Open loop Sagnac optical fiber sensor for detecting acoustic emission

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ABSTRACT

A novel open loop Sagnac optical fiber sensing system for detecting AE(acoustic emission) has been proposed and demonstrated. The fiber loop of the Sagnac interferometer was cut off and formed two fiber ports, they were bound and made into the fiber probe. It was placed in the front of the reflector attached to the measured solid. The light from one port was reflected by the reflector and injected into the other fiber port. On the basis of the output optical field distribution function, the position of maximum reflected light intensity was theoretically analyzed. The best work region between the fiber probe and the reflector was ascertained by the experiment. Phase modulation property of the optical fiber sensor was discussed and the optimal working state was obtained by the computer simulation. The optical phase was modulated by the vibration of the reflector generated by the AE. The AE signals were obtained though the optoelectronic conversion, and the frequency of the AE were acquired by using Fourier transform. The experiment results show that the system could be used to detect the ultrasonic waves that propagating on the surface of the solid. The open loop Sagnac optical fiber interferometer sensor has potential for the structural integrity monitoring and NDT applications.

Key words: open loop Sagnac interferometer; optical fiber sensor; acoustic emission, characteristic of phase modulation.

1. INTRODUCTION

Acoustic emission is generally defined as the internally stored energy in a material under load, appearing as a transient stress wave [1]. The detection of the acoustic emission for the purpose of the structural integrity monitoring and the nondestructive evaluation (NDE) using optical fiber sensors has been the subject of many research efforts over the last 20 years. Claus and Cantrell [2] described an experiment by which they were able to detect ultrasonic pulses with a coiled optical fiber embedded in the solidified plastic resin. In 1980, Cielo and Lapierre [3] described two types of optical fiber sensors to be used in a similar way to the surface contact piezoelectric ultrasonic transducers. Meltz and Dunphy [4] used a high birefringence optical fiber embedded to various materials to detect the ultrasonic induced by a CO_2 laser pulses on the surface of these materials. Fomitchov et al. [5] compact phase-shifted Sagnac interferometer for ultrasound detection. Yuan L B et al..[6] detected the acoustic emission in structure using Sagnac-like fiber-loop interferometer. Tae S J et al.[7] used surface-bonded optical fiber Sagnac sensors to detect ultrasound.

In this paper, we report an open-loop fiber optic sensor based on Sagnac-like interferometer for detecting acoustic emission. Due to the nature of the Sagnac's optical configuration, the optical phase shift induced by the surface being probed is differentiated, therefore the results in a measured optical phase shift that is directly proportional to the vibration generated by ultrasonic waves propagating on the surface of a solid plate can be detected accurately. The amplitude and the frequency of the ultrasonic signal are obtained by using Fourier transform technique. Through analyzing the frequency characteristic of the ultrasonic signal, we can identify various ultrasonic signals. It shows that this sensor can be used to detect the acoustic emission associated with the micro crack occurring in concrete structure or as a structural integrity monitor to detect the existence of the ultrasonic waves in structures and successfully actualize the non-destructive evaluation.

2. PRINCIPLE OF THE OPEN LOOP OPTICAL FIBER SENSOR

The principle of the open-loop optical fiber sensor for the ultrasound detection is shown in Fig.1. A laser beam is generated by a laser and coupled into a single mode fiber. This laser beam is split into two arms by a 2×2 coupler. The length of one of the fiber arms with a polarization controller is l_1 while the length of other fiber arm with a time delay

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fiber loop is l_2. The distance between the fiber ends to the reflector is $l^{'}$. The reflectivity of the fiber end is R ($R=r^2$) and assuming the two fiber ends to be the same. The reflectivity of the reflector is $R^{'}$ ($R^{'}=r^{'2}$).

When a laser beam is divided by 3dB coupler into two waves, the two waves are running in the direction to the fiber ends.

