Study on Dust Measurement Technology by Oscillating Balance Method

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Abstract. By comparing the advantages and disadvantages of various dust measurement methods, the oscillating balance method is chosen to measure dust. According to the measuring principle of the oscillating balance method, a particle weighing device based on the oscillating balance method is developed. The device avoids the interference of temperature, humidity and mutual inductance to the magneto-electric speed sensor, improves the amplitude of the magneto-electric speed sensor to receive the oscillation signal, and improves the signal-to-noise ratio of the system as much as possible. According to the phase-frequency characteristics of the oscillating system, an overall structure of the system is designed. The system consists of a drive module, harmonic oscillator, measurement module, and phase-locked loop automatic phase modulation circuit and frequency measurement module. These five modules constitute a system that can automatically adjust the natural frequency. And the list confirms the accuracy of the frequency that is measured by FPGA and STM32 processor. The dust mass is calculated according to the formula. Finally, the reliability of the device is confirmed by a parallel comparison with the internationally recognized filter membrane weighing method. The reliability of the device is confirmed.

1. Introduction

In actual working sites, such as factories, a large amount of dust will be produced in the process of production. If dust is not treated [1], it will affect workers' health and cause pneumoconiosis [2], and serious dust accidents will cause explosions [3]. Therefore, the monitoring of dust particles can effectively protect people's safety and health. Dust monitoring means are various, the main methods can be divided into sampling method and non-sampling method. The sampling methods include the weighing filter paper method, beta ray method [4], piezoelectric crystal method, and oscillating balance method. As a reference method in the international dust measurement standard, the weighing filter paper method has a high precision, but its automaticity is low, so it cannot measure in real-time. Beta rays are reflective rays, although they can be measured in real-time. The instrument must be well shielded, otherwise, it will do harm to the operator's body, so this method is not suitable for laboratory development. The piezoelectric crystal method is used to measure the dust by using the Piezoelectric Effect. Although the measurement results are relatively reliable, the surface of the piezoelectric crystal must be cleaned after measuring the dust every time. The method is not suitable for continuous measurement. Although the non-sampling method can continuously measure in real-time, it is generally
affected by particulate size and color, which will cause deviation to the measurement results. However, the oscillating balance method [5] is based on conical oscillating elements, which can not only measure in real-time but also be unaffected by the size and color of particles. Therefore, based on the principle of oscillating balance method, this paper finally develops a dust measuring instrument that can be measured in real-time, so that the personal health and safety of workers can be guaranteed.

2. Principle Of Oscillating Balance
When an oscillating system experiences a simple harmonic oscillation, the following equation is satisfied [6].

\[ \omega = \frac{K}{M} \]  

(1)

\( \omega \) is the natural oscillation frequency of the oscillating system, \( K \) is the coefficient of elasticity, \( M \) is the mass of the system.

\[ f = \frac{\omega}{2\pi} \]  

(2)

Combined with the above formula:

\[ m = \frac{K}{4\pi^2} \frac{1}{f^2} \]  

(3)

Since the elastic coefficient of the oscillating system is a fixed constant, it can be seen from the above equation when the oscillating system experiences a simple harmonic oscillation, its natural frequency is only related to the mass of the oscillating system. By measuring the two natural frequencies of the system \( f_1 \) and \( f_0 \) in this period. According to formula (3), the total mass of the oscillating system in this period is \( m_1 \) and \( m_0 \) respectively. You can get the cumulative mass on the membrane over time is the difference between these two masses. To keep the tube oscillating at its natural frequency, a periodic force \( B \sin \omega t \) is applied. The attenuation oscillation equation of the oscillation system can be expressed as:

\[ m\ddot{x} + c\dot{x} + kx = B \sin \omega t \]  

(4)

The amplitude-frequency characteristic and phase-frequency characteristic of the oscillating system can be obtained by solving the differential equation. Through the analysis of amplitude-frequency and phase-frequency characteristics of the oscillating system, it is found that when the oscillating system is under a Simple Harmonic Excitation, that is, when the excitation frequency is exactly at the natural frequency of the oscillating system, the displacement phase of the oscillating system will lag behind the excitation force phase of the oscillating system, and its phase displacement is -90°. Because the phase of the velocity signal of the oscillating system is 90° ahead of the phase of the displacement signal in the case of Simple Harmonic Excitation, when the excitation frequency is at the natural frequency of the oscillating system, the phase between the velocity phase of the oscillating system and the excitation force of the oscillating system is 0°.

3. Overall Design Of The System
The overall scheme of the system includes the design of a quality sensor and corresponding measurement and control circuit. Through the system, the oscillator tube can automatically adjust to the natural frequency of the oscillation at this time. The measurement and control circuit can be divided into the driver module, speed signal measurement, Phase-locked loop automatic phase modulation module, and frequency measurement. The phase-locked loop is a locked phase loop, which is a typical feedback control circuit, composed of the phase comparator, loop filter, and VCO. The overall scheme is to connect two external input signals to the two input terminals of the phase comparator of the PLL. The phase comparator detects the phase difference between the two signals and converts them into voltage
signal. After filtering the high-frequency component of the voltage signal through the loop filter, a DC voltage about the phase difference is obtained. The input of this DC voltage signal to the VCO input can make the VCO output square wave signal, the square wave signal through a bandpass filter, make it into a sine wave. However, the output capacity of this sinusoidal signal is not enough to stimulate the oscillator tube, so it is necessary to connect a power amplifier at the back end of this sinusoidal signal to improve its output capacity. The oscillating tube will induce a sinusoidal signal from the magneto-electric speed sensor on the output side through vibration. Then the two signals are connected back to the two input terminals of the phase comparator to form an automatic phase modulation system. When the phase difference between the two input terminals of the phase comparator is 0, the frequency measurement module starts to work, and the measured frequency is the natural frequency of the oscillator tube.

