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Optimization design for medium-high frequency FBG accelerometer with different eigenfrequency and sensitivity

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ABSTRACT

A simple empirical equation of rotational stiffness for single-notch circular flexible gemel is proposed. Based on the parameter optimization, we have discussed how to choose the structural parameters to achieve the balance between the sensitivity and the eigenfrequency. By using sequential quadratic programming (SQP) method, two prototypes of FBG accelerometers with eigenfrequency of 650 Hz and 3050 Hz are designed. Furthermore, we also perform the shaking table test for the fabricated prototype sensors. The experimental results show that the measured eigenfrequency and sensitivity are approximately identical to design values. Also, the FBG accelerometers show great anti-interference capacity in flat range which may be applied to the structural–health monitoring.

1. Background

Vibration measurement is an important and key issue in modern engineering application. Meanwhile, accelerometer shows superior characteristics in structural health monitoring, earthquake detection and measurement compared to traditional electromagnetic sensors [1–3]. Conventionally, accelerometers were piezoelectric type and piezo-resistive type, etc. [4,5]. However, their major drawbacks can be accounted for a number of factors such as electromagnetic interference, humidity effect and lack of sensor multiplexing capabilities. To address these problems, the design of accelerometers with improved optimizing performance is necessary and relevant literature suggests that accelerometer based on optical technology is a much better choice than the conventional electronic ones. Over last two decades, FBG (fiber Bragg grating) based accelerometers have caught much more attention from both researchers and engineers. Many advantages of accelerometers based on FBG, such as immunity to electromagnetic radiation, resistance to chemical corrosion, low noise, multiplexing capabilities, small size, high accuracy and capability of remote operation have been discovered in previous studies [6,7].

Over past several years, various types of accelerometers based on FBG were proposed. Liu designed a kind of FBG accelerometer based on diaphragm which has large frequency ranging from 50 to 800 Hz [8,9]. Basumallick improved the structure of the typical foundation that one's maximum sensitivity can reach more than 1000 pm/g [10,11]. However, either type of diaphragm-based or cantilever-based FBG accelerometers whose eigenfrequency and sensitivity are dependent produced a propagation error on some lever since it is composed of more than one part. Stefani demonstrated polymer optical fiber FBGs (POF FBG) based accelerometers for operation at both 1550 and 850 nm [12]. However, the polymer fiber is difficult to used in long-term structural health monitoring.

In our previous work, we demonstrated a new type of FBG accelerometer with integrative matrix structure, which are primarily based on flexible gemels [13]. Flexible gemels have been widely applied as gyroscopes, accelerometers, balance scales, and multiplying linkages benefiting from their numerous advantages such as direct transmission, no friction, no backlash, compactness, satisfactory stiffness and resolution [14]. The prototype sample of that accelerometer demonstrated, whose eigenfrequency is near 3000 Hz, has been experimentally tested, but its sensitivity failed to achieve the desired results.

In this paper, a simple empirical equation of rotational stiffness for single-notch circular flexible gemel is proposed. The eigenfrequency of this prototype accelerometer can reach a broad range from 600 to 3000 Hz by using sequential quadratic programming (SQP) methods [15,16], which have proved to be highly effective in solving constrained optimization problems with smooth nonlinear functions in the objective and constraints [17] and the sensitivity improved from dozens to hundreds pm per gravitational acceleration.

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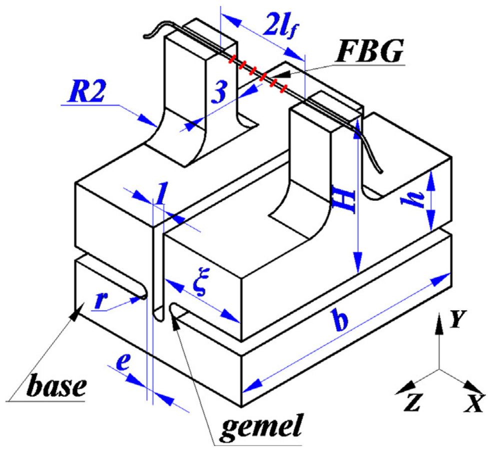

Fig. 1. Architecture structure of the accelerometer.

2. The structure and principle of the sensor

The architecture of the proposed accelerometer is as illustrated in Fig. 1. It has an integrative matrix with three sections, including base, flexible gemels with inertia masses and a fiber with Bragg grating adhered on the bilateral grooves. Obviously, the composition of the accelerometer is extremely simple so that it can be fabricated only via heat treatment and wire-electrode cutting. Another important characteristic is that the size of the structure can be modified to attain the desired eigenfrequency.

