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Influences of modulation frequency on dynamic performance of vibration sensor based on Φ-OTDR

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Abstract: The acousto-optic modulator (AOM) is an important component of fiber-optic distributed vibration sensing system based on Φ-OTDR which can modulate the CW light to pulsed light. The frequency of AOM directly affects the dynamic performance of the system. Based on the sensing mechanism of the system, the influence of modulation frequency on the frequency response was analyzed theoretically. The results show that the utmost frequency of the vibration signal regenerated by the system is limited by the modulation frequency. The range of frequency response extends with the increase of the modulation frequency, which means the limitation of frequency response increases and the distortion of the vibration signal decreases when a laser source with constant optical power is utilized. On the contrary, the high frequency vibration signal will be severely distorted when the modulation frequency is insufficient.

Key words: modulation frequency; dynamic performance; Φ-OTDR; fiber-optic distributed vibration sensor

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调制频率对 Φ-OTDR 分布式光纤扰动传感系统动态性能的影响

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摘　要: 调制器将输入连续光调制成脉冲光,是基于 Φ-OTDR 分布式光纤扰动传感系统的重要组成部分，其调制频率直接决定了系统的监测距离并影响系统的动态特性。对调制频率对系统动态响应范围的影响进行了理论分析及仿真研究。结果表明,脉冲调制频率决定了系统所能还原的外界扰动信号的最高频率。调制频率越高,系统的频率响应范围越大,可探测到的扰动的极限频率越高,采集到的信号失真度越低;反之,调制频率较低甚至低于扰动信号频率时,采集到的信号将严重失真。

关键词: 调制频率； 动态性能； 光时域反射计； 光纤扰动传感

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0 Introduction

Dynamic performance is a very important indicator in vibration sensing. In some special monitoring areas such as security monitoring, crack detection of materials and anomaly detection of engines, the frequency range of these events could be as high as several kHz or even higher. In these cases, the vibration sensors with high frequency response, high spatial resolution, and large monitored length among the sensing fiber are highly desirable in order to prevent potential disasters[1].

The distributed fiber-optic sensor based on phase-sensitive optical time-domain reflectometry(Φ-OTDR) attracts intense attention for vibration monitoring. Compared with the conventional sensor, it has many advantages such as simple structure, high sensitivity, low cost, good concealment, anti-electromagnetic interference and the capability of detecting the multi-vibration within the optical fiber simultaneously, etc. Recently, vibration sensing systems based on Φ-OTDR has gradually become an active research area since Φ-OTDR with narrow injecting linewidth than that of conventional OTDR was proposed by H.F. Taylor in 1993[2]. Then Juan C. Juarez, Rao Yunjiang and Xiaoyi Bao improved the performance of Φ-OTDR in extending monitoring distances, improving spatial resolution and expanding frequency response range[3-5] respectively.

We present the theoretical analysis and simulate about the influence of the modulation frequency on the dynamic performance of vibration sensing system based on Φ-OTDR, and investigate the frequency response limitation of the system.

1 Principle

Fiber-optic distributed vibration sensing system based on Φ-OTDR utilizes coherent interference of Rayleigh backscattering detecting the interference of the backscattered light waves from different locations to obtain the weak vibration signal.

Compared to conventional OTDR system, the Φ-OTDR used for vibration sensing requires a laser with minimal frequency drift as well as a narrow linewidth[6-8]. The former will lead to trace to fluctuations, which will obscure the effect of a vibration. The latter is necessary for Φ-OTDR to enhance interference and achieve high phase sensitivity so that weak refractive index change could be detected. The Schematic diagram of fiber-optic distributed vibration sensor based on Φ-OTDR is shown in Fig.1. An acousto-optic modulator (AOM) modulates the CW light emitted by a laser with minimal frequency drift to generate the light pulses injecting into the optical fiber and the backscattered light from the fiber is monitored with a photodetector(PD).

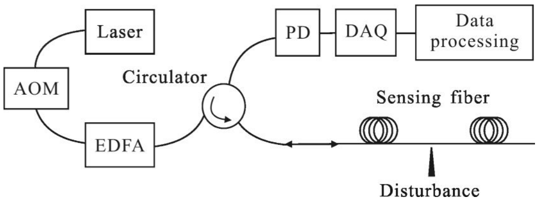

Fig.1 Schematic diagram of fiber-optic distributed disturbance sensor based on Φ-OTDR

According to the one-dimensional pulse-response model of Rayleigh backscattering in a single-mode fiber [9-10], it is supposed that the light injected into the sensitive optical fiber when $t_0=0$ is quasi-monochromatic rectangular pulse with frequency v, pulse width w, and the coherence time of the laser is much larger than the pulse width. Then the field amplitude of the Rayleigh backscattering light can be represented by

$$e(t)=\sum_{i=1}^{N} a_i\exp\left(-\frac{\alpha}{2}\frac{c\tau_i}{n}\right)\exp[\mathrm{j}2\pi v(t-\tau_i)]\mathrm{rect}\left(\frac{t-\tau_i}{w}\right) \quad (1)$$

where N is the number of scattering center; a_i is the amplitude of backscattering wave with the code number of i, α and n are attenuation coefficient and refractive index of the fiber respectively, c is the velocity of light in vacuum; τ_i is the time delay of backscattering wave with the code number of i which can be described as

$$\tau_i=2nl_i/c \tag{2}$$

where l_i is the distance from the input terminal to the code number of i. As illustrated in Fig.2, when the sensing fiber and light source are stabilized, the Rayleigh backscattering trace exhibits a unique temporal signature characteristic of the state of the sensor. The backscattering trace changes when the vibration occurs and the disturbance time are proportional to the range (distance along the fiber from the proximal end). The relationship between the change appearing time t and the vibration location z can be described as

$$t=2nz/c \tag{3}$$

where t is the time interval relative to t_0.

