and reversible compared to the traditional methods. Wet sensitive characteristics of the quartz crystal, which is regarded as the humidity sensing element in Colpitts oscillator, is analyzed. The electrical parameters of the quartz crystal are changed due to proactive condensation, then vibration of oscillator will stop if the magnitude of the reactance of the quartz crystal is lower than the reactance threshold of the Colpitts circuit. Combining the theoretical analysis with experiment data, it indicates that the Colpitts circuit is feasible to measure dew point.

Introduction

Humidity is the amount of moisture in the air and can be expressed in different ways such as relative humidity, absolute humidity and dew point temperature. Humidity measurements are crucial in many fields, such as industrial uses, textiles, agriculture, etc. And the dew point temperature measurement is regarded as the most accurate method for measuring humidity[1, 2].

Recently many efforts have been paid on the investigation of humidity sensors with high sensitivity, rapid response, fast recovery and small hysteresis. Humidity sensing mechanism and material are always the research priorities of humidity sensors[3, 4]. In the dew point measurement, the detection and recognition of dew point are viewed as the key technology. The typical recognition way of dew point is making use of a Peltier module and an optical emitter-detector[5, 6]. However, the detection system is easily affected by dust and pressure. Since a quantitative relationship between the shift in frequency and mass deposition in quartz crystal was derived by Sauebrey, quartz crystal microbalance (QCM) has been widely used as a gravimetric sensors. An EBVD model which is appropriate to describe the quartz crystal in contact with Newtonian fluid was showed by Martin[7]. And it is convenient to use an equivalent circuit model to describe the electrical characteristics of the quartz crystal resonant. However, to date few researches or related application have been conducted on QCM dew point sensors.

Considering the accuracy, response time and sensitivity, a new measuring method of dew point temperature is proposed. Since Colpitts circuit cannot drive quartz crystal oscillator when the phenomenon of moisture condensation on the surface of quartz crystal occurs, the oscillation characteristics of the Colpitts circuit is used in the experiments to identify the time of condensation. Combined with theoretical analysis and experimental results, it is proved that the quartz crystal as a sensing element in Colpitts circuit has great sensitivity and accuracy for dew point measurement.

Experimental System

The sensing device of dew point measurement is shown in Fig. 1, which consists of an AT-cut quartz crystal resonator, a Peltier module, a Copper retainer and a water recycle radiator. In order to make the sensing device more sensitive to the change of dew point, the device is placed in the sealing environment. One side of quartz crystal is glued on the Copper retainer, two wires are led out

respectively from the two electrodes of quartz crystal and connected to Colpitts circuit. Furthermore, temperature is measured by three platinum thermal resistances, one platinum thermal resistance is affixed to the Copper retainer to acquire the temperature of quartz crystal surface, another is stuck on the cold surface of Peltier element to acquire the temperature of the cold surface of Peltier, then the temperature difference between the cold surface of Peltier and quartz crystal surface can be obtained and temperature compensation can be considered in the experiment. The third one is exposed in the experimental environment to record the ambient temperature synchronously. A thermoelectric cooler (TEC-12706) is stuck on the other side of the Copper retainer to set the temperature of the quartz surface for inducing condensation, the heat surface of the thermoelectric cooler is attached to the water recycle radiator in order to provide a better cooling effect.



Figure1. Schematic diagram of sensing device

Method

Humidity Sensitive Characteristics of Quartz Crystal. The quartz crystal resonant commonly consists of a thin disk of AT-cut quartz with metal film electrodes patterned on both sides. And it is convenient to use an equivalent circuit model to describe the electrical characteristics of the quartz crystal resonant. Electrical equivalent circuit parameters of the quartz crystal can be predicated from the model and computed by using an impedance analyzer. As is shown in Fig.2a, the BVD (Butterworth-Van-Dyke) equivalent circuit is always used to describe the unperturbed quartz crystal resonant. The BVD equivalent circuit consists of a static capacitance C_0 in parallel with a motional branch (L, C and R). During the measurement of the dew point, due to the change in viscosity and density of the surrounding environment, the crystal is immersed from air into a liquid. Taking into account the boundary conditions and the physical properties of the quartz, the resulting model is a modified Butterworth-Van Dyke equivalent circuit as is shown in Fig. 2b. The circuit elements for the modified BVD model are

$$C_0 = \frac{\varepsilon_{22} A_s}{l_q}$$
(1)

