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Experimental study on transient response of the fiber optic seismic accelerometer

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ABSTRACT

Transient response accuracy of the fiber optic seismic accelerometer influences greatly the seismic reservoir monitoring in the smart oilfield fields. This study demonstrates the transient response analysis of an optimized fiber optic seismic accelerometer, and the effects of damping on the transient response are experimentally verified. The silicone oil is injected into the accelerometer structure to increase the damping, and an additional elastic rubber ring is used to provide an adjustable damping. The experimental results show that the injected silicone oil increases obviously the stamper damping, and the variations of torsional moment also modify slightly the damping of the accelerometer. The increase of the damping avoids the oscillation tailing phenomenon, and therefore largely improves the transient response, which is confirmed by the commercial piezoelectric accelerometer. This study can be used to modify the measurement error and improve the accuracy of the seismic reservoir monitoring in the smart oilfield applications.

1. Introduction

The online permanent monitoring is the continuing interest in the fields of oilfield and well logging [1–3]. In the smart oilfield applications, the online permanent monitoring of the oil well and the oilfield is especially important [4]. Generally, the 3-components detector systems are installed in the oil well to monitor periodically the Vertical Seismic Profiling data [5,6], and therefore realize the high-accuracy monitoring of the oilfield reservoir. As for the detector system, the accelerometers are the key sensitive elements. Nowadays, the fiber optic based accelerometer is one of the main sensing technique solutions [7–11]. When compared with the electronic-based accelerometer, the fiber optic accelerometer owns several advantages such as high sensitivity, immunity to the electromagnetic interference, easiness to form sensing network, particularly, it is capable of operating under the harsh environment. Among all types of fiber optic accelerometer, the accelerometer based on the unbalanced Michelson interferometer is the most classic one [12–15], which is able to realize the large-scale multiplexing array. For example, P. Nash et al. proposed a multiplexing architecture combining up to 256 Michelson based accelerometer channels onto a single optical fiber pair [15]. The fiber optic Michelson interferometer is wrapped onto a compliant cylinder structure, and the seismic signals can be demodulated based on the phase variations of the interferometric light.

The main performance parameters of the fiber optic seismic accelerometer include on-axis sensitivity, operating bandwidth, natural frequency, cross-axis sensitivity etc. Besides, the damping is also one of the important parameters which describes the gradual decline of the seismic signals. Generally, it can be mainly classified as viscous damping, material damping, structural damping and proportional damping, they are influenced by various factors such as viscosity, materials, stiffness and mass of the accelerometer etc., and each type of damping influences the accelerometer based on its specific mechanism.

The transient response of the accelerometer determines the sensing performances of the detector system. For the Vertical Seismic Profiling applications, a good transient response performance is vital to the recognition of the seismic event and the separation of P wave and S wave, which finally used for the orientation location of the epicenter [16,17]. Actually, the transient response strongly depends on the frequency-dependent sensitivity characteristics, and they vary from the different accelerometers, for example, the natural frequency of the fiber optic accelerometer distributes normally about several thousand hertz, while this value is several tens of thousands hertz for the piezoelectric accelerometer and several tens hertz for the moving-coil accelerometer. Different mechanisms of the accelerometers lead to different transient

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responses, which affect greatly the interpretation of the seismic signal. Until now, there are few experimental studies on the transient response analysis of the fiber optic seismic accelerometer and in particular, its comparison with the traditional electronic accelerometers for the seismic reservoir monitoring applications. Besides, the effects of damping on the transient response of the fiber optic accelerometer is unknown, all these challenges and doubts lead to the objectives of this study.

In this study, we demonstrate the transient response analysis of an optimized fiber optic seismic accelerometer, and the effects of damping on the transient response are particularly focused. The damping of the proposed accelerometer is adjusted to evaluate the transient response under different damping conditions. Firstly, the structure of the proposed fiber optic seismic accelerometer is introduced and the theories including the frequency-dependent sensitivity and the transient response are illustrated. Then the effects of damping on the transient response of the fiber optic accelerometer are evaluated experimentally, and the experimental results are compared with a commercial piezoelectric accelerometer. This study is useful to modify the measurement error of the fiber optic seismic accelerometer due to the damping factor, and therefore improves the measurement accuracy of the seismic signal, which finally lays a good foundation for the seismic data interpretation process in the smart oilfield applications.

2. Theory

Fig. 1 presents the cross-section configuration of the fiber optic seismic accelerometer based on the compliant cylinder structure, it consists of a base, a metal mass, a metal plate and an elastic enhanced layer which is fixed by the metal mass and supported by the bottom base. An unbalanced Michelson interferometer together with the Faraday mirrors are wrapped around the elastic enhanced layer. When comparing with the traditional accelerometer, an additional elastic rubber ring is fixed between the metal mass and the top metal plate, and therefore the torsional moment can be adjusted by rotating the screw on the top metal plate.

Generally speaking, the damping of the accelerometer strongly depends on its structure. When the single-freedom vibration is applied vertically on the accelerometer, the metal mass moves back and forth in the vertical direction, and the distance variation between the metal mass and the base generates the air compression, then the compressive air moves horizontally towards two sides, and this damping force is defined as the stamper damping. The main factors which influence the stamper damping include the viscosity coefficient, the dimensions of the base, and the distance between the metal mass and the base. In this study, the silicone oil is injected into the accelerometer via the bottom hole, which evacuates the air between the elastic enhanced layer and the metal mass, and finally increases the global viscosity coefficient and adjusts the stamper damping of the accelerometer.