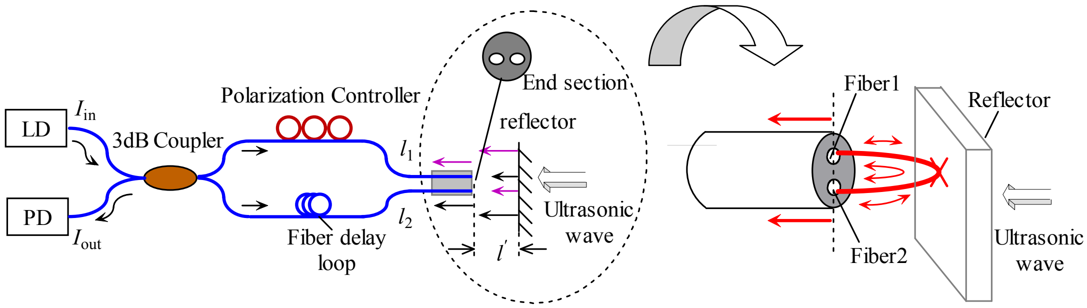


Fig.1. The principle of the open-loop fiber optic sensor

The two light beams are transmitted and/or reflected at the two fiber ends and follow one of the six paths as shown in Fig.1 and combined again at the coupler.

The first light path is "input $\rightarrow l_1 \rightarrow l^{'} \rightarrow l_2$ output" and the corresponding light field at the output can be expressed as

$$E_1 = r^{'}(1-R)E_0 e^{-j[kn(l_1+l_2)+kl'+\phi_0]} \tag{1}$$

Where E_0 is the magnitude of the input optical field; $k=2\pi/\lambda$ is the optical wave number; λ is the laser light wavelength; l is the distance that is from l_1 fiber end to the reflector then returns to l_2 fiber end. n is the effective refractive index of the fiber mode and ϕ_0 is an initial phase.

The second light path is "input $\rightarrow l_2 \rightarrow l^{'} \rightarrow l_1$ output", and the output light field is given by

$$E_2 = r^{'}(1-R)E_0 e^{-j[kn(l_1+l_2)+kl'+\phi_0+\pi]} \tag{2}$$

Where the π phase shift is due to the fact that the light beam is coupled twice at the coupler, each of which introduces a π / 2 phase shift.

The third light path is "input $\rightarrow l_1 \rightarrow$ back-reflected $\rightarrow l_1 \rightarrow$ output", the output light field is

$$E_3 = rE_0 e^{-j[2knl_1+\phi_0+\pi/2]} \tag{3}$$

The fourth light path is "input $\rightarrow l_2 \rightarrow$ back-reflected $\rightarrow l_2 \rightarrow$ output", the output light field is

$$E_4 = rE_0 e^{-j[2knl_2+\phi_0+\pi/2]} \tag{4}$$

The fifth light path is "input $\rightarrow l_1 \rightarrow l^{'} \rightarrow$ back-reflected $\rightarrow l_1 \rightarrow$ output", the output light field is

$$E_5 = (1-R)r^{'}E_0 e^{-j[2knl_1+k2l^{'}+\phi_0+\pi/2]} \tag{5}$$

The sixth light path is "input $\rightarrow l_2 \rightarrow l^{'} \rightarrow$ back-reflected $\rightarrow l_2 \rightarrow$ output", the output light field is

$$E_6 = (1-R)r^{'}E_0 e^{-j[2knl_2+k2l^{'}+\phi_0+\pi/2]} \tag{6}$$

The total light intensity at the sensor output is

$$I = \left(\sum_{i=1}^{6} E_i\right)\left(\sum_{j=1}^{6} E_j\right)^* = E_0^2[2+2\cos 2kn(l_2-l_1)][R+(1-R)R^{'}+2(1-R)\sqrt{RR^{'}}\cos(2kl^{'})] \tag{7}$$

It can be seen from Eq. (7) that, if we select $l_1 \cong l_2$ and keep l_1 and l_2 within the same optical cable, the environmental effect on the lead in/out fibers (i.e. l_1 and l_2) would be minimized, and the variation in the output light intensity would primarily depend on the phase change occurring within the distance between the fiber ends to the reflector.