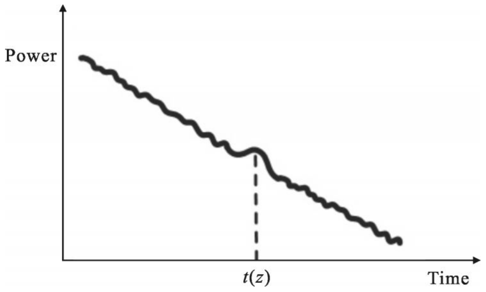

Fig.2 Rayleigh backscattering trace in a period

In order to confirm the starting point of time, sync pulse is brought in to acquire modulated pulses and the backscattering signal simultaneously. The rising edge of the sync pulse corresponds to the starting point of the sensing fiber, so that the vibration position z can be recognized through time t when the backscattering trace changes. We choose the G.652 standard single mode fiber with refractive index of 1.468 in Φ-OTDR system. Then we can get the position z via Eq.(3) as

$$z=1.022\times10^8\cdot t \tag{4}$$

Thus, the power of the Rayleigh backscattering signal at time t just matches the position z.

Assuming the modulation frequency is f, we can obtain a continuous Rayleigh backscattering signal with a period of $T=1/f$. Injecting in pulses continuously, the amplitude of the kth period can be expressed as

$$e'(t)=\sum_{i=1}^{N} a_i\exp\left(-\frac{\alpha}{2}\frac{c\tau_i}{n}\right)\exp\left[\mathrm{j}2\pi\upsilon\left(t-\frac{k}{f}-\tau_i\right)\right]\cdot$$

$$\mathrm{rect}\left(\frac{t-k/f-\tau_i}{w}\right) \tag{5}$$

Then the optical power of the Rayleigh backscattering light can be described as

$$p'(t)=|e'(t)|^2=P_a'(t)+P_b'(t)$$

$$P_a'(t)=\sum_{i=1}^{N} a_i^2\exp\left(-\alpha\frac{c\tau_i}{n}\right)\mathrm{rect}\left(\frac{t-k/f-\tau_i}{w}\right)$$

$$P_b'(t)=2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} a_i a_j\exp\left[-\frac{\alpha}{2}\frac{c(\tau_i+\tau_j)}{n}\right]\cos[2\pi\upsilon(\tau_i-\tau_j)]$$

$$\mathrm{rect}\left(\frac{t-k/f-\tau_i}{w}\right)\mathrm{rect}\left(\frac{t-k/f-\tau_j}{w}\right) \tag{6}$$

where $P_a'(t)$ represents the sum of the optical power of every independent backscattering center, which provides the conventional OTDR waveform, $P_b'(t)$ is induced by the interference of different backscattering center in pulse width.

As shown in Fig.3, the vibration signal at position z could be regenerated through linking the scattering signal taken out at time t in m periods.

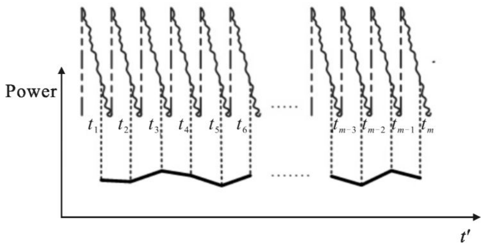

Fig.3 Reproduced/regenerated vibration signal

For a certain vibration point, each period, the Φ-OTDR system can only detect a single effective signal. Therefore, the modulating frequency of AOM determines the interval of collecting the effective signals and hence influences the frequency response range. In the case that the sample rate of data acquisition(DAQ) is high enough, the frequency of the regenerated vibration signal depends mainly on the modulating frequency of AOM. Furthermore, the frequency of the retrieved signal is affected by the system noise and data processing algorithms.

According to shannon theorem, the regenerated signal can retain the dynamic performance integrity of the original signal when sampling frequency is greater than twice of the highest signal frequency. So the ultimate frequency of the regenerated signal can reach $f/2$ for the fixed modulating frequency f. In fact it is difficult to achieve $f/2$ because of the system noise and data processing algorithms.

Based on the model and analysis mentioned above, simulation is carried out to study the frequency response of the Φ–OTDR system with various modulating frequency.

2 Simulation

In the Φ–OTDR system, if modulating frequency of AOM is too low, the vibration signal detected by the PD will appear severe distortion, impacting the subsequent data processing and accurate location.

