A study on the precision of a confocal probe from its fork frequency and amplitude

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Abstract. The confocal probe is a kind of non-contact measurement probes. Through an optical system containing an oscillating tuning fork, it converts displacement measurement to time difference measurement. For the measuring precision, the oscillation stability and swing of the tuning fork are important. Based on analysis, the relationship between the measuring precision and the frequency and amplitude of the tuning fork is described, and the means to obtain stable frequency and amplitude is introduced.

Key words. Resonance Frequency and Amplitude, Confocal probe, Measuring Precision Non-contact measurement.

1. INTRODUCTION
Optical non-contact probes have the advantages of no measuring force, high speed, etc [1]. However, surface conditions, including color, surface, roughness, and inclination greatly affect the accuracy of the probes [2]. As the traditional optical probes, out-of-focus probes have very high sensitivity near the focus, but they have tiny measuring ranges [3-5]. Therefore, the dynamic active confocal measuring instruments have been developed. They have high accuracy, a wide measurement range, and good dynamic performance. More important, they are suitable of measuring highly reflective surfaces, such as high-accuracy metallic and optical pieces [6].

The confocal probe we study works by time difference measuring. The measuring signal is obtained through the light focusing point modulated by the oscillating fork scanning on the surface twice periodically. Both the signal period and the laser focus' syntonic movement are determined by mechanical resonance of the fork. To get high measuring precision, we study the stability of the tuning fork, and the means to improve the stability.

2. PRINCIPLE OF THE CONFOCAL PROBE
Figure 1~3 shows the principle of confocal probe. It converts displacement measurement to time difference measurement [7]. In figure 1, a laser beam emits from light source 1. It is focused on measured surface 8 by lens 5 attached to a tuning fork 6, which is used to modulate the focal position of the optical system. The beam return from the surface 8, and then is focused on the pinhole 3. Detector 4 receives the beam behind the pinhole 3 and transforms the beam to an electrical signal. A peak signal is formed on receiving element 4, when the focal plane coincides with surface 8. Since the fork is oscillating, the light focusing point moves accordingly and scans on the surface twice
periodically. Therefore, in one period, two peaks (hump signal) are formed as figure 2 shows. In figure 2, $\Delta t$ is the time difference between the time when the focal plane is in the neutral position and the time when the focal plane coincides with the surface measured. The displacement of surface measured leads to the difference of $\Delta t$. The relationship between the both is described as follows.

The oscillation equation of lens is

$$\Delta w = A \sin \omega_0 (t_0 + \Delta t)$$  \hspace{1cm} (2.1)

where $\Delta w$ is the displacement of lens, $A$ is amplitude, $\omega_0$ is angular frequency, $\Delta t$ is difference of time, $t_0$ is original time when the fork is in the neutral position, therefore, $t_0 = 0$. When the focal plane coincides with the measured surface,

$$\Delta w = A \sin \omega_0 \Delta t$$  \hspace{1cm} (2.2)

Then the time difference of lens to reach this position is

$$\Delta t = \frac{1}{\omega_0} \arcsin \left( \frac{\Delta w}{A} \right)$$  \hspace{1cm} (2.3)

When the lens move, the focal plane moves accordingly. The relationship between the displacement of the focal plane and the displacement of lens can be described by equation (2.4) as figure 3 shows [6].

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**Figure 1.** Working principle of confocal probe.

**Figure 2.** The method of time difference measurement.
\[
\Delta' = \frac{f'^2 \Delta w}{2 \Delta w^2 - (f'^2 - b) \Delta w + f'^2} + \Delta w
\]  \tag{2.4}
\]

where \(f'\) is foci of \(L_1, L_2\), \(b\) is distance between the two lenses when they are static, \(\Delta w\) is displacement of the two lenses.

Therefore, through measuring \(\Delta t\) from the hump signal \(^8\), we could obtain the displacement of lens, and then obtain the displacement of surface measured by equation (2.4). The displacement measurement converts to time difference measurement.