Assuming an array of ultrasonic waves powering at the reflector, there is

$$2kl' = \phi_s + \Delta\phi \tag{8}$$

Where ϕ_s is the phase change by harmonic ultrasonic waves powering at the reflector, $\Delta\phi$ is initial phase.

We pay attention to the AC portion of interferometric detection, so Eq. (7) can be expressed as

$$I \propto 2E_0^2[2+2\cos 2kn(l_2-l_1)](1-R)\sqrt{RR'}\cos(\phi_s+\Delta\phi) \tag{9}$$

The ultrasonic waves can be expressed as

$$u_s(t) = u_{s0}\cos\omega t \tag{10}$$

So Eq. (9) can be expressed as

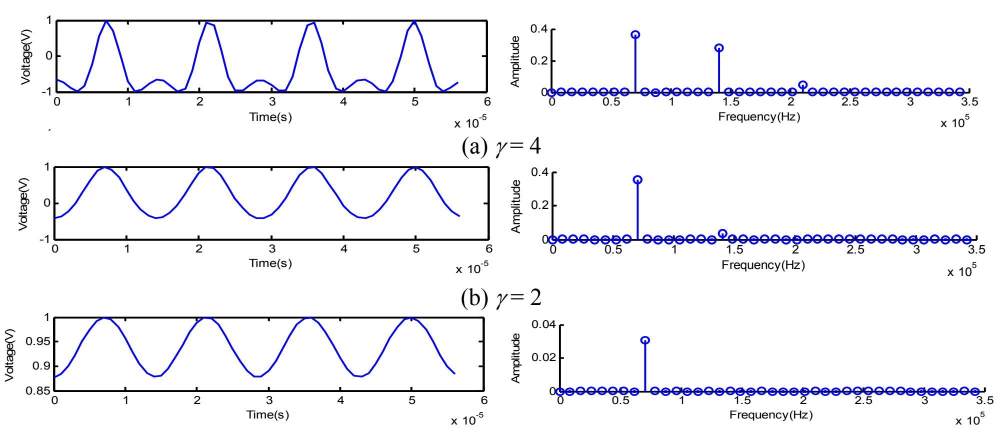
$$I \propto A\cos(\gamma\cos\omega t + \Delta\phi) \tag{11}$$

Where $A = 2E_0^2[2+2\cos 2kn(l_2-l_1)](1-R)\sqrt{RR'}$; γ is a constant that is in proportion to the amplitude of the ultrasonic wave.

3. SIMULATION OF THE COMPUTER

We apply the MATLAB software to make a simulation in order to validate the accuracy of the principle of the open-loop fiber optic sensor and obtain the optimal condition of the experiment. Adopting sine wave as the input signal and the frequency of the sine wave is $\omega/2\pi$ =35kHz. Three conditions of output voltage signal waveform and its spectrum which is converted by photoelectric conversion are respectively simulated.

In Eq. (11), it can be seen as $\Delta\phi$ =0, respectively set γ =4, γ =2, γ =0.5, the simulation curves of the voltage signals waveform corresponding to the output intensity of the sensor and the corresponding Fourier spectrums are shown in Fig.2(a), (b), (c).



(a) $\gamma = 4$

(b) $\gamma = 2$

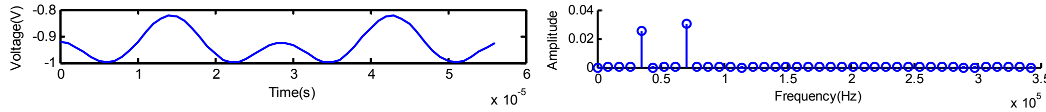
(c) $\gamma = 0.5$

Fig.2.The time domain signals and the frequency domain signals

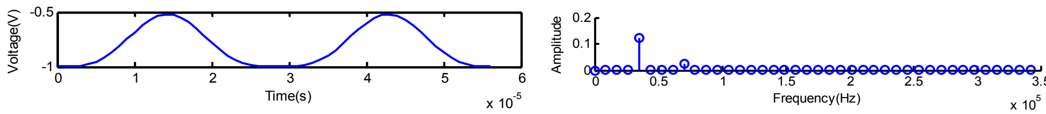
From Fig.2, it can be seen that with the decreased value of γ , the output signal is closed to sine wave and has no harmonic wave. The frequency of the output signal is inclined to the single frequency, but the frequency is twice as large as that of the ultrasonic signal.

