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应用石英音叉谐振器的智能温度传感器

徐　军[1,2],尤　波[1],李　欣[3],马　静[1]
(1.哈尔滨理工大学 自动化学院,黑龙江 哈尔滨 150080;
2.哈尔滨理工大学 测控技术与通信工程学院,黑龙江 哈尔滨 150080;
3.哈尔滨理工大学 计算中心,黑龙江 哈尔滨 150080)

摘要:为了实现高精密温度测量,设计了高性能数字温度传感器,该传感器由石英音叉谐振器,数字接口电路和基于现场可编程门阵列的传感器重置控制算法构成。依据石英晶体压电效应原理,对石英音叉谐振器的热敏切型和电极设置进行了研究;基于力学振动原理,导出石英音叉谐振器弯曲振动模式的微分方程;讨论了谐振式温度传感器的工作原理,提取出石英音叉温度传感器的特征参数并进行了非线性误差分析;采用光刻和侵蚀技术加工制作了石英音叉谐振器。该传感器的频率输出信号通过数字接口进入现场可编程门阵列,通过重置控制算法实现传感器的重置和现场自动校验。实验结果表明,在-20 ~140 ℃,该传感器的灵敏度可达65×10^{-6}/℃,测温分辨率为 0.001 ℃,响应时间为 1 s,测温精度为 0.01 ℃。

关　键　词:智能传感器;温度传感器;石英音叉谐振器;数字设计
中图分类号:TP212.11　　**文献标识码**:A

Fully digital smart temperature sensor with quartz tuning fork resonator

XU Jun[1,2], YOU Bo[1], LI Xin[3], MA Jing[1]

(1. *School of Automation*, *Harbin University of Science and Technology*, *Harbin* 150080, *China*;
2. *School of Measurement-control Technology & Communication Engineering*,
Harbin University of Science and Technology, *Harbin* 150080, *China*;
3. *Computer Center*, *Harbin University of Science and Technology*, *Harbin* 150080, *China*)

Abstract: In order to measure temperature in high-precision, a high-performance and fully digital smart temperature sensor is designed, which comprises a quartz tuning fork resonator, an interface with Complementary Metal Oxide Semiconductor(COMS) and a controlling algorithm for sensor reconfiguration based on the Field Programmable Gate Array(FPGA). According to the piezoelectricity effect of a quartz, the thermosensitive cut for the quartz tuning fork resonator and the electrode configuration are analyzed, and the resonant differential equation of the quartz resonator working in a flexural vibrating mode is derived from mechanical vibration. Then, the design principle for the quartz tuning fork temperature sensor is discussed, and the characteristic parameter of temperature sensor is extracted. Finally, the nonlinear error of the sensor is analyzed. The quartz tuning fork resonator is

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fabricated by a photolithography and an etching technology, in which the frequency output is from the interface IC to FPGA and the special controlling algorithm may easily realize the sensor reconfiguration and the automatic calibration in the field. The experimental result indicates that the sensitivity of this sensor can reach 65×10^{-6}/℃ at the temperature ranges from −20 ℃ to 140 ℃, which guarantees the precision of 0.01 ℃, the resolution of 0.001 ℃, and the response time of 1 s.

Key words: smart sensor; temperature sensor; quartz tuning fork resonator; digital design

1 Introduction

With the rapid development of science and technology, the high-performance and low-power systems have been introduced to meet the continuous needs of market. The requirement of high-precision temperature measurement becomes higher and higher. Piezoelectric resonators have been widely utilized not only for time keeping devices but also for temperature measurement sensors[1]. The prediction of their temperature-frequency characteristic as well as the impedance at their electrical terminals are the primary importance for their design. The anisotropy of quartz as well as usage of different types of vibrations make it possible to control these parameters, such as temperature, force, mass, pressure, acceleration, humidity, etc[2-3].

Many previous studies have been addressed about the development and application of bulk acoustic wave (BAW) as temperature sensor. Those sensors mainly based on thickness-shear model resonators or tuning fork resonators. The BAW sensor is small, light, reliable, stable and sensitive. The key part of resonant temperature sensor is the oscillator's structure. The oscillator frequency nearly doesn't alter when the outside voltage is changing. In addition, its quality factor is up to more than 10^4, so the drifts of outside circuit's temperature nearly have no effects on the measurement accuracy.

