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A SENSITIVE AND STABLE CONFOCAL FABRY–PÉROT INTERFEROMETER FOR SURFACE ULTRASONIC VIBRATION DETECTION*

DING HONG-SHENG(丁红胜)[a)b)], TONG LI-GE(童莉葛)[c)], and CHEN GENG-HUA(陈赓华)[a)]

[a)] *Institute of Physics, Chinese Academy of Sciences, Beijing* 100080, *China*

[b)] *Department of Physics, University of Science and Technology, Beijing* 100083, *China*

[c)] *Mechanical Engineering School, University of Science and Technology, Beijing* 100083, *China*

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A new confocal Fabry–Pérot interferometer (CFPI) has been constructed. By using both of the conjugate rays, the sensitivity of the system was doubled. Moreover, the negative feedback control loop of a single-chip microcomputer (MCS-51) was applied to stabilize the working point at an optimum position. The system has been used in detecting the piezoelectric ultrasonic vibration on the surface of an aluminium sample.

Keywords: confocal Fabry–Pérot interferometer, ultrasonic detection, sensitivity, stability
PACC: 4262, 4385

I. INTRODUCTION

Optical methods of non-destructive testing for detecting ultrasonic waves or ultrasonic pulses are of great interest in materials science. They complement many of the features offered by high-power lasers for the generation of ultrasonic waves.[1,2] One of the most outstanding features is that they require no mechanical contact with the sample which is to be examined. Conventional ultrasonic techniques, in which the piezoelectric transducer elements are normally bonded or coupled to the sample, have some problems from coupling response and variability of couplant. Being of non-contact testing, the application of this technique can be extended to probing specimens with irregular shapes at elevated temperatures.

It is known that when ultrasonic waves are generated in a solid sample, its surface will be in oscillation. Then, if a light beam is incident on the surface, the frequency of the reflected (or scattered) light will be modulated by the oscillation containing the ultrasonic information of the surface. The ultrasonic effect can be described as a phase modulation of the reflected light, or a Doppler shift of the instantaneous frequency, or the generation of sidebands.[4] The ultrasonic signal is demodulated when reflected light passes through a confocal Fabry–Pérot interferometer (CFPI), which has a typical response curve, as shown in Fig.1. Ideally, the frequency discrimination

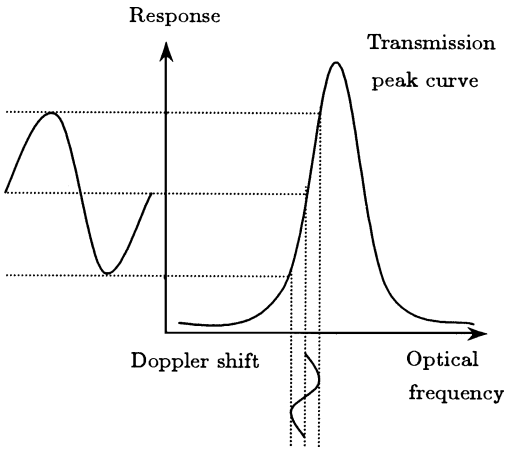


Fig.1. The principle of CFPI demodulation. The frequency variations of the incoming light are demodulated by the CFPI when the laser frequency is set on the slope of a response peak.

requires an optimum setting of the laser frequency at one of the steepest points on the interferometer response curve. At these points, the best demodulation sensitivity can be achieved. Obviously, the steeper the curve, the higher the demodulation sensitivity. However, for a sensitive system, any change of the CFPI spacing and fluctuation of laser-beam frequency can drive the working point away from the best setting and make the system less sensitive and unstable. In a similar system,[3,4] only transmission rays were used, in which the reflection rays did not contribute to the sensitivity. Also, a hardware circuit feedback control loop was used to adjust the operation point, in which a constant reference voltage (called the half-

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peak voltage) was set by the manual method. Sometimes, this method can induce control error because the half-peak voltage is supposed to remain unchanged at all times. The control error will decrease the demodulation sensitivity of the CFPI. Moreover, when using this method, the stability of the CFPI is not good enough for a long-time operation. In order to obtain higher sensitivity and stability, in this paper we propose and construct a new optical system with a single-chip microcomputer (MCS-51) feedback control loop and with double paths of the conjugate rays.

