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Development of an optical accelerometer with a DVD pick-up head

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Abstract
A low-cost highly sensitive optical accelerometer is developed based on the pick-up head of a commercially available DVD. The proposed accelerometer detects the focus error signal (FES) generated by a moving object using a built-in four-quadrant photodiode. The linear range of the FES curve is employed to indicate the displacement of the seismic mass relative to the base of the accelerometer. The acceleration acting on the base is then determined on the basis of the measured displacement.

Keywords: accelerometer, optical sensor, DVD pick-up head, focus error signal (FES)

1. Introduction

Vibration sensor designs generally involve the measurement of displacement, velocity, acceleration, etc. Although highly sophisticated, modern vibration measurement instruments tend to be complex and highly expensive. The accelerometer is a standard vibration measurement instrument, which, as its name implies, measures vibration by detecting acceleration. Nowadays, this instrument is the method of choice for shock measurement and vibration monitoring applications. In its simplest form, an accelerometer employs a displacement sensor to record the relative displacement between a seismic mass and the base. The acceleration acting on the base is then calculated from the measured displacement [1]. The published literature discusses many different displacement sensing techniques, including variable capacitance, piezoelectric, piezoresistive, reluctive, magnetic, strain methods, etc [2, 3].

Optical sensing techniques have been broadly applied in the development of measurement systems in recent years. For example, Poffo *et al* [4] proposed a glass-integrated sensor capable of indicating the sign of the displacement using a single optical output. The optical interferometer displacement sensor designed in their study used a piezoelectric element positioned over a reference arm to produce a longitudinal acoustic wave, which then created a small phase modulation of the reference light beam at a high frequency (1.28 MHz). Tyrrell *et al* [5] integrated a quartz tuning fork and an innovative diamond probe to construct a compact scanning probe microscope sensor head. The compact sensor head was designed to mount around a standard microscope objective lens, thereby creating a hybrid instrument capable of high spatial resolution over a large sample area. Wang *et al* [6] applied the optical interferometry method to develop a measurement system for testing the deformation of a microbeam in an accelerometer under point-force loads and for measuring the displacement of a membrane in a microphone under applied voltages. Li *et al* [7] designed and fabricated a compact precision optical displacement sensor based on a newly developed ultra-thin film photodiode with an active layer thinner than one half of the incident light wavelength. It was demonstrated that the optical sensor was capable of detecting displacements with a precision of ± 30 nm over a range of 2 μm.

Although optical sensing techniques have been successfully applied to various types of measurement system, the use of such techniques to construct optical accelerometers has received relatively little attention. Kalenik *et al* [8] presented a compact, simple amplitude-modulated fibre-optic linear acceleration sensor. In their design, one optical fibre was arranged as a cantilever beam, i.e. fixed at one end and unsupported at the other, while a second optical fibre was fixed in place facing the free end of this ‘cantilever’. When a vibration was applied to the structure, the cantilever deflected, causing a corresponding reduction in the transmission of light to the second optical fibre. The acceleration was then calculated on the basis of the reduction

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in the transmitted light. Bochobza-Degani *et al* [9] designed an open-loop micromachined accelerometer. In their design, the mechanical structure of the accelerometer was fabricated using bulk micromachining techniques. The structure was then attached to a CMOS chip containing photodiodes and readout electronics, which indicated the movements of the proof-mass in response to an applied acceleration.

The design of accelerometers based on optical principles tends to be more complicated than those based on more established techniques. Furthermore, optical accelerometers are generally more expensive than other types of accelerometer. Therefore, optical accelerometers tend not to be widely utilized in the commercial arena. However, optical accelerometers provide the potential for high-resolution displacement measurement and therefore merit further investigation.

Since CD (compact disc) technology first emerged in 1982, the capabilities of laser-based data acquisition techniques have continuously improved. As a result, the optical pick-up technology within today's commercially available DVD players is well developed and comparatively inexpensive. The optical and electronic circuitry designs of modern DVD players and the excellent focusing characteristics of their pick-up heads are ideally suited to the development of low-cost optical metrology applications. The published literature presents various applications of the DVD pick-up head, including as autocollimators [10], velocimeters [11], profile measurement devices [12, 13], straightness measurement instruments [14] and confocal compact scanning systems in optical microscopes [15].