The selection of quartz crystal cuts is an important problem in BAW-based sensor design. Using different quartz crystal cuts, BAW sensors will have different performances. Thus, it is necessary to select the optimal quartz crystal cut which yields the best performance for the BAW sensor. In 1962, Wade designed a BAW temperature sensor based on thickness-sheared quartz resonators[4]. As his followers, Smith and Spassov proposed using Y-cuts as temperature sensors[5-6]. Hammond working at Hewlett-Packard located a cut of quartz named LC-cut for the temperature sensor whose resonance frequency is substantially linear with the temperature[7]. Those temperature sensors using high resonance frequency have larger volume and higher power consumptions.

In order to miniaturize the construction of the sensor and reduce the power consumption, a good resonator type of tuning fork shape is used to design the resonators. A miniature resonator as a temperature sensor was described by Dinger[8]. By using a orientation crystallographic rotating far away from the usual watching crystal orientations, a flexural quartz tuning fork resonator was used for temperature sensor by Ueda[9]. The low resonance frequency of tuning fork which allows low power consumption of CMOS electronics and the miniaturized volume by using photolithography and etching technology are very attractive properties for sensor applications. Based on the preliminary work[10], in this paper, the frequency shift of quartz tuning fork temperature sensor (QTTS) caused by the temperature is analyzed with theoretical method. Using lithography type setting and erosion techniques, size of quartz tuning fork is reduced much. The software and hardware of quartz tuning fork temperature sensor are respectively designed with special algorithms and FPGA. Applying the smart sensor concept, frequency adjustment step at 0 ℃ can be avoided, and the calibration curve can be stored in the Transducer Electronics Data Sheets (TEDS). The temperature-frequency characteristics of QTTS have been investigated through experiments.

2 Sensor design

Quartz crystals are widely used for BAW-based temperature sensors. The crystal cuts can be expressed with the Euler angle (θ, φ, ψ) which reflects the rotation angles from the crystal axes (X, Y, Z) to the substrate coordinate axes (x, y, z). The readers can refer to IEEE Standard on Piezoelectricity (IEEE Std 176-1978) for the definition of quartz cuts. In this paper, in order to get higher sensitivity and better linearity, a doubly rotated orientation cutting method with ZYtw(118°, 18°, 0°) (Rotated at θ about the x-axis as a rotary axis, then rotated at φ about the y-axis as a rotary axis, where $\theta=118°$, $\varphi=18°$, define x-axis as electric axis, y-axis as mechanical axis and z-axis as optical axis) is used. The geometrical orientations of the quartz crystal tuning-fork resonator are shown in Fig. 1.

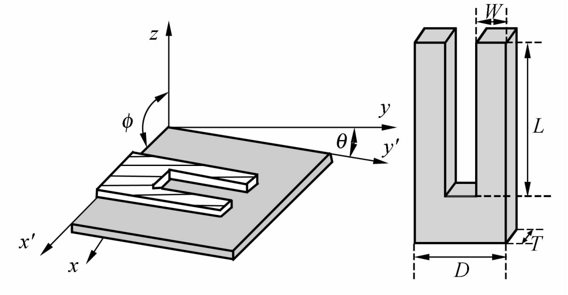

Fig. 1 Crystallography of tuning fork

The electrode layout of quartz tuning fork is illustrated in Fig. 2, where one can see the tuning fork cantilever's crossing section, using the quartz tuning fork as the center axis and the positive strain and negative strain separately locates on the two sides of quartz tuning fork. We apply the mirror method to get the other tuning fork cantilever, and use the electrode to indent the quartz tuning fork. On the surface, the beam perpendicular to the thick silver or gold electrodes is deposited silver which covers only a part of the surface[11-13].