![Figure 3.](image)

**Figure 3.** Relationship between the displacement of the focal plane and the displacement of lens.

3. VIBRATION OF FORK AND DESIGN

3.1. Principle of the Fork Self-Oscillation

Figure 4 shows the fork self-oscillation system, which consists of two parts. One is fork and lens, and the other is positive feedback circuit composed by coils and amplifiers. The sensing coil senses the amplitude of the fork and this signal is amplified and fed back to excite the fork. When the energy consumed by fork equals the energy supplied by the circuit, the system achieves stable state. Since the amplitude and frequency of the fork are relatively constant, they can be used for measuring.

![Figure 4.](image)

**Figure 4.** Principle of the fork self-oscillation.
3.2. Analysis of the Measuring Precision from the Fork

As equation (2.3) shows, there will be error, if the amplitude and frequency vary. Both the factors are analyzed as follows.

When the frequency of fork oscillating changes $\Delta \omega$, the time error accordingly is

$$d\Delta t = -\frac{1}{\omega_0^2} \arcsin\left(\frac{\Delta \omega}{A}\right)d\omega_0$$  \hspace{1cm} (3.1)

Since the nonlinearity of sinusoid, the precision decreases as $\Delta \omega$ increases. The ultimate value of $\Delta \omega$ used in our system is $0.8A$. So that, $\arcsin\left(\frac{\Delta \omega_{\text{max}}}{A}\right) = 0.927$ and equation (3.1) is changed to

$$d\Delta t_{\text{max}} = -\frac{0.927d\omega_0}{\omega_0^2}$$ \hspace{1cm} (3.2)

When the amplitude of fork oscillating changes $dA$, the time error accordingly is

$$d\Delta t = -\frac{\Delta \omega}{\omega_0 A\sqrt{A^2 - \Delta \omega^2}} dA$$ \hspace{1cm} (3.3)

Since $\Delta \omega_{\text{max}} = 0.8A$, equation (3.3) is changed to

$$d\Delta t_{\text{max}} = -\frac{4dA}{3\omega_0 A}$$ \hspace{1cm} (3.4)

As it is analyzed above, equation (3.2) and equation (3.4) indicate that the amplitude of fork has more obvious effect on the precision of measuring system than the frequency. The following section will show the details to obtain the stability of fork oscillating.

3.3. Design of the Fork

To obtain stable frequency, we choose 3J53 [Ni42CrTiAl] to make the fork. 3J53 is one kind of constant elastic alloys. These alloys have stable natural frequency, low temperature coefficient of elastic modulus and good time stability. They are widely used as exactitude elasticity component or standard frequency component in precision instrument, communication technology, and computer technology [9].

When the material is selected, the capability of fork is determined by its figuration. Figure 5 shows the theoretical oscillating model of cantilever beam, where $l$ is length of the beam, $a$ is height of the section of the beam, $b$ is width of the section of the beam, $m$ is mass of the beam, and $M$ is mass of the end of the beam. The natural angular frequency of cantilever beam is described by equation (3.5).

$$\omega^2 = \frac{3EI}{l^3(M + (33/140)m)}$$ \hspace{1cm} (3.5)

where $E$ is elastic modulus of cantilever beam, and $I$ is inertia moment of cantilever beam. Since the section of this cantilever beam is rectangular, equation of inertia moment is

$$I = \frac{ba^3}{12}$$ \hspace{1cm} (3.6)

For convenience to design the size of fork, the angular frequency $\omega$ is replaced by frequency $f$. We change equation (3.5) to equation (3.7).

$$f = \frac{1}{4\pi} \left(\frac{Eba^3}{l^3[3M + (33/140)b\rho]}\right)^{1/2}$$ \hspace{1cm} (3.7)

where $\rho$ is density of material.
Higher natural frequency is beneficial to oscillation stability and measuring speed of the system, but the amplitude will be small, which limits the measuring range of the system. Hence we choose the natural frequency as high as possible under the premise that the amplitude of fork is large enough for measurement.