$$C_1 = \frac{8K_0^2 C_0}{(N\pi)^2}$$
(2)

$$L_{1} = \frac{1}{\omega_{s}^{2}C_{1}}$$
(3)

$$R_1 = \frac{\eta_q \omega^2}{\overline{c_{66}} C_1 \omega_s^2} \tag{4}$$

$$\Delta R = \frac{\omega_s L_1}{N\pi} \left(\frac{2\omega\rho_l \eta_l}{\overline{c_{66}}\rho_q}\right)^{\frac{1}{2}}$$
(5)

$$\Delta L = \frac{2\omega_s L_1 \rho_q + \sqrt{2\rho_l \eta_l}}{N\pi\sqrt{c_{66}\rho_q}} \tag{6}$$

Where A is the effective electrode surface area, l_q is the thickness of crystal, ε_{22} is the permittivity of the quartz, N (N=1, 3, 5...) is the harmonic resonance of quartz, K_0 is the effective electromechanical coupling factor, e_{26} is the piezoelectric stress constant, $\omega_s = 2\pi f_s$, f_s is the series resonant angular frequency, $\overline{c_{66}}$ is the piezoelectric stiffened quartz elastic constant, η_q is the effective quartz viscosity, ρ_l and η_l are the surrounding media density and viscosity ,respectively, and ρ_q is the quartz mass density.



Figure 2a. Equivalent circuit model of QCM

Figure 2b. Equivalent circuit modified model of QCM

The condition for the circuit to be resonant is that the imaginary of the impedance should be equal to zero. The impedance of the quartz crystal is given by:

$$Z = \frac{\left[R + j(L\omega - \frac{1}{C\omega})\right] \frac{1}{j\omega C_0}}{\frac{1}{j\omega C_0} + R + j(L\omega - \frac{1}{C\omega})} = R_e + jX_e$$
(7)

The imaginary component X_e of the impedance are as follows:

$$X_{e} = \frac{(L\omega - \frac{1}{C\omega})(1 + \frac{C_{0}}{C} - C_{0}L\omega^{2}) - R^{2}C_{0}\omega}{(1 + \frac{C_{0}}{C} - C_{0}L\omega^{2})^{2} + (RC_{0}\omega)^{2}}$$
(8)

Analysis of Colpitts Oscillation Circuit. The Colpitts circuit is a typical oscillation circuit which is often utilized as a driving circuit in quartz crystal resonant. As is shown in Fig. 3a, Colpitts oscillation circuit is a positive feedback oscillation based on the transistor. In order to maintain self-sustained oscillating the circuit should simultaneously fulfill the phase condition and the amplitude condition. The basis expression are as follows:

- (1) Amplitude condition : the total loop gain |G| = 1
- (2) Phase condition: the total phase is $\varphi = 2n\pi$ (n=0, 1, 2, ...)

Fig. 3b is the equivalent circuit of the Colpitts circuit.
$$u_b' = -g_{fc}u_b \frac{Z_2Z_3}{Z_1 + Z_2 + Z_3}$$
,
 $Z_1 = R_1(R_e + jX_e + \frac{1}{j\omega C_1}) / (R_1 + R_e + jX_e + \frac{1}{j\omega C_1})$, $Z_2 = R_2 \frac{1}{j\omega C_3} / (R_2 + \frac{1}{j\omega C_3})$

 $Z_3 = R_i \frac{1}{j\omega C_2} / R_i + \frac{1}{j\omega C_2}$, $\beta = \beta_0 / (1 + jf/f_\beta)$, β_0 is the amplification of common emitter

current, f_{β} is the frequency of common emitter transistor cutoff, R_i is amplifier input resistance.



Figure 3a. Colpitts circuit

Figure 3b. Equivalent circuit of Colpitts circuit

From what have been discussed above, it is obvious to get that:

$$G = \frac{u_b'}{u_b} = -g_{fc} \frac{Z_2 Z_3}{Z_1 + Z_2 + Z_3} = |G| e^{j\varphi}$$
(9)

In order to satisfy the resonant condition of the Colpitts circuit, the quartz crystal should be equivalent to an electric resistance R_e and series inductance impedance X_e . So the external circuit could be equivalent to a negative resistance R_N and series capacitance impedance X_{CL} . When the circuit is in resonant state, it should satisfy the amplify and phase conditions : |G| = 1, $\varphi = 2n\pi$.

$$g_{fc}Z_{2}Z_{3}+Z_{1}+Z_{2}+Z_{3}=0$$
(10)