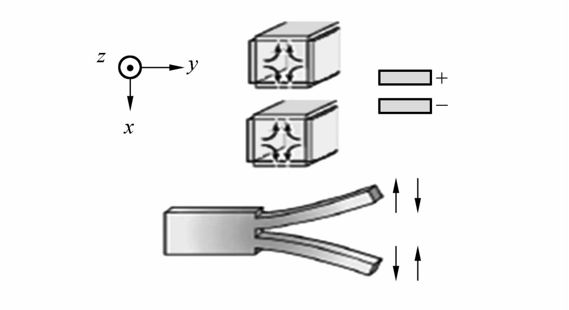

Fig. 2 Quartz tuning fork element

In this analytical method, a quartz tuning fork works in a flexural vibrating mode, each beam of the tuning fork is considered separately. The flexural vibration wave mode can be described by the differential equation as below

$$\begin{cases} \dfrac{\partial^2\delta(y,t)}{\partial t^2}+\alpha^2\dfrac{\partial^4\delta(y,t)}{\partial y^4}=0 \\ \alpha^2=EI/\rho A \end{cases}, \qquad (1)$$

where δ is the relative offset of the tuning fork cantilever L, A is the cross section area of the cantilever, E is the quality hardness, ρ is the density of the quartz crystal, and I is the movement inertia of the tuning fork. The derivation is used in this model where shear effects are neglected. The resonant frequency is

$$f=\frac{1}{4\pi}\frac{\lambda^2}{L^2}\frac{W}{\sqrt{3\rho S_{yy}}}, \qquad (2)$$

where W is the width of the beam, S_{yy} is the flexible coefficient, and λ is the solution of an eigenfrequency equation which depends on the boundary conditions. For a fixed-free beam, the eigenfrequency equation is $1+\cos\lambda\cosh\lambda=0$.

The frequency-temperature characteristics $f(T)$ of the flexural vibration tuning-fork at the reference temperature T_0 may be described as a

Taylor series (neglecting the high-order terms):

$$\frac{f(T)-f(T_0)}{f(T_0)} = \sum Tf_n * (T-T_0)^n, \quad (3)$$

The n^{th} temperature coefficient is

$$Tf_n = \frac{1}{n! \ * f(T_0)} \left(\frac{\partial^n f}{\partial T^n}\right)\bigg|_{T=T_0}. \quad (4)$$

For a high thermo sensitivity, the value of 1st temperature coefficient should be as large as possible, the value of 2nd temperature coefficient and 3rd temperature coefficient should be as small as possible, which raise the output of signals and improve its linearity. ZYtw(118°, 18°, 0°) cut has a large first temperature coefficient and a large electromechanical coefficient.

Another subject for miniaturization is fine patterning and productivity. Fig. 3 shows the summary of process flow which was applied to a new element. The cross sectional views of elements are also shown by Fig. 3. Process flow is composed of wafer cleaning, tuning fork shape etching, electrode patterning, inspection and assembly. The photolithography technology in tuning fork shape etching process and electrode patterning process is described elsewhere[14-15]. The quartz tuning fork temperature sensors are prepared by synthetic quartz with Q-factor over 6. 104 on ZYtw-cut plates. The resonators are installed in standard capsules of package Φ2 mm× 6 mm holders and filled with Helium of 90 Pa as shown in Fig. 4.