However, as discussed above, the complexity and cost of traditional optical accelerometers have tended to limit their application in the commercial domain. Accordingly, the aim of the present study is to develop a low-cost high-precision optical accelerometer based on the proven technology of a commercially available DVD pick-up head.

2. Operational principles

Typically, an accelerometer comprises a spring, a damper, a seismic mass and a displacement sensor arranged within a housing attached to a base. In operation, the base is mounted on the vibrating structure of interest, and the relative displacement between the seismic mass and the base is recorded by the displacement sensor. The magnitude of the acceleration acting on the base is then calculated on the basis of the measured displacement. In a novel approach, the present study measures the relative displacement between the seismic mass and the base using a commercial DVD optical pick-up head.

Figure 1 illustrates the basic components and operating mechanisms of the commercial DVD pick-up head. Initially, a laser diode generates a beam of light, which passes through a diffraction grating where it splits into three separate beams. These beams pass through a polarization beam splitter, a quarter wavelength plate, a collimator lens and finally through an objective lens, which focuses the beams upon the surface of the object which is to be measured. The beams are then reflected back along their original paths until they pass through the polarization beam splitter, at which point they pass through

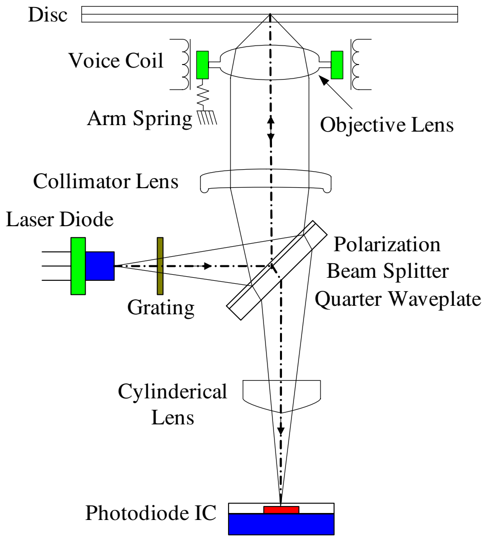

Figure 1. Basic structure of DVD pick-up head.

a cylindrical lens and finally project onto a four-quadrant photodiode. The photodiode outputs a focus error signal (FES) whose magnitude is dependent upon the distribution of the main beam spot across its four quadrants. After an appropriate processing of the FES, the resulting signal is used to drive the voice coil motor (VCM) in such a way that the objective lens is shifted to a point at which its focal point falls upon the surface of the object of interest. The VCM displacement can then be used to determine the surface profile variation of the measured object. In the present study, the linear range of the FES curve is used to measure the relative displacement between the seismic mass and the base, hence the VCM is glued in position to create a focusing probe.

3. Design, analysis and fabrication

When the accelerometer has no internal damping, the magnitude of the acceleration can be correctly measured only when the acceleration acting on the base does not exceed 20% of the resonance frequency of the accelerometer. This limit of 20% is referred to as the frequency response of the accelerometer. Generally, an accelerometer is designed to provide a frequency response specific to the particular application for which it is to be employed. In the present study, the accelerometer is intended to measure the movement of the Earth's crust (approx. 0.1–10 Hz). Therefore, the frequency response of the accelerometer must be greater than 10 Hz. However, the accuracy of the displacement measurement is adversely affected if the frequency response is too high. Accordingly, the maximum frequency response of the present accelerometer is limited to 15 Hz. To minimize errors when calculating the acceleration, and assuming that a low damping ratio material is employed for the structure of the accelerometer, the designed frequency response of the current accelerometer is specified as 10% of the resonance frequency of the system. Therefore, the required resonance frequency value of the accelerometer should lie between 100 and 150 Hz.