Ⅱ. EXPERIMENTAL ARRANGEMENT

A CFPI was set up in our laboratory, having a piezoelectric ceramic actuator for adjusting the cavity with a cavity length of 298mm, free spectral range of 251MHz, minimum resolvable frequency difference of 6.5MHz, fineness of 38.5 and mirror reflectivity of 98%. The optical layout of the CFPI is sketched in Fig.2. The mirror foci are superimposed (the centre of one mirror is found on the other), i.e. the spacing d equals the mirror radius at the confocal position. This configuration ensures that all the emerging rays (there are four beams, two in transmission and two in reflection) overlap after two round trips. The transmission and reflection rays are mutually conjugate in the whole frequency range. Their response curves have a shape of reversed peak at the resonant frequency.[5] In our experiment, both the reflection and the transmission rays of the CFPI are used simultaneously by subtraction from them. In this way, the peak height of the synthetic curve is doubled and, clearly, the demodulation sensitivity is doubly improved, as shown in Fig.3.

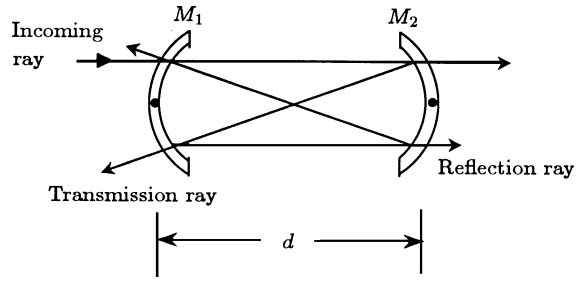


Fig.2. A sketch of the CFPI and the ray paths. For clarity, only two transmission rays and two reflection rays are presented.

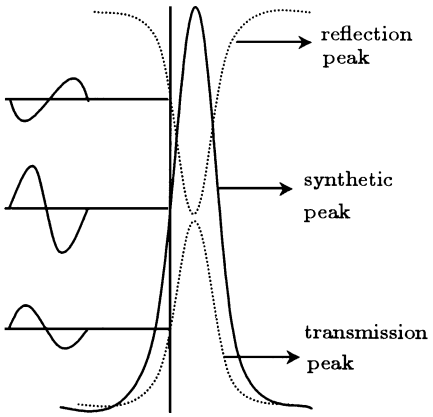


Fig.3. Conjugate analysis.

A schematic diagram of the arrangement of our ultrasonic detection system is shown in Fig.4. The operation beam is provided by a 0.5mW single-mode He–Ne laser. The beam splits into two at BS1. The beam that passes through BS2, CFPI, PBS3 and L_4 is used to control the operation point of the CFPI. The other, being a forward-going beam, is used for detecting the ultrasonic vibration. The half-wave plate (HF) has a function of rotating the polarization of the beam. Through HF the beam is transmitted through PBS1 and focused onto the sample surface, which has been mechanically polished. The backscattered light from the sample surface is collected and collimated by a telescope formed by the lens combination of L_1 and L_2. A quarter-wave plate (QW1) ensures that the polarization of the backscattered light is orthogonal to that of the initial beam. The backscattered light is then reflected successively by PBS1 and PBS2 and transmitted into the cavity of the CFPI, forming interference. The ultrasonic signal will be detected after the beam is demodulated by the CFPI. In particular, the transmission and reflection rays from the CFPI are detected by photodiodes PIN1 and PIN2 respectively in this system.

Generally, the spacing of mirrors in the CFPI must be adjusted to the vicinity of its confocal state before the piezoelectric ceramic actuator (PZT) comes into operation. We assume that the spacing has a small deviation $\varepsilon \ll$ d from its confocal position (see Fig.5), the four-transit ray path exceeds the corresponding paraxial ray path $4(d+\varepsilon)$ by an amount of[6]