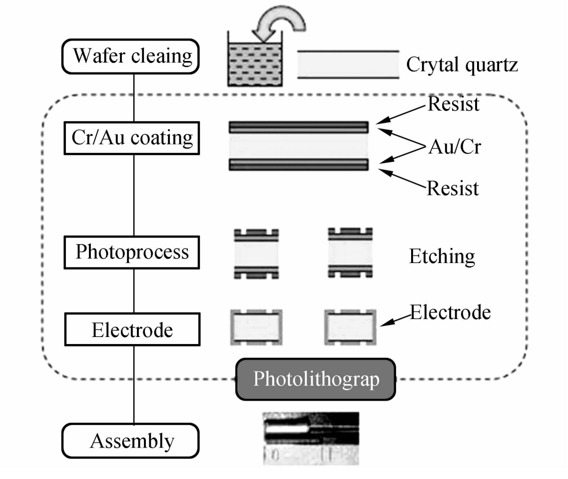

Fig. 3 Summary of process flow

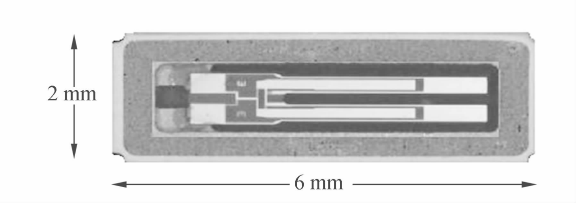

Fig. 4 Mount structure of tuning fork resonator

3 Experiments and results

The fully digital smart temperature sensor based on QTTS is realized basing on a programmable chip technology, which is realized by integrating various main function modules on a piece of FPGA chip[16-17]. They offer many advantages to digital designer, especially the ability to reprogram in a short time. Moreover, computer-aided design tools that simplify the complexity of FPGA basing on hardware design are available. The peripheral electronic element consists of an analogue part and a digital part. The signal conditions of the sensor signal and the amplifiers for the actuation signal are located on the analogue PCB. The digital PCB includes the Oscillator circuit, FPGA, memory, and the data interface converter. The design is based on the opportunity to use the circuit as a guideline for an ASIC. The major part of the functionality is placed in the FPGA that is described in VHDL as shown in Fig. 5.

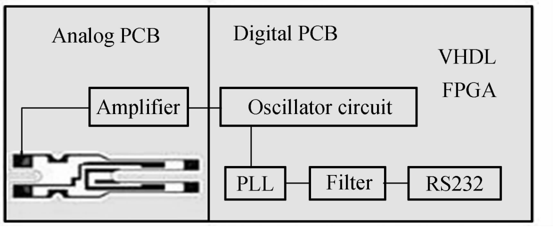

Fig. 5 Schematic graph of sensor and electronics

A PC-based temperature calibration system for measuring temperature-frequency characteristic has been arranged. It includes a personal computer (PC) for digital processing and displaying, a quartz tuning fork temperature sensor of array samples and a high-performance thermostat. The measured temperature range is from −20 ℃ to 140 ℃, and we change it by 5 ℃ to measure the frequency. The sample points are 32 data points together. Using a method of the least square fitting for each sample, the line shows the relationship between frequency and temperature as the polynomial of the third order approximating nonlinearities.

The temperature-frequency curve of the quartz crystal tuning fork temperature sensor is shown in Fig. 6, which shows a linear relationship approximately. Using a mean squared algorithm for each sample, we computed the temperature-frequency characteristic carefully with PC programs. We found the line of the temperature-frequency shows the linear relationship between temperature and frequency.

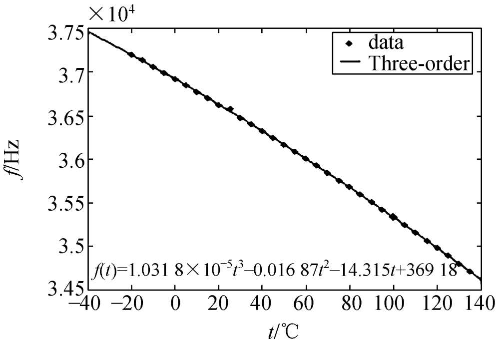

Fig. 6 Temperature-frequency characteristics of QTTS

The deviation from the linearity of the TFC (Temperature-frequency Curve) is shown in Fig. 7. The largest deviation of the TFC does not exceed ±0.047 ℃ in a temperature interval from −30 ℃ to 180 ℃, which is close to the theoretically calculated value. The experimental results indicate that the variation in device stability of the micro tuning-fork temperature sensor is very small. The precision of the testing system is 0.03 ℃. Fig. 8 presents the time response of the quartz tuning-fork temperature sensor. The response time of the proposed micro quartz tuning-fork temperature sensor is determined to be 5 s in the relative temperature range from 0 ℃ to 100 ℃.

