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2008 Meas. Sci. Technol. 19 084012

(http://iopscience.iop.org/0957-0233/19/8/084012)

Meas. Sci. Technol. **19** (2008) 084012 (7pp) doi:10.1088/0957-0233/19/8/084012

Development of an optical accelerometer for low-frequency vibration using the voice coil on a DVD pickup head

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Received 23 November 2007, in final form 13 May 2008
Published 4 July 2008
Online at stacks.iop.org/MST/19/084012

Abstract
In this paper, an economical and highly sensitive optical accelerometer using a commercial optical pickup head is proposed. In the proposed design, the moving part of a voice coil motor (VCM) built in the DVD pickup head is used as the seismic mass which combines with the optical system of the DVD pickup to form an accelerometer. This system not only reduces the design complexity and the manufacturing process but also obtains good measurement effect. Experimental results have shown that the accelerometer at low frequency has a sensitivity of 24.362 V/g.

Keywords: accelerometer, optical sensor, DVD pick-up head, low frequency

(Some figures in this article are in colour only in the electronic version)

1. Introduction

During the measuring process in the nanometer scale, we must consider the effect of environmental vibration. If various sources of environmental vibration could not be eliminated completely, a vibration control technique would be the best solution. Considering vibration isolation techniques for precision mechanical equipment, the main problems involve the design of appropriate sensor techniques and control schemes, and these designs have a fundamental influence on the characteristics of the entire active vibration isolation system. In terms of the frequency of vibration, the vibration generated by personnel walking on the floor of the laboratory is in the range of 1–3 Hz, while that of the Earth's crust movement lies in the range of 0.1–10 Hz. Accordingly, the accelerometer used in measuring the environment vibration has to be designed specifically for low frequency.

Shock and vibration can be measured and characterized in terms of displacement, velocity, acceleration and the rate of acceleration change. An accelerometer is the preferred motion sensor for most shock and vibration monitoring applications because of its high accuracy, wide-band frequency, small size, light weight and ease of installation. 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].

There are various displacement sensing techniques, such as variable capacitance, piezoelectric, piezoresistive, magnetic and strain methods [1–3]. There are also some optical accelerometers based on the changes in light intensity [4–6], phase [7], wavelength [8, 9], coherence [10] or the photo-elastic effect [11]. With the progress of micro/nano technology, some silicon-based optical accelerometers have been studied [6, 10, 12]. In addition, polymers have recently received much attention in the design of an optical accelerometer due to its low cost, simple technology and good optical properties [13, 14]. Some examples are given below.

Kalenik *et al* [4] presented a simple fiber-optic accelerometer. The optical accelerometer consists of segmented fiber optics acting as a 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 fiber. The acceleration was then calculated on the basis of the reduction in the transmitted light. Abushagur *et al* [9] applied the fiber Bragg grating (FBG) to develop a three-axis accelerometer. In their design, the device used an inertial mass that stressed or compressed an FBG, which caused its Bragg wavelength to increase or decrease in proportion to the acceleration. Nilsson *et al* [15] presented fast four-channel fiber-optic displacement. In their design, light from an LED emitter is sent through a plastic fiber and reflected from the surface back into the fiber. The intensity of the reflected light gives the distance to the surface. Freitas *et al* [16] presented a procedure to measure the misalignment between a fiber-optic accelerometer transducer axis and the axis of its cylindrical mounting can. Wang *et al* [17] designed a fiber-optic disk accelerometer (FODA). In their design, displacement of the disk results in strain on the disk surface. The strain is transferred to the fiber, leading to a change in the fiber length. The phase is modulated by the acceleration, and the strain is directly proportional to the vibration acceleration. Lee *et al* [6] developed a silicon-based micro-opto-mechanical accelerometer. In their design, the applied accelerations are detected only in the sensing axis direction and are not affected by accelerations along orthogonal sensing axes. Lolbera *et al* [13, 14] presented an integrated polymer optical accelerometer based on SU-8. The results confirm that it is possible to define a complex polymer micro-opto-electro-mechanical system (MOEMS) with a reduction in the complexity and number of technological step, together with outstanding optical sensitivity.

In addition to the above-mentioned technologies, the focusing characteristics could be another way to make a sensor. The optical pickup technology within today's commercially available DVD players is well developed and comparatively inexpensive. The optical and electronic circuitry designs of modern DVD players, with the excellent focusing characteristics of their pickup heads, are ideally suited to the development of a new generation of low-cost optical metrology applications. Some published articles presented various applications of the DVD pickup head, including autocollimators [18], velocimeters [19], profile measurement devices [20, 21], straightness measurement instruments [22] and optical accelerometers [23, 24]. The aim of the present study is to simplify Chu's structure [23] for a low-cost, high-precision and low-frequency optical accelerometer based on the commercial DVD pickup head.