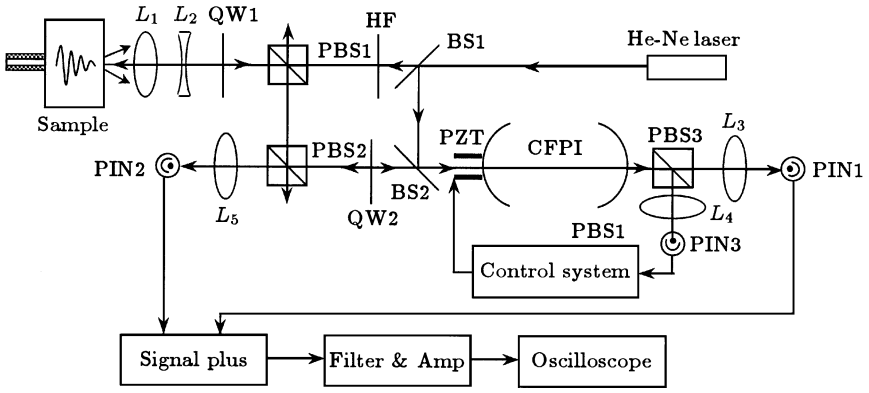


Fig.4. Experimental configuration for the detection of piezoelectric ultrasonic vibration: $L_1 \sim L_5$, lenses; QW1∼2, quarter-wave plate; HF, half-wave plate; PIN1∼3, photodiodes; PBS1∼3, polarizing beam-splitter; PZT, piezoelectric actuator; BS1∼2, beam splitter; : piezoelectric sensor.

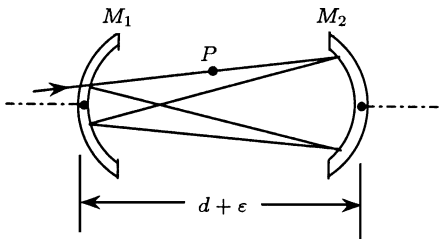


Fig.5. Ray path in the CFPI in the paraxial approximation.

$$\Delta(\rho) \approx \rho^4/d^3 + 4\varepsilon\rho^2/d^2,$$

where ρ is the height of point p at which an entering ray crosses the central plane of the CFPI. Bright fringes are formed in the central plane of the CFPI when $\Delta(\rho)$ satisfies $\Delta(\rho) = m\lambda$, where m is a positive or negative integer, giving an order of interference relative to the order on the axis, and λ is the wavelength of the incident light. Based on the above equation, the fringe radius ρ as a function of ε for given d and λ is plotted in Fig.6. It can be seen clearly that the number of visible rings (ρ is within the field of view) increases and the diameters for given order fringes decrease when the spacing of the CFPI is adjusted away from the confocal position, and vice versa. Figures 7(a), 7(b) and 7(c) successively show the appearance of the fringes and the change of ring number when the mirror spacing of the CFPI is manually adjusted toward the confocal position. The manual adjustment is completed when the diameter of the central fringe reaches its maximum value while the number of rings is the least.

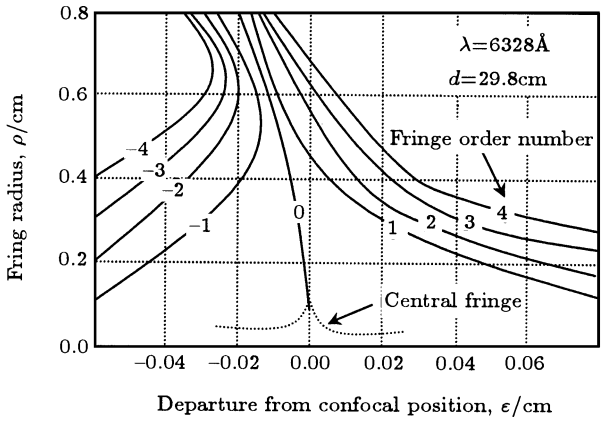


Fig.6. Near confocal FPI fringe patterns.

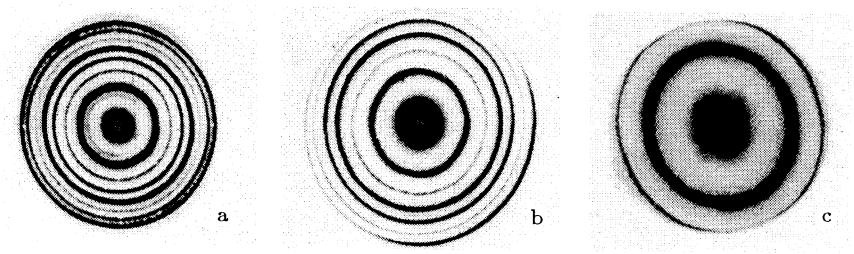


Fig.7. Typical fringe patterns when the mirror spacing of the CFPI is manually adjusted toward the confocal position.

In fact, the state of an interferometer is always somewhat away from its optimum working point because of the change of cavity length and the fluctuations of the laser-beam frequency with time. In order to stabilize the working point, an MCS-51 feedback control loop is used for compensating any deviation. This is achieved by adjusting the voltage of PZT to be fixed to one of the interferometer mirrors. The elongation or shortening of the piezoelectric ceramic will change the cavity length of the CFPI.

