Optik 158 (2018) 91–96

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

High-resolution distributed strain sensing system for landslide monitoring

Zhihua Yu [a,b,*], Haolong Dai [a,b], Qi Zhang [a,b], Mingyu Zhang [a,b], Li Liu [a,b], Jingjing Zhang [a,b], Xing Jin [a,b]

[a] *School of Automation, China University of Geosciences, Wuhan, Hubei, China*
[b] *Hubei Key Laboratory of Advanced Control and Intelligent Automation for Complex Systems, Wuhan, Hubei, China*

ARTICLE INFO

Article history:
Received 26 October 2017
Received in revised form 5 December 2017
Accepted 5 December 2017

Keywords:
Landslide monitoring
Distributed sensor
Fiber sensor
Coherent optical time-domain reflectometry (COTDR)
Rayleigh scattering

ABSTRACT

A novel fiber-optics landslide monitoring system is proposed to achieve distributed,high-sensitivity and high-resolution strain measurement. The whole system adopts Rayleigh backscatter-based coherent optical time-domain reflectometry (COTDR) technique to realize long-distance, real-time monitoring with a resolution of 0.1 $\mu\varepsilon$ and a spatial resolution of one meter.

1. Introduction

Landslide is one of the most costly catastrophic events in terms of human lives and infrastructure damage, early warning monitoring for landslides becomes more and more important.Especially, the monitoring for landslides in man-made structures, such as bridges, dams and hydraulic engineering, plays a key role in the prevention and mitigation of risks related to natural and technological hazards [1,2].In most cases the occurrence of landslides is originated by the loss in equilibrium of the soil mass due to changes in one or more parameters, such as seismic noise, ground displacements, piezometric level and rainfall, which contribute to leaving the mass itself stable.Through continuous monitoring the correlative parameters, the dynamics activity of the landslide can be observed.In spite of their respective advantages, geophysical method, clinometers, "3S" technology, time domain reflectometry technology (TDR), optic time domain reflectometry technology (OTDR), Brillouin optical time domain reflectometry technology (BOTDR), and Brillouin optical time domain analysis technology (BOTDA), etc. are limitedly applied in landslide monitoring [3–6], for they fail to meet the requirements of low-cost auxiliary materials, distributed, real-time, remote telemetry and high initial measurement accuracy at the same time. In fact, the landslide will occur when the balance between the hill's weight and the countering resistance forces is tipped in favor of gravity [7–10].So, if the intra-stress distribution and changes of the landslide bodies can be monitored, the occurrence of landslides will be predicted accurately.According to the characteristics of the intra-stress distribution and changes detected by the distributed

* Corresponding author at: School of Automation, China University of Geosciences, Wuhan, Hubei, China.
E-mail address: yuzhihua@cug.edu.cn (Z. Yu).

https://doi.org/10.1016/j.ijleo.2017.12.013

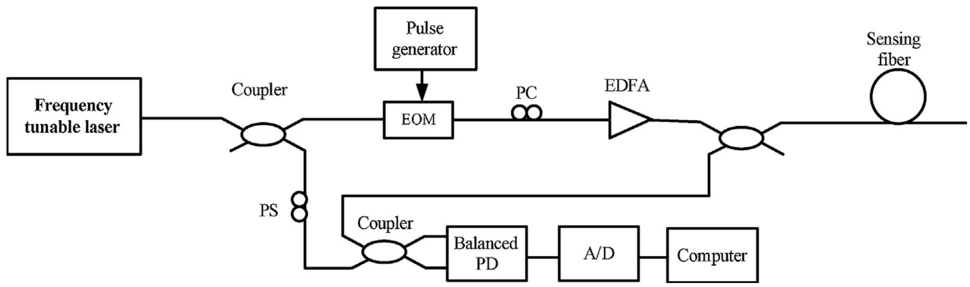

Fig. 1. Basic schematic diagram of COTDR.

fiber optic stress sensor, combining with some applications of specific mathematical models.the movement the landslides call be predicted, thus the disaster could be avoided.