Figure 2 presents a schematic illustration of the present optical accelerometer. In this design, a cantilever beam and a mirror act as the spring and the seismic mass of the

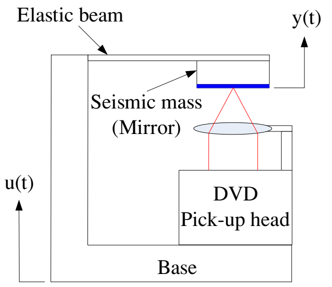

Figure 2. Schematic illustration of optical accelerometer.

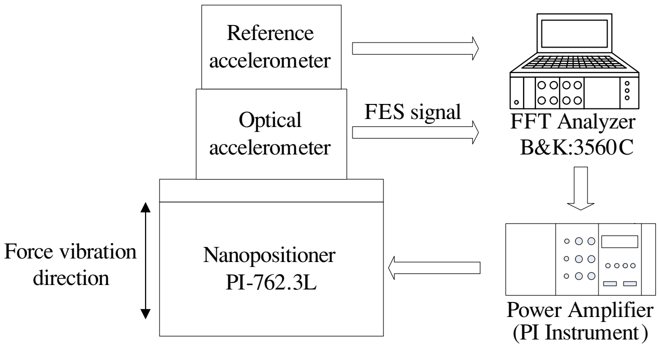

Figure 3. Schematic illustration of experimental set-up for accelerometer calibration.

accelerometer, respectively. The present study simulates the corresponding single degree of freedom accelerometer model using the parameter definitions presented in equation (1) [16], i.e.

$$k_{\mathrm{eq}} = \frac{3EI}{L^3} \qquad I = \frac{bt^3}{12} \qquad \omega_n = \sqrt{\frac{k_{\mathrm{eq}}}{m + 0.23M}} \qquad (1)$$

where E is the Young's modulus of the beam, I is the area moment of inertia of the beam, L is the length of the beam, b is the width of the beam, t is the thickness of the beam, M is the mass of the beam and m is the mass of the mirror.

The simulations assume that the beam is fabricated from S304 stainless steel and has a Young's modulus of 193 GPa and a mass density of 7.86×10^3 kg m^{-3}. The length, width and thickness of the beam are specified as 30 mm, 3 mm, and 0.70 mm, respectively, and the mass of the mirror is taken to be 2.90 g. From equation (1), the equivalent elastic stiffness, k_{eq}, is found to be 1.84×10^3 N m^{-1} and the equivalent seismic mass to be 3.01 g. Therefore, the resonance frequency, ω_n, of the accelerometer is calculated to be 124 Hz. Clearly, this frequency lies in the range of 100–150 Hz, and is therefore in accordance with the resonance frequency specified for the accelerometer.

This study fabricated an accelerometer using the simulation results presented above as the design specification for the beam and mirror components. The dimensions of the completed accelerometer were as follows: length, 50 mm; width, 29 mm and height, 48 mm. Moreover, the total weight of the accelerometer was 94.5 g. As shown in figure 2, in the fabricated accelerometer, the mirror was fixed to the underside of the beam tip and the DVD pick-up head was positioned directly below the mirror. The objective lens inside the DVD pick-up head was fixed in place. In operation, the base of the accelerometer is attached to the vibrating structure. Vibrations of this structure cause a displacement of the seismic mass (i.e. the mirror) within the accelerometer. These displacements are detected by the DVD pick-up head, which generates a corresponding output voltage (FES) signal. The FES signal is acquired and used to calculate the acceleration acting on the base.

4. Experimental set-up and measurement results

In general, accelerometers are calibrated by recording their output under a particular excitation force and then comparing this output with that generated by a reference accelerometer under the same excitation conditions. This type of calibration approach is known as the comparison calibration method. Since this method is straightforward, convenient and provides rapid results, it is widely used in measurement and calibration laboratories and by many accelerometer manufacturers. Accordingly, the present study applies the same calibration approach to characterize the performance of the developed accelerometer, choosing an ultra-low frequency reference accelerometer (Wilcoxon Research Inc. model number 731A, sensitivity 10 V g^{-1}) for comparison purposes.