The control system can have a relevant half-peak voltage according to the response peak curve when a saw-tooth wave voltage is applied on the PZT. Figure 8 shows the saw-tooth wave voltage and the response curve for a process in searching for the half-peak voltage value. The relevant half-peak voltage, say point a in Fig.8, is stored in a random-access memory (RAM) and used as a reference voltage. The control system continually tests the output of PIN3 in Fig.4. The relevant operation of increasing or decreasing the voltage applied on the PZT will be performed when the tested voltage is not equal to the reference voltage.

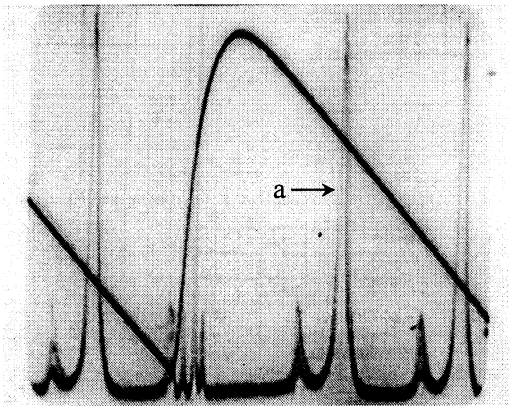


Fig.8. The transmission peaks and the saw-tooth voltage waveform connected to the PZT.

This method can not only meet the needs of real-time measurement but also reset the operating point at any half-peak voltage value if necessary.

Ⅲ. EXPERIMENTAL RESULTS AND CONCLUSION

An experiment for detecting ultrasonic vibration on an aluminium surface has been performed using the above system. The surface ultrasonic wave excited by a piezoelectric transducer has been recorded and shown in Fig.9. The period of excitation is about 1ms. The scale of Fig.9(b) is magnified compared to Fig.9(a). The vibration amplitude decay curve can be fitted with $M = M_0\exp(-t/t_0)$, where M_0 is the vibration amplitude at $t = 0$. The time decay constant can be figured out to be t_0=51±3 (μs). In conclusion, a new optical detection system including a MCS-51 feedback control loop has been introduced. The demodulation sensitivity of the CFPI is improved because of the use of transmission and reflection rays. The detection of ultrasonic vibration excited by a piezoelectric transducer on an aluminium surface shows that the system is both sensitive and stable.

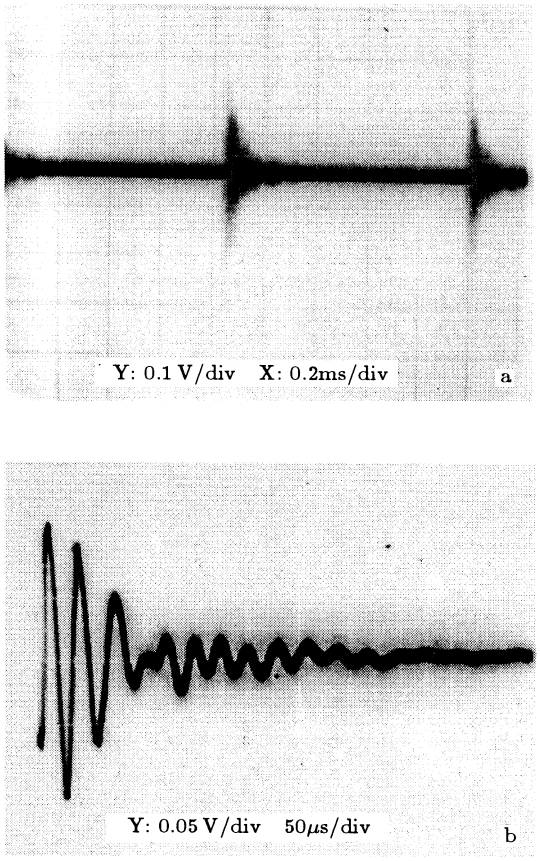


Fig.9. The ultrasonic waveform on an aluminium surface excited by a piezoelectric transducer.

In order to make use of the advantages of the ultrasonic laser, a detection system with ultrasonic vibration excited by high-power laser pulses is in progress. The combination of laser generation and reception of ultrasonic waves offers not only non-contact, but also entirely remote transduction, potentially high bandwidths and high spatial resolution.[1,2] Probably, more interesting phenomena might be found with this system.

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