2. Operational principle of the DVD pickup head

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. With a novel approach, the present study measures the relative displacement between the seismic mass and the base using a commercial DVD optical pickup head.

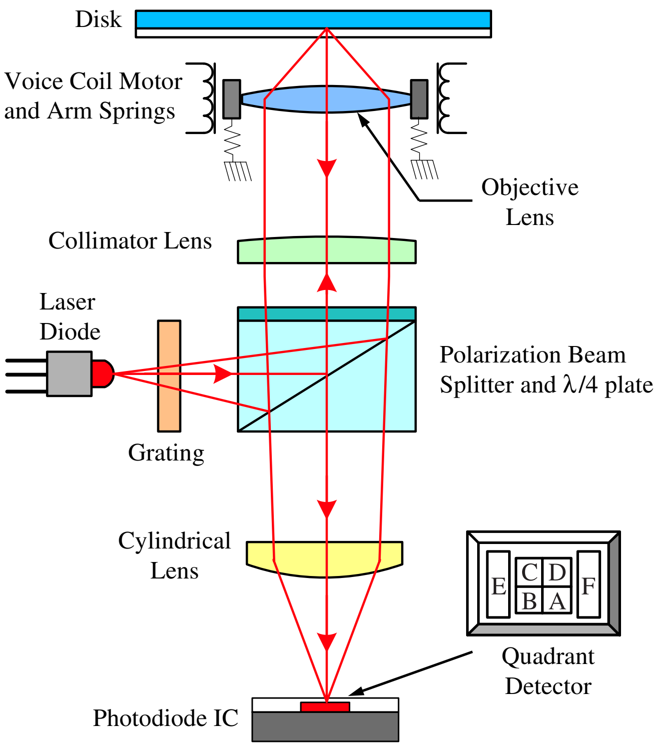
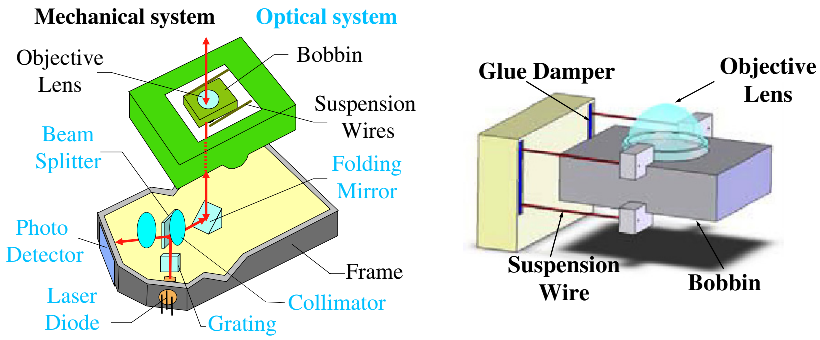


Figure 1. Basic structure of the DVD pickup head.

Figure 1 illustrates the basic components and operating mechanisms of the commercial DVD pickup 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 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.

3. Structure of the one-dimensional optical accelerometer

In the author's previous research [23], the special geometric size of the cantilever beam for a particular application was



(*a*) Basic structure of DVD pick-up head (*b*) Mechanism of VCM

Figure 2. Configuration of a DVD pickup head: (*a*) basic structure of a DVD pickup head; (*b*) mechanism of VCM.