In this paper, we proposed a novel fiber-optics landslide monitoring system to achieve distributed、high-sensitivity and high-resolution strain measurement. The whole system adopts Rayleigh backscatter-based coherent optical time-domain reflectometry (COTDR) technique to realize long-distance, real-time monitoring with a resolution of 0.1 $\mu\varepsilon$ and a spatial resolution of one meter.

2. Measurement principle

2.1. The basic principle of COTDR

The measurement principle of COTDR technique is using a one-dimensional impulse-response model of the backscattering from a fiber [shown in Fig. 1]. The light source is a frequency tunable laser and the laser frequency can be adjusted precisely with an amount of frequency shift. A coupler divides the CW light into two paths to provide a signal and a local oscillator. Probe pulses are produced by an electro-optic modulator (EOM) which is driven by a pulse generator. The state of polarization state is scrambled by the polarization controller (PC). An erbium-doped fiber amplifier (EDFA) amplifies the probe pules and launches them into the sensing fiber. The backscattered wave from the sensing fiber is mixed with the local optical oscillator signal and detected with a photodiode receiver, and then the signal is sampled and processed by signal processing unit. The polarization scrambler (PS) is used to eliminate polarization mismatching induced noise. When we launch a coherent light pulse with a pulsewidth W and an optical frequency υ into a fiber at t = 0, we obtain a backscattered wave e (t)that is given by [13]

$$e(t) = \sum_{i=1}^{N} \alpha_i \exp\left(-\alpha \frac{c\tau_i}{n_f}\right) \exp\left\{j2\pi\upsilon(t-\tau_i)\right\} rect\left(\frac{t-\tau_i}{W}\right) \tag{1}$$

N is the total number of scatterers, c is the velocity of light in a vacuum, $\alpha$is the fiber attenuation constant, n_f is the refractive index of the fiber. The delay τ_i corresponds to the distance $\mathcal{Z}_i$ from the input end to the ith scatterer through the relation $\tau_i = 2n_f\,\mathcal{Z}_i/c$. and $rect[(t-\tau_i)/W] = 1$ when $0 \le (t-\tau_i)/W \le 1$, and is zero otherwise.

The optical power $p(t)$ associated with the backscattered wave is given by

$$p(t) = \left|e(t)\right|^2 = p_1(t) + p_2(t) \tag{2}$$

$$p_1(t) = \sum_{i=1}^{N} {\alpha_i}^2 \exp\left(-2\alpha\frac{c\tau_i}{n_f}\right) rect\left(\frac{t-\tau_i}{W}\right) \tag{3}$$

$$p_2(t) = 2\sum_{i=1}^{N}\sum_{j=i+1}^{N} \alpha_i\alpha_j \cos\phi_{ij} \exp\left\{-\alpha\frac{c\left(\tau_i+\tau_j\right)}{n_f}\right\} \times rect\left(\frac{t-\tau_i}{W}\right) rect\left(\frac{t-\tau_j}{W}\right) \tag{4}$$

where the phase difference $\phi_{ij}$is proportional to the laser frequency υ, the refractive index n_f, and the scatterer space $s_{ij} = \mathcal{Z}_i - \mathcal{Z}_j$ as described by $\phi_{ij} = 4\pi\upsilon n_f s_{ij}/c$. n_f and s_{ij} depend on the strain in the fiber, and hence $p_2(t)$changes with them. Using this feature, we can measure the distributed strain by analyzing the measured backscatter power $p(t)$ provided that we can precisely control the laser frequency of the pulse.

As shown in Fig. 2, the backscatters power of each position represents the intensity distribution of the scattered light power over a period of time. We can see the Rayleigh scattering optical coherence formed a sawtooth waveform. The small figure in Fig. 2 gives the attenuation of reflected light power trends using sample average method. Since the incident light must make a double pass along each section of fiber, the backscatter light impulse would be caused a double pass loss, which is about 0.44 dB/km. The maximum range of the system occurs when the amplitude of the reflected pulse becomes so low it