The frequency-dependent phase sensitivity of the proposed accelerometer $\frac{\partial\varnothing}{a}$ is [12]:

$$\frac{\partial\varnothing}{a} = \left(\frac{\partial\varnothing}{a}\right)_0 \frac{1}{\sqrt{\left(1-\frac{w^2}{w_0^2}\right)^2 + 4\xi^2\frac{w^2}{w_0^2}}} \tag{1}$$

$$\left(\frac{\partial\varnothing}{a}\right)_0 = \frac{8\pi^2 nbvNM}{\lambda HAK}\left\{1-\frac{1}{2}n^2[(1-v_f)p_{12}-v_f p_{11}]\right\} \tag{2}$$

$$\xi = \frac{\varepsilon}{2\sqrt{MK}} \tag{3}$$

where $\left(\frac{\partial\varnothing}{a}\right)_0$ is the phase sensitivity in the flat bandwidth, A is the coefficient which describes the effects of the wrapped fiber optic on the elastic enhanced layer. ξ, ε are the damping factor and the damping coefficient. w_0 is the nature frequency, n, v_f, λ are the refractive index, the Poisson ratio, the wavelength of the wrapped fiber, p_{11}, p_{12} are the elasto-optic coefficient, K, M are the stiffness and the mass of the accelerometer, E, v, b, a, H are the Young's modulus, the Poisson ratio, the outer radius, the inner radius and the height of the elastic enhanced layer, E_{fn}, $S_{fn}$are the Young's modulus, the cross section area of the wrapped fiber. N is the number of turns of the wrapped fiber.

In addition, the transient response characteristic of the accelerometer is analyzed. The presented accelerometer is equivalent to a second-degree mass-spring system, and its transfer function in Laplace space H(s) is:

$$\mathrm{H(s)} = \frac{Y(s)}{X(s)} = \frac{w_0^2}{(s^2 + 2\xi w_0 s + w_0^2)} \tag{4}$$

where s is the Laplace factor, $X(s)$, $Y(s)$ are respectively the excitation signal and corresponding transient response in Laplace domain. From Eq. (4), it is observed that the transient response of the accelerometer mainly depends on the natural frequency and the damping. During the seismic reservoir monitoring, the perforating shot test is usually conducted before the seismic test to acquire the P wave and S wave, and then locate the epicenter. If the perforating shot signal is simulated as an impulse response function, then its corresponding transient response is expressed as:

$$Y(s) = \mathrm{H(s)}X(s) = 1\cdot\frac{w_0^2}{(s^2 + 2\xi w_0 s + w_0^2)} = \frac{w_0^2}{(s^2 + 2\xi w_0 s + w_0^2)} \tag{5}$$

$$Y(t) = \frac{w_0^2 \sinh\left(\sqrt{\xi^2 w_0^2 - w_0^2}\, t\right)}{e^{\xi w_0 t}\sqrt{\xi^2 w_0^2 - w_0^2}} \tag{6}$$

3. Experimental setup

The experimental setup of vibration test system is firstly built up to measure the phase sensitivity of the fiber optic seismic accelerometer, and the diagram is presented in Fig. 2. A commercial piezoelectric accelerometer (Lance, LC0401T, charge sensitivity 23.1 pC/g) is used to calibrate the sensitivity, and both accelerometers are placed on the

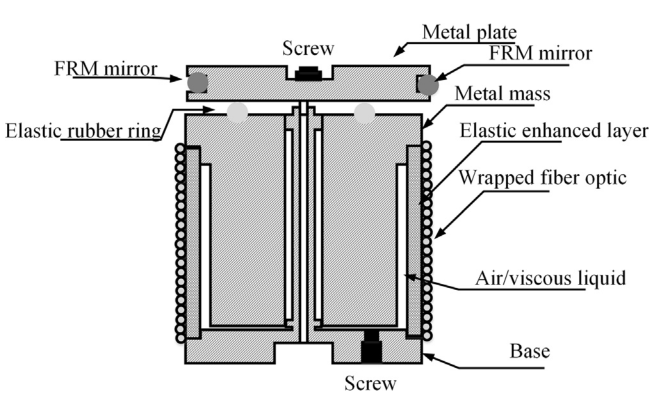

Fig. 1. Cross-section configuration of the fiber optic accelerometer.

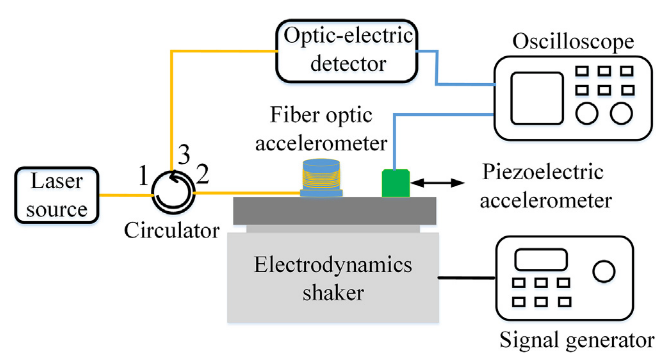

Fig. 2. Experimental setup for the phase sensitivity test.