Figure 3 provides a schematic illustration of the experimental set-up employed for the comparison calibration test. In this arrangement, the z-axis movement of a three-axis nanopositioner (model number PI-762.3L, Physik Instrumente (PI) Co. Germany) was used to provide the excitation force. During the calibration experiment, an FFT analyser (model number 3560C, Bruel & Kjaer Denmark) was used to generate excitation signals, which were then amplified by a power amplifier and used to drive the nanopositioner. As shown, the optical accelerometer and the reference accelerometer were positioned on top of the nanopositioner. The output signals of the two accelerometers were then acquired and analysed by the FFT analyser.

4.1. *Resonance frequency measurement*

The resonance frequency of the current optical accelerometer was obtained using the same experimental set-up shown in figure 3. The FFT analyser was used to output a swept sine waveform signal, which was input to the power amplifier, amplified and then supplied to the nanopositioner, causing it to vibrate in the z-axis direction. Due to the arrangement of the current and reference optical accelerometers, both instruments underwent the same oscillatory movement. Transforming the output signal from the reference accelerometer and the FES output from the current optical accelerometer into corresponding displacement signals, the FFT analyser recorded the amplitude ratios of the reference accelerometer and the optical accelerometer every 0.25 Hz. The corresponding results are presented in figure 4. It can be seen that the first resonance frequency of the optical accelerometer is 130 Hz, which is 4.61% higher than the value predicted by equation (1). The peak amplitude ratio of the resonance frequency indicates that the cantilever beam of the optical accelerometer has low damping characteristics.

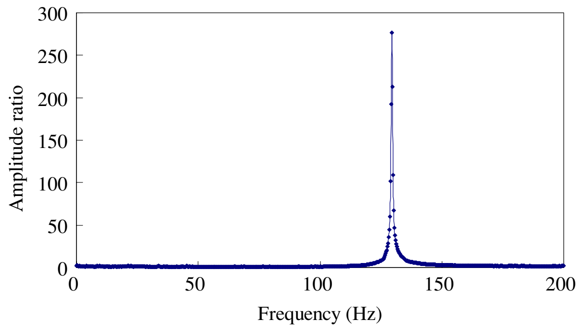

Figure 4. Resonance frequency response.

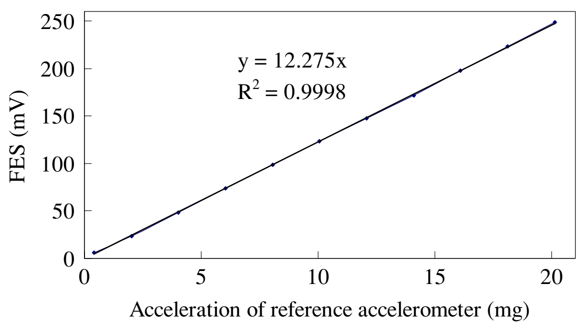

Figure 5. Low-frequency acceleration response.

4.2. *Low-frequency acceleration response measurement*

The experimental set-up shown in figure 3 was also used to investigate the low-frequency acceleration response of the optical accelerometer. Using a forced vibration with a frequency far lower than the resonance frequency, the output amplitude of the nanopositioner was changed, and the outputs of the reference accelerometer and the optical accelerometer were recorded.

As stated previously, the optical accelerometer developed in this study is designed to measure movements of the Earth's crust. Therefore, the present experiments employed a sine waveform with a constant frequency of 10 Hz as the excitation signal and varied the output amplitude of the nanopositioner within the range of 1–50 μm. The resulting acceleration signal of the reference accelerometer and the output voltage (FES) of the optical accelerometer are presented in figure 5. From inspection, it is found that the sensitivity of the optical accelerometer is 12.3 V g^{-1}, which indicates that the optical accelerometer has excellent linearity characteristics.