According to above simulation results and the corresponding frequency spectrums we know that when γ =0.5, the curve is closed to sine wave, and its frequency is inclined to the single frequency. In addition, the amplitude of the ultrasonic waves which are generated by PZT is small, so set γ = 0.5.

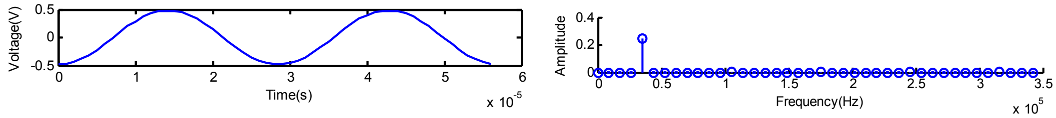
When γ=0.5, in Eq.(11) respectively set $\Delta\phi$ =29π/30 , $\Delta\phi$ =5π/6 , $\Delta\phi$ =π/2 , $\Delta\phi$ =π/6 , $\Delta\phi$ =π/30 the simulation curves of the voltage signals waveform corresponding to the output intensity of the sensor and the corresponding Fourier spectrums are shown in Fig.3(a), (b), (c), (d), (e).



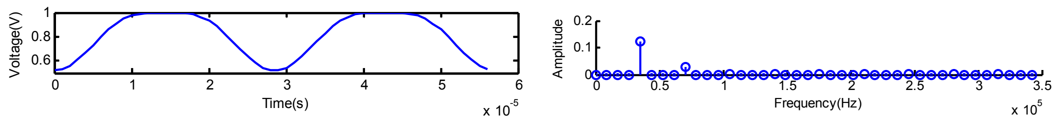
(a) $\Delta\phi$ =29π/30



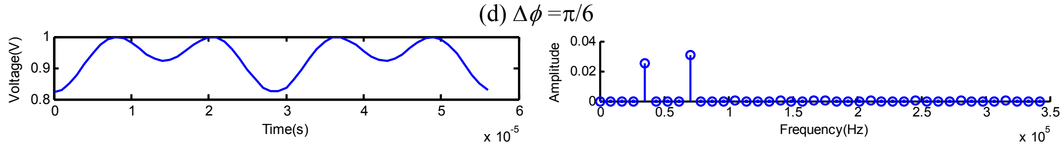
(b) $\Delta\phi$ =5π/6



(c) $\Delta\phi$ =π/2



(d) $\Delta\phi$ =π/6



(e) $\Delta\phi$ =π/30

Fig. 3. The time domain signals and the Frequency domain signals

From Fig.3, it can be seen that only when the value of $\Delta\phi$ is closed to π/2, the output signal is similar to the sinusoid and have no harmonic wave. We can see that the frequency is the same to that of the ultrasonic source from the frequency spectrum.

From the above analysis, it can be seen that when the value of γ is small and $\Delta\phi$ is closed to π/2, the basic frequency of the output signal from the sensor is the same to the ultrasonic wave modulation signal. So as long as the optical fiber sensor system is properly constituted to work at high sensitivity field which $\Delta\phi$ is closed to π/2, the basic frequency of the output signal is the frequency of the ultrasonic wave.

4. ANALYTIC MODEL OF THE FIBER OPTIC PROBE

Generally, the reflected optical fiber probe is consisted by two fibers. One fiber is light source and the other fiber is light receiver. The light source fiber illuminates the reflecting surface, and the receiving fiber receives the reflected light. By measuring the light intensity of the output of the receiving fiber, one can determine the displacement between the fiber and the reflecting target. For this optical fiber constitution, when a fiber is used as the detector to receive the intensity of the output optical field formed by the source fiber end, thus, the received intensity can be given by

$$I(x) = \frac{RSI_0}{\pi\omega^2(2x)} \cdot \exp\left[-\frac{d^2}{\omega^2(2x)}\right] \tag{12}$$

Here, $\omega(x) = \sigma a_0\left[1 + \xi(x/a_0)^{3/2} \tan\theta_c\right]$.