Take Z_1 , Z_2 , and Z_3 into Eq. (10) to get that: $g_{ic}Z_2Z_3+Z_1+Z_2+Z_3$

$$=\frac{jR_{1}\omega C(R_{e}+jX_{e})+R_{1}}{j\omega C_{1}(R_{1}+R_{e}+jX_{e})+1}+\frac{R_{2}+R_{i}+jR_{2}R_{i}\omega (C_{2}+C_{3})+g_{fc}R_{i}R_{2}}{(jR_{2}\omega C_{3}+1)[jR_{i}\omega C_{2}+1]}$$

$$=R_{N}+R_{e}+j(X_{CI}+X_{e})$$
(11)

$$R_N$$
 is a negative resistance, X_{CL} is active circuit equivalent capacitance reactance. Solving Eq. (11) to get that:

$$X_{CL} = -\frac{1}{\omega} \left(\frac{1}{C_3} + \frac{1}{C_2} + \frac{1}{C_1} \right)$$
(12)

We can define $-X_{CL}$ as the reactance threshold. It is to say that the Colpitts oscillation circuit will stop oscillation when the reactance X_e is lower than the threshold $-X_{CL}$.

Results and discussion

In order to get the reason why the Colpitts circuit cannot work in the liquid environment, firstly the change of electrical characteristics of the quartz crystal is analyzed. The shift of equivalent electrical parameters varying with the environment humidity of the quartz crystal is measured. The special parameters components of the Colpitts circuit are as follows: C_1 =30PF, C_2 =330PF, C_3 =270PF, and resonant frequency of quartz crystal resonant is 4MHz. It is shown that the moment of circuit stopping oscillation is exactly the moment that gas-liquid phase transform on the quartz surface.

Due to gas-liquid shift on the surface of the quartz crystal during the active condensation processes,

a change in the motional impedance is caused, represented by the \triangle L and \triangle R in Eq. (5, 6). By combining the circuit model of the Colpitts oscillator (Fig.3b) with the equivalent circuit model of the resonator (Fig.2b), total responses varying with the humidity during the condensation are simulated. The variation of the imaginary of the impedance of the quartz crystal vs. the equivalent resistance is represented in Figure.4a. The phenomenon that the value of the reactance R_e will decrease with the increasing of the equivalent resistance R is revealed. The Colpitts circuit stopped oscillating when the value falls above the line of the reactance threshold. Considering the influence in the variation of the equivalent induction, the variation in reactance X_e is shown in Fig.4b. It illustrates the relationship between the two electrical parameters (R, L) and the reactance of quartz crystal (X_e).



Figure 4a. The relationship between R and Xe Figure 4b. The relationship between R,L and Xe

The value of quartz crystal parameters is measured by an Impedance Analyzer (Agilent 4294A). Electrical impedance or admittance is measured at a range of frequencies near resonance. Therefore, a measurement of reactance of quartz crystal is recorded when the surface of quartz crystal changes from the original dry condition to deep condensation. And the measured result is close to the value calculated by the modified-BVD model. The reactance X_{CL} is calculated by Eq. (12). It is approximately 1586.3 Ω . The shift of reactance of the quartz is determined by the measurement result of impedance analyzer, which agrees well with the value calculated by Eq. (8). Five groups of X_e varying with the state of quartz surface are shown in Fig.5. A highly level of repeatability and reproducibility in these experimental curves are observed. On the one hand it demonstrates that X_e is of the same value approximately 1366.8 Ω at the moment of the circuit stopping oscillation, and on the other hand, X_e under the original dry environment is also at the same magnitude approximately 1597.2 Ω which is a little greater than the threshold. Furthermore, the X_e will decrease with the deepening of the extent of the condensation.



Fig 5. Trend of quartz crystal reactance

Summary

The condition of self-sustaining oscillation of Colpitts circuit and the humidity sensing properties of quartz crystal are qualitatively analyzed in this paper. During the process of humidity measuring, the quartz crystal surface experiences from original dry condition to moisture condensation. Parametric impedance plane plots are introduced to analyze the effect of gas-liquid shift in the surface of the quartz crystal. The response of the Colpitts oscillator varies in direct proportion to the extent of vapor adsorption, which is typically both rapid and reversible. Quantitative comparisons of two electrical parameters, reactance of the quartz crystal and threshold reactance of the Colpitts circuit, demonstrate the accuracy and feasibility of the dew point detection.

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