Under the condition of ambient vibration, the accelerometer will vibrate with the excited frequency synchronously. Therefore, the two symmetrical inertia masses will produce micro vibration and swing angle around respective flexible gemels. Meanwhile, the ends of the FBG will produce counter deformations in its axial direction which yields to resultant double deformations due to amplitude superposition effect, and thus doubling its sensitivity. As an elastic element, flexible gemel can transform vertical acceleration to axial strain of the FBG. As we can see, the flexible gemels are key elements in this structure benefiting from its advantages of little friction and high precision.

However, according to the previous papers, there is no universal stiffness equation for the single-notch circular flexible gemel but we adopt it this paper. The main limitation comes from the values of r and e/r [18] (e is the neck thickness and r is the radius as shown in Fig. 2). To make up, we have to deduce an empirical equation of rotational stiffness of the flexible gemel for the proposed accelerometer through the method of surface fitting.

Firstly, we set r and the ratio e/r as the variable parameters to calculate the simulation value of the rotational stiffness. And then, consider the neck (gemel) thickness e from 0.4 to 1 mm in steps of 0.1 mm, e/r from 0.4 to 1 in steps of 0.1 according to the following material properties: Young's modulus E = 200 GPa and Poisson ratio ν = 0.3. Subsequently, record the rotational stiffness data on the basis of finite element analysis (FEA). In the end, the relation between r, the ratio e/r and the rotational stiffness can be fitted with a four-order poly-nominal function, as shown in Fig. 2 (the dark spots are simulation values, the color plane is fitting surface).

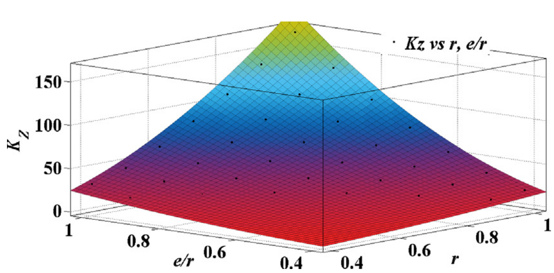

Fig. 2. Fitting surface of empirical equation, K_Z.

Accordingly, the empirical equation about the rotational stiffness K_z can be expressed as

$$K_Z = Eb\left[r^2\sum_{i=0}^{3} c_k\left(\frac{e}{r}\right)^i\right] \tag{1}$$

where b is matrix thickness (Z-axis) of the accelerometer, c_k are coefficients of this polynomial functions. By fitting, the coefficients are finally decided as: c_0 = 0.00096375, c_1 = −0.0086757, c_2 = 0.0442, c_3 = 0.0048125.

The root mean squared error of the fitting surface is 1.022, and the coefficient of determination is 0.9993. In the field of operational research, the closer the coefficient of determination is to 1, the more accurate the fitting is Fig. 3.

The theoretical model and the mechanical model of the accelerometer are shown in Fig. 3. As we can see, the mass can be simplified as a rigid rod with the equivalent quality m, which is rotating about the flexible gemel. The fiber with Bragg grating can be regarded as a spring. Set the coordinate system on basis of the angle of the flexible gemel β, and establish dynamic equations like following

$$J\frac{d^2\beta}{dt^2} + \left(K_Z + k_f \times (H+r)^2\right)\beta = x_w ma\ \sin\omega t \tag{2}$$

where x_w denotes the length from barycenter of the mass to flexible gemel in X-axis, J is inertia moment of the mass along the flexible gemel, H is the distance from FBG to flexible gemels in Y-axis, k_f is the stiffness of the fiber, a is the maximum vibration acceleration in Y-axis, and ω is the vibration frequency by external force. From the above equation, the eigenfrequency can be derived as

$$f = \frac{1}{2\pi}\sqrt{\frac{K_Z + k_f \times (H+r)^2}{J}} \tag{3}$$

where the stiffness of the fiber k_f can be expressed as

$$k_f = \frac{E_f A}{l_f} \tag{4}$$

where E_f represents the Young' modulus of the fiber, A is the cross sectional area that is 1.227 × 10−8 mm^2 normally, and l_f denotes half of length between the two grooves.

According to the Eqs. (2), the angle β can be obtained as in the following equation

$$\beta = \frac{x_w ma}{K_Z + k_f \times (H+r)^2 - J\omega^2}\sin\ \omega t \tag{5}$$

Because of symmetrical structure, the wavelength shift of the FBG will produce double deformations which can be defined as

$$\Delta\lambda = 2(1-P_e)\lambda\frac{\delta}{2l_f} \tag{6}$$

where P_e is the effective elasto-optical coefficient, λ is FBG's central wavelength and δ is Fiber's total deformation. Since it affects the narrow angle, the total deformation can be expressed as

$$\delta = 2(H+r)\beta \tag{7}$$

Then theoretical sensitivity can be written as

$$S = 2(1-P_e)\lambda\frac{1}{l_f} \times \frac{(H+r)(x_w-e)m}{K_Z + k_f(H+r)^2 - J\omega^2} \tag{8}$$