Where R is the reflectivity of the reflector, S is the receiving area of the fiber end; x is the distance between fiber end and reflector. The single-mode fibers are used for the experimental design, σ=1, the radius of the fiber core is a_0 (a_0=0.00185mm), the distance of two fibers is d (d=0.3mm), integrated modulation parameter is ξ (ξ=1.15), θ_c is the maximum incident angle for the fiber (θ_c =0.171) [8].

The theoretical curve coming from Eq. 12 is given as Fig.4.

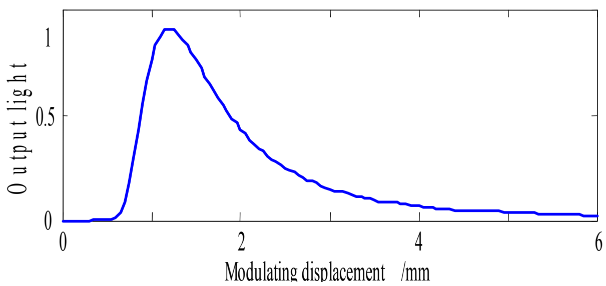


Fig. 4. Theoretical curve

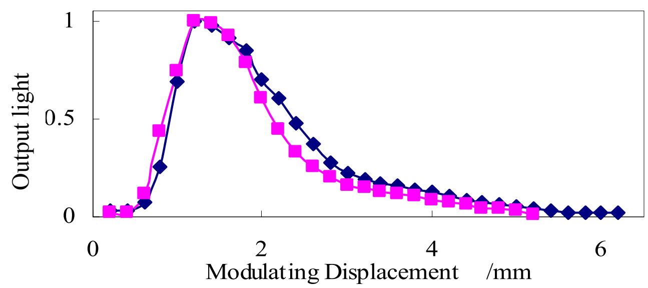


Fig. 5. Normalized experimental curves

From Fig.4, it can be seen that as long as the value of *x* properly, we can detect the maximal reflected light intensity. Under this condition of doing the experiment, high sensitivity field of the sensor system can be obtained. In the experiment, the two fiber ends of the open-loop Sagnac fiber optic sensor are not only as light sources but also as light receivers. The photoelectric testing apparatus is used to measure the received light intensity of the fiber probe of the open Sagnac sensor. The two reflected light intensity curves are shown in Fig.5. On the whole, the distributed regularities of two paths light intensity are same to the theoretical curve, and the two light can be interference. So we ascertain the best working region between the fiber ends of optic fiber detecting probe and the reflector. The experiment result is shown in Fig.5. From Fig.5, it can be seen the best working region is from 1.0mm to 1.2 mm.

5. EXPERIMENT SETUP

The experimental setup for the ultrasonic signal detection is depicted in Fig.6. The experimental system includes a LD laser (λ = 650nm, $\Delta\lambda$ =0.01nm, coherent length is 4.225cm), two FC connectors, a 3dB single-mode fiber coupler, a Polarization Controller, an inching regulating device, a Reflector, a PD (photo detector), a home-made Amplifier, a PC Based Digital Storage Oscilloscope with a Logic Analyzer and FFT (Mode No.DSO-2902, 256k), a Computer, a PZT transducer and an Ultrasonic signal Generator.