We select the amplitude of fork to be 0.1mm to 0.2mm, while its natural frequency is about 300Hz to 500Hz. The fork designed is shown in figure 6. Two cantilever beams of fork are connected by the pedestal, and there are screwed holes to fix the fork. Two beams are designed in the same shape to eliminate effect on oscillation of the pedestal [10]. To get more stable frequency, we conducted heat treatment to the fork. The parameters of the fork are listed below: \( l = 49.5 \text{mm}, b = 5.5 \text{mm}, a = 2 \text{mm}, M = 0.00194 \text{kg} \). Elastic modulus of 31J53 is \( 1.85 \times 10^9 \text{MPa} \), and density is 7900kg/m\(^3\). The theoretical frequency of the designed fork is about 380Hz by equation (3.7). Due to the complexity of oscillating system, practical frequency was tested in experiment. This will be shown in the section 3.5.

![Figure 5. Theoretical model of cantilever beam.](image)

![Figure 6. Figuration of the fork.](image)

3.4. Design of the Fork Self-Oscillation
The base circuit of the fork self-oscillation is shown in figure 7. It is an amplifier circuit with the core OP07. The exciting coil is joined between pin 1 and pin 2, while the sensing coil is joined between pin 3 and pin 4. This circuit is simply designed according to the section 3.1, but the amplitude of fork presents inferior stability in practice. Consequently, we improved the circuit as figure 8 shows.

The major improvement is that an AD5280 is added to the circuit to work together with Rw1. AD5280 is one kind of DCP (Digitally Controlled Potentiometers). It can offer resistance value varied from \( 1k \Omega \) to \( 200k \Omega \).
To make the resistance value of AD5280 vary automatically, we design a control system as figure 9 shows. There is a threshold value set in FPGA (Field-Programmable Gate Array). When the sensing coil signal is greater than threshold value, the value of AD5280 will be adjusted lower; when the signal is less than the threshold value, the value of AD5280 will be adjusted higher. The gain of amplifier can be adjusted in real time through the control system to keep the amplitude of fork stable.
3.5. Experiment

Since the sensing coil senses the oscillation of the fork, the sensing coil signal was detected to reflect the oscillation of the fork. Figure 10 shows the frequency of the fork.

The frequency of the fork is about 343.785Hz, and it approaches the theoretical frequency. The maximum offset value of frequency is 0.045Hz in 6 hours’ running time. The relative error is $1.31 \times 10^{-4}$. From equation (3.2), we calculated the maximum time error $\Delta t_{\text{max}}$, $3.53 \times 10^{-7}$s. Therefore, the error of frequency can be ignored in measuring system.

Figure 11 shows the amplitude of the fork. The value is about 0.107mm. The maximum offset value of amplitude is $3.1 \mu m$ in 4 hours’ running time. The relative error is $1.2 \times 10^{-2}$. From equation (3.8), we calculated the time error $\Delta t_{\text{max}}$, $4.7 \times 10^{-5}$s. Therefore, the error of amplitude can also be ignored in measuring system. As a comparison, we do the experiment according to the circuit in figure 7. The maximum offset value of amplitude is about $20 \mu m$ in a shorter running time, and it affects the precision greatly. Therefore, the improved circuit is much better for the confocal probe.

![Figure 9. Control system for fork oscillation.](image)

![Figure 10. The frequency of oscillating fork](image)
4. CONCLUSION

(1) The precision of confocal probe has more effect from the amplitude of its fork rather than the
frequency of its fork.
(2) The effect of frequency of the fork on measuring precision can be diminished negligible through
proper design of fork.
(3) Since the amplitude of the fork can be maintained stable through controlling the amplification gain
of amplifier in circuit continuously, the effect of amplitude of the fork on measuring precision can also
be ignored in the system.

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