4.3. *Frequency response measurement*

Using the experimental set-up shown in figure 3, the FFT analyser was used to output swept sine waveform signals with frequencies in the range of 0.5–30 Hz. The signals were amplified by the power amplifier and used to drive the nanopositioner, which was regulated to provide a fixed displacement amplitude output of 50 μm. The output voltage (FES) of the optical accelerometer was then converted into the corresponding acceleration by using the sensitivity value obtained from figure 5. The FFT analyser simultaneously recorded the accelerations of the reference accelerometer and the optical accelerometer every 0.5 Hz. The corresponding results are presented in figure 6. It

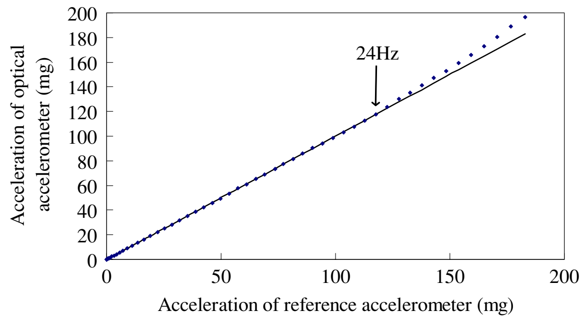

Figure 6. Frequency response (operating frequency range 0.5–30 Hz).

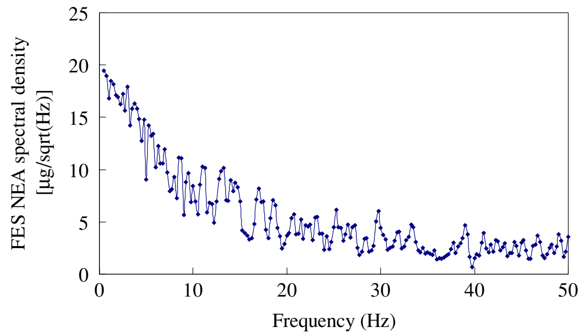

Figure 7. NEA spectral density.

can be seen that the acceleration results obtained using the optical accelerometer are in good agreement with those of the reference accelerometer at operating frequencies below 24 Hz.

4.4. *Noise equivalent acceleration (NEA) measurement*

The electronic components and OP amplifiers used in the electronic circuit design of the current optical accelerometer are the major sources of noise. The fluctuations of the photocurrent signals output from the laser diodes of the pick-up head caused by variations in the ambient temperature are a further source of noise. Accordingly, the present study not only specified ultra-low noise electronic components and amplifiers for the electronic circuit of the accelerometer, but also implemented an APC circuit to improve the stability of the laser output power. A detailed description of the APC design and its performance evaluation is provided by the current authors in [13].

To measure the NEA of the current optical accelerometer, the output voltage (FES) noise was recorded by the FFT analyser while the nanopositioner was turned off. The spectral density of the NEA was calculated using the sensitivity value calculated from figure 5. Figure 7 plots the FES NEA spectral density against the frequency. It can be seen that the electronic circuit of the current optical accelerometer generates an electrical noise of less than 20 μg Hz$^{-1/2}$ over the frequency range 0.5–50 Hz.

5. Conclusions

This study has successfully developed a low-cost highly sensitive optical accelerometer comprising a cantilever beam, a mirror and a base. A modified commercially available DVD pick-up head is used as the basis of the displacement measurement system. The experimental results have shown that the accelerometer has a sensitivity of 12.3 V g^{-1} and a noise equivalent acceleration (NEA) of less than 20 μg $Hz^{-1/2}$. It has been demonstrated that the performance of the developed accelerometer compares favourably with that of a commercially available ultra-low frequency high-sensitivity accelerometer.

The accelerometer developed in this study is intended for use in measuring the acceleration of the Earth's crust and that of other low frequency vibration generators, such as subways, buses, tides, winds, etc. Therefore, the designed frequency response is specifically restricted to the range of 0.5–24 Hz, i.e. approximately 20% of the cantilever resonance frequency. However, the frequency response can be increased by changing the dimensions of the cantilever beam, e.g. reducing its length or increasing its moment of inertia, or by reducing the seismic mass. Furthermore, specifying different cantilever beam materials in order to increase the damping ratio, or adopting a high damping ratio design, can also increase the frequency response such that the proposed system can be applied to the acceleration measurement of a broader range of vibrational fields, such as machine tools, motor vehicles, etc.

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