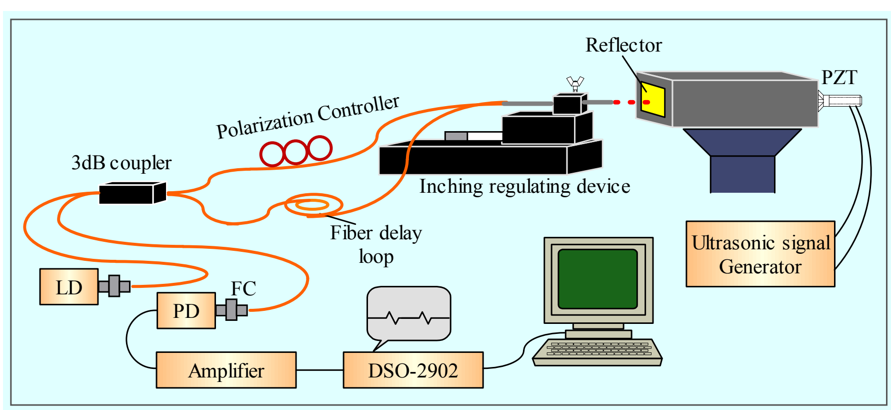


Fig.6. Experimental setup of open-loop Sagnac fiber optical sensor system

A concrete slab is adopted as the ultrasonic transmission medium and the size of the concrete slab is 250×250×70mm^3. The reflector and PZT are respectively adhered to the front and the back of that concrete slab. The reflector is adhered to the front of the concrete slab. The fiber delay loop is used to adjust the lengths of the two fiber arms to be nearly equal. So that light signals can interfere. The distance between the fiber optic probe and the reflector is regulated by an inching regulating device with a micrometer screw rod and locking apparatus. We can adjust the place of the fiber probe to the best working state with the inching regulating device and the photoelectric detector. When the ultrasonic wave propagates in the concrete slab, the reflected light will be modulated by the ultrasonic signal, we can collect the ultrasonic signal by the photoelectric transducer and Digital Storage Oscilloscope (DS0-2902), and finally we can analyze and process the collected signal with the computer.

6. EXPERIMENT RESULTS

6.1. Simulated source

An ultrasonic signal generator with a standard piezoelectric ceramic transmitter (PZT) is adhered to the back of the concrete slab and is used to generate the ultrasonic wave. The operating frequency is 35 kHz. The Polarization controller is used to adjust the input state of polarization to maximize the sensor response that $\Delta\phi$ is closed to $\pi/2$.The fiber optical probe is plated to the reflector in the best working region (1.0mm-1.2mm) which is obtained by the experimental result. The waveform of the output voltage of the system is shown in Fig.7, and the corresponding Fourier transform is shown in Fig.8.

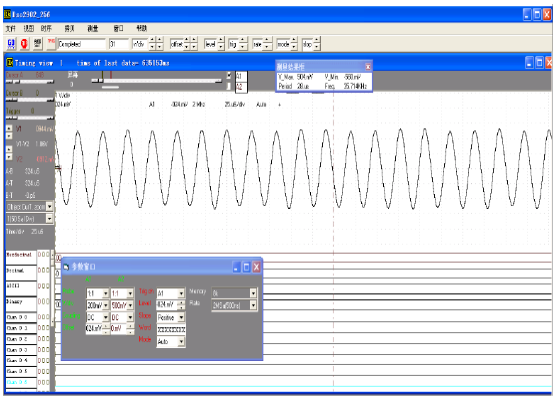


Fig.7. Output voltage of the experimental system

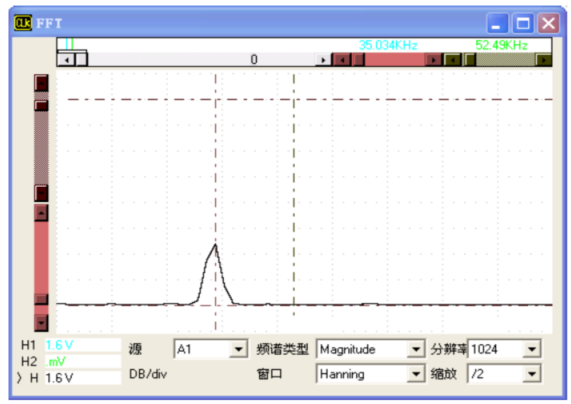


Fig.8. Frequency spectrum of Fourier transform for the output signal

From the above figures, we can see that when the frequency of sine signal which is generated by the signal generator is 35kHz, the frequency of the detected signal is also 35kHz, and there isn't any harmonic wave. So it shows that the structure of this optic fiber sensor is perfect, because $\Delta\phi$ is closed to $\pi/2$, we detect the signal frequency is the AE signal frequency, and the detecting sensitivity of the optic fiber sensor is relatively high.