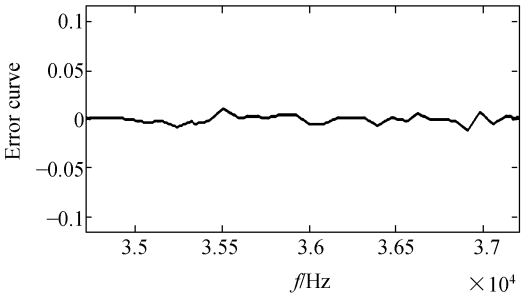

Fig. 7 Deviation of linearity of temperature-frequency characteristic of QTTS

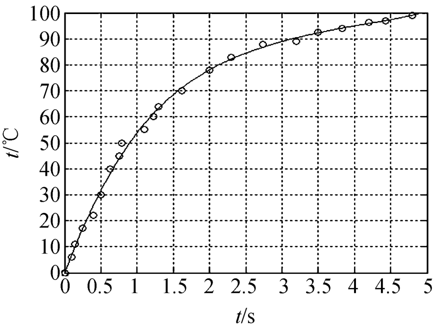

Fig. 8 Time response of QTTS

4 Conclusions

In this paper, we have presented a simple, low-power consumption and low cost quartz tuning fork temperature sensor. We have analyzed the characteristics and manufacturing method of the quartz tuning fork temperature sensor. The temperature test shows that the precision of the temperature sensor designed in this paper can achieve 0.01 ℃, and the hysteresis can be totally neglected when the temperature range is from −20−140 ℃. We have pointed out that the single point calibration methodology of quartz tuning fork temperature sensor are necessary for the application of low cost calibrated sensors. By applying the smart sensor concept, the calibration curve can be stored in the TEDS. And the future work is how to improve the accuracy of temperature examination and how to arrange the number of revising points reasonably in the whole temperature range.

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Authors' biographies:

XU Jun (1968—), male, Ph. D. candidate, associate professor of the School of Automation, Harbin University of Science and Technology, his research interests are sensor technology, *etc*.. **E-mail**: xujun@hrbust. edu. cn.

YOU Bo (1962—), male, Ph. D. tutor, professor of the School of Automation, Harbin University of Science and Technology, his research interests are Robotic *etc*. **E-mail**: youbo @ hrbust. edu. cn

LI Xin (1968—), female, associate professor of the Computer Center, Harbin University of Science and Technology, her research interests are simulation *etc*. **E-mail**: Lixin68 @ hrbust. edu. cn.

MA Jing (1979—), female, Ph. D. candidate of the School of Automation, Harbin University of Science and Technology, her research interests are MEMS devices *etc*. **E-mail**: majing@hrbust. edu. cn

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●**下期预告**

用自由移动的刚性球杆校准多摄像机内外参数

张灵飞，陈　刚，叶　东，车仁生
（哈尔滨工业大学 自动化测试与控制系，黑龙江 哈尔滨 150001）

针对用于大空间运动分析的运动参数光电探测系统的多台高速摄像机的内外参数校准需求，制作了一种两端及中间各安装一个红外反光标志球且两端球距为已知（精确校准）的刚性球杆，只需将这种特制的刚性球杆在测量空间内多次随意移动，并用多台前端安装有红外发光板和滤光片的高速摄像机摄取其图像，即可实现焦距不同的多台摄像机的内外参数校准。首先，假定主点位于像面中心附近的某个位置，通过 Hartley 改进 8 点法求出基本矩阵，利用极点和外极线约束线性地求出各台摄像机的焦距。接着，求出本质矩阵，对其奇异值分解后得到旋转矩阵和比例因子意义下的平移向量。然后，利用三角法确定刚性球杆两端点的重建坐标和距离，并与标准距离对比确定比例因子。最后，通过评价函数将摄像机校准转换成寻找摄像机最佳主点配对的非线性最小化问题，运用改进的模拟退火进化策略迭代优化求解出最佳主点配对，继而求解出摄像机其它内外参数。标定实验结果表明，焦距和主点求解精度达到了 0.1 pixel。对比测量实验表明，对长为 750.607 mm 的刚性杆进行长度测量，标准差达到了 0.046 mm。与传统方法相比，本方法扩展到了多台摄像机应用场合并允许摄像机焦距各不相同，不需要对球杆的运动做任何限制，而且能够同时求解出摄像机内外参数，改进的模拟退火进化策略改善了算法收敛速度和全局收敛性能。