In this module diagram, the most important is the design of the oscillator tube and the automatic phase modulation circuit.

4. Development Of Mass Sensor
Through the analysis of the overall scheme, the structure of particle weighing device of oscillating balance can be designed [7].

Figure 1. Block diagram of overall system work.

Figure 2. Structure of particle weighing device.
The quality sensor is the core of the whole system, and also the difficulty of system implementation. The quality sensor design directly affects the measuring accuracy. Therefore, it is necessary to design a quality sensor with good repeatability and high sensitivity.

The Drive coil on the right serves as the driving part of the oscillation system, which is used to output a sinusoidal signal of a specific frequency and is used to generate periodic excitation force to excite the oscillation tube.

The coil on the left is a signal detection module, which uses a magnetoelectric speed sensor. Based on the principle of electromagnetic induction, its output voltage signal is proportional to the rate of change of magnetic flux. Eventually, it receives a speed signal that oscillates back and forth from the oscillator tube.

The intermediate fixed magnet is designed to avoid direct coupling of two coils of mutual inductance voltage. If this mutual inductance voltage exists, the voltage on the output side coil will be the superposition of the induced voltage and the mutual inductance voltage, in other words, the phase of the output will change. When the input-output phase difference is zero, the excitation frequency will not be the natural frequency of the system.

5. Development Of Mass Sensor

The two square wave signals input into two terminals of the phase comparator, and then a DC voltage signal related to phase difference is obtained through a loop filter. Finally, the DC signal input to the end of the VCO, so that a square wave signal related to phase difference can be output, achieving the effect of phase difference control square wave frequency. The phase lock loop [8] for this module use CD4046. CD4046 is general CMOS phase-locked loop integrated circuit, its characteristic is wide range of supply voltage (3V to 18V), high input impedance (about 100 MΩ), in the center frequency of 10 KHz power consumption is 600μW, belongs to the micropower consumption devices.

![Figure 3. Phase-locked loop automatic phase modulation circuit.](image)

Through the circuit above, by adjusting C20 and R35, the lower limit oscillation frequency of VCO can be set. The ratio of R33/R35 determines the ratio of upper limit oscillation frequency and lower limit oscillation frequency of VCO.

If the phase-locked loop is adjusted so that the phase difference between the two input signals of the phase comparator is equal, then the oscillator tube oscillates back and forth at the natural frequency. At this point, the one pin of the CD4046 chip will output a high level, informing the FPGA to start measuring the frequency. This frequency is the natural oscillation frequency of the oscillating system.

The frequency measurement method chooses to use the FPGA equal precision counting method [9], this method has high measurement accuracy, high speed, and is suitable for different frequency, different accuracy frequency measurement needs. In addition, compared with the traditional frequency meter, the
relative error has nothing to do with the measured signal frequency. Finally, the equal precision measurement of FPGA [10] and communication of STM32 are realized.

![Equal-precision frequency measuring sequence diagram.](image)

By analyzing the sequence diagram of the above equal-precision frequency meter, it can be seen that the equal-precision frequency meter does not influence the count value clk_fx of the measured signal. The error only exists in the standard signal clk_fs, which will cause the error of positive and negative one of the standard signal clk_fs. As long as the standard signal frequency is high, the effect is negligible.

According to formula (3), the dust measurement accuracy is directly determined by the resonant frequency. So it is absolutely necessary to design an accurate frequency meter for this system. In this experiment, a standard frequency signal is generated by the signal generator, and then the frequency meter and multimeter are required to measure this frequency signal. The experimental frequency range ranges from 300Hz to 400Hz. Experimental data are as follows:

| signal generator/Hz | FPGA/Hz          | multimeter/Hz   |
|---------------------|------------------|-----------------|
| 300                 | 299.9999847      | 299.9945        |
| 310                 | 309.9999847      | 309.9945        |
| 320                 | 319.9997405      | 319.9945        |
| 330                 | 329.9997405      | 329.994         |
| 340                 | 339.999756       | 339.994         |
| 350                 | 349.999756       | 349.9935        |
| 360                 | 359.9997405      | 359.9935        |
| 370                 | 369.999756       | 369.9935        |
| 380                 | 379.999756       | 379.993         |
| 390                 | 389.999756       | 389.993         |
| 400                 | 399.999725       | 399.993         |

The above table shows that the frequency meter can meet the precision requirements of the system.

6. Conclusion
In this paper, the phase-locked loop is used in dust measurement of oscillating balance for the first time, a dust measuring device of oscillating balance is designed, and the circuit design and debugging of each module of the system is analyzed. An equal precision frequency meter based on FPGA is designed to
verify the accuracy of this frequency meter, which can meet the actual requirements. But in the
measurement process, it is found that the resonant frequency will be affected by the external temperature
and humidity. According to the above analysis, due to the influence of temperature and humidity, the
measurement accuracy of dust will be reduced. In order to improve the measurement accuracy of dust,
it is necessary to design a constant temperature and humidity environment. Through this instrument,
workers' health and life safety can be guaranteed.

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