6.2. Impact source

The ultrasonic signal generator is closed, and then impacts the surface of the concrete slab. The impact action will produce a blast signal which is equivalent to an acoustic emission signal. The output signal due to impact is shown in Fig.9.

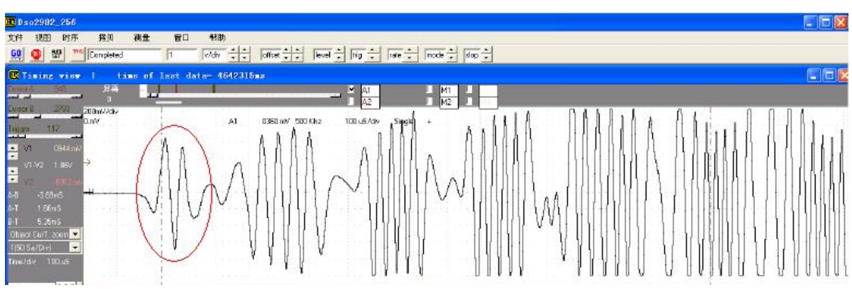


Fig.9. Output signal due to impact

From Fig.9, it can be seen that the red region which is the initial vibration of the output signal that is the typical acoustic emission signal and the rest segment of the output signal is the reflected waves because the concrete slab's size is limited. So the red region of the output signal is extraction-step for the analysis of data collected, we use the Matlab software to process the data. The waveform and the frequency spectrum of Fourier transform of that are respectively shown in Fig.10 (a), (b). From Fig.10 (b), the main response frequency of the output signal is around the 10 kHz, so we can identify the acoustic emission signal by the main response frequency characteristic of that.

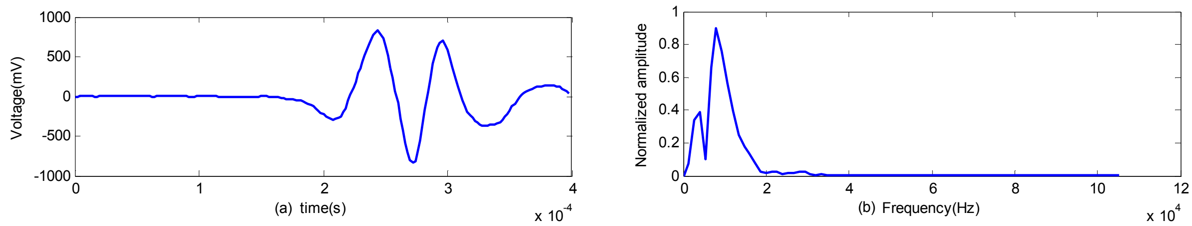


Fig.10. the initial vibration of the output signal

(a) Time domain signal (b) Frequency domain signal

Because the traditional PZT detecting technology is limited by the resonance frequency, the detecting range is finite interval. The optic fiber detection is all-channel detection, so it is proper to detect all acoustic band signals.

7. CONCLUSION

One Open-loop Sagnac optical fiber sensor system for the ultrasonic detection is proposed and demonstrated. The best working region of the optical fiber sensing probe is defined by theoretical derivation and experimental results. The optimal working state of the fiber optical sensor is obtained by the simulation of the computer, so it can be known that the signal frequency detected by the sensor is the frequency of the input signal. Now the acoustic emission has been widely used for non-destructive evaluation application, so the blast wave is adopted to simulate acoustic emission signal in the experiment, and then the frequency characteristic of acoustic emission signal is obtained by Fourier technique. The experimental results indicate that the system can identify the acoustic emission signal by the frequency characteristic of that, and it can be also used to detect the surface feeble vibration which is generated by the ultrasonic waves propagating in the concrete structure. The open Sagnac fiber optic interferometer sensor has potential for the structural integrity monitoring and NDT applications. In the future, it is can be used to monitor and evaluate structure health of the bridge, tunnel, dam and the large storage tank and so on, detect the leak of the oil pipeline, and monitor the some of the key joints of the water and electricity industries civil construction for long time and be on-line.

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