Figure 4 shows the frequency spectrum of the original vibration signal and detected signal, where the highest vibration frequency is 10 kHz.

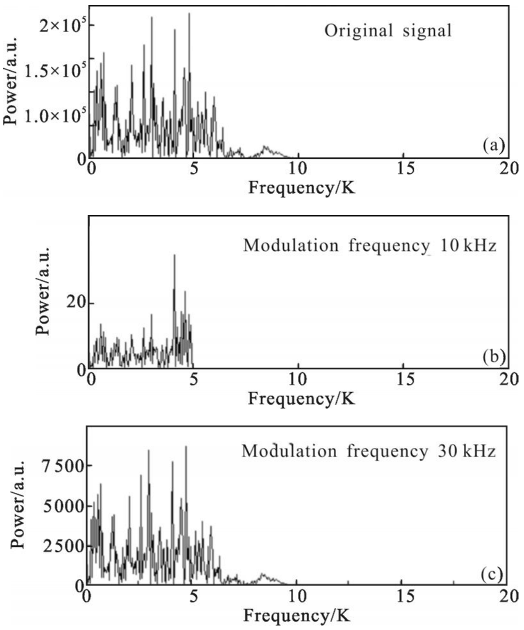

Fig.4 Frequency spectrum of original and regenerated signal

As illustrated in Fig.4, under the modulating frequency of 10 kHz, the maximum detectable frequency is only 5 kHz. However, with the same vibration signal, the system has better frequency response to the vibration signal when the modulating frequency is up to 30 kHz.

The original vibration signal and the regenerated signals with different modulating frequency of 10 kHz and 30 kHz are shown in Fig.5. It is obvious that the vibration signal appears serious distortion when the modulating frequency is 10 kHz, while the vibration signal information can be well reproduced with the modulating frequency of 30 kHz.

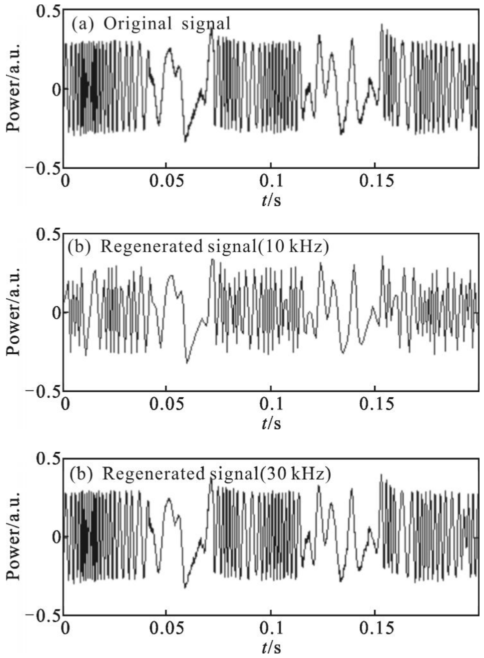

Fig.5 Original and regenerated signal

The distortion can be evaluated by root mean square error(RMS) as follows

$$RMS=\sqrt{\frac{\sum_{i=1}^{N} d_i^2}{N}} \tag{7}$$

where N is the number of equidistant sampling points, d_i is the deviation between the original signal and the regenerated signal in i.th frequency component. For this vibration signal with a maximum frequency of 10 kHz, RMS is 0.7 when the modulating frequency is 10 kHz, while RMS could reduce to 0.23 when the modulating frequency is 30 kHz.

The distortion of the signal, with different modulating frequency, is quite different from each other when a laser source with constant power is employed.

As can be seen from Fig.6, in the case of identical modulating frequency, RMS improved with the increase of the frequency of vibration signal. It means that for a certain system, the distortion will be higher as the signal frequency increases. However, RMS decreases with the raise of the modulating frequency for the given vibration signal, which means the frequency response to the vibration signal improves.

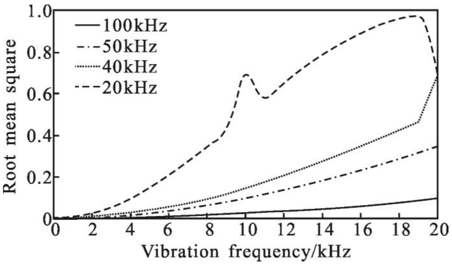

Fig.6 Distortion of the signal with different modulating frequency, the *x* label is the frequency of vibration signal, different curves represent different modulation frequencies of AOM

3 Conclusion

In this paper, we analyzed the effect of modulating frequency on the dynamic performance of vibration system based on *Φ*-OTDR. The results show that the frequency of AOM has a significant influence on the dynamic performance. The frequency response rises with the increase of modulating frequency, which means the detectable vibration signal range extends as well. However, in practical applications, since the averaging method is usually utilized in data processing to improve the spatial resolution, it is difficult to achieve the frequency response limitation. In the future, we can optimize data processing algorithm to improve the real-time performance, and hence further improve the frequency dynamic performance and promote the practical application of the *Φ*-OTDR system. Our research makes an exploration to improve the frequency dynamic performance of the system.

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