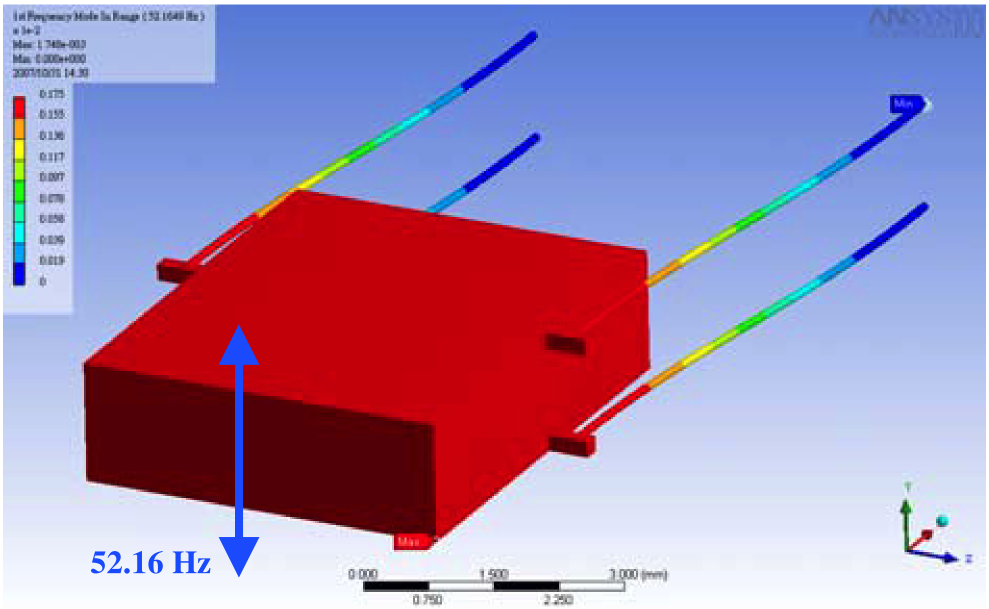


Figure 3. The analysis result by ANSYS.

designed. A cantilever beam and a mirror served as the spring and the seismic mass of the accelerometer, respectively. A DVD pickup head was employed as the detector for measuring the relative displacement between the seismic mass and the base, and hence the acceleration was calculated.

The design and manufacture of the special geometric size of the cantilever beam for the accelerometer would take time and increase cost. In this study, in order to simplify the design and manufacturing process, the moving part of the voice coil motor (VCM) built in the DVD pickup head is directly used as the seismic mass which combines with the optical system of the DVD pickup head to form an accelerometer. Figure 2(*a*) illustrates the basic components and operating mechanisms of the commercial DVD pickup head which can be divided into two parts: mechanical and optical systems. The mechanical system consists of a VCM (objective lens, bobbin and suspension wires) and its frame, where an objective lens and a bobbin act as the seismic mass and suspension wires act as the spring, as shown in figure 2(*b*). The suspension wire is fabricated from copper wire, and the length and diameter of the wire are specified as 9 mm and 100 μm, respectively. The mass of the seismic structure (i.e. an objective lens and a bobbin) is 0.32 g. The ANSYS analysis indicated that the resonant frequency of the seismic structure is 52.16 Hz, as shown in figure 3. The dimensions of the completed optical accelerometer are as follows: length, 66 mm; width, 35 mm; height 36 mm. Moreover, the total weight of the accelerometer is 110 g. The VCM is employed as the seismic structure so that the design and manufacturing process can be simplified. Figure 4 presents a photograph of the completed optical accelerometer.

In operation, the base of the accelerometer is attached to the vibrating structure. Vibrations of this structure cause corresponding displacements of the seismic mass (i.e. the VCM) within the accelerometer. These displacements are detected by the DVD pickup head, which generates a corresponding output voltage (FES) signal. The FES signal is acquired and used to calculate the acceleration acting on the base.

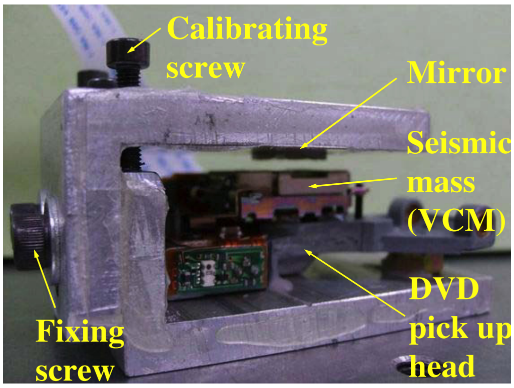


Figure 4. Photographic representation of the current optical accelerometer.

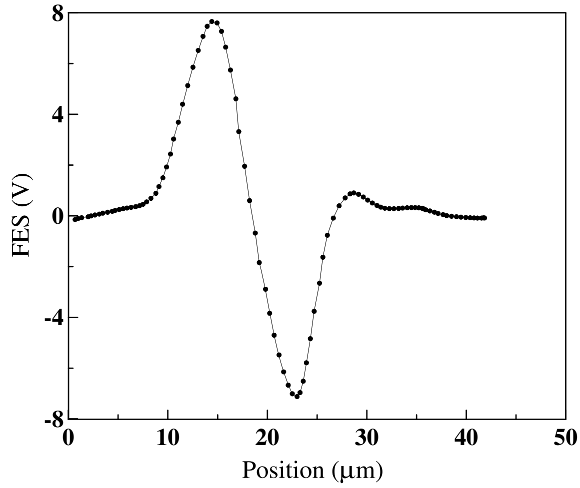


Figure 6. Calibrated results for the S-curve.

4. Experimental setup and measurement results

4.1. S-curve measurement

An optimal FES curve should look like an S-curve. To establish the maximum detectable acceleration range of the accelerometer and the maximum displacement of the seismic mass, this study performed an experiment to calibrate the S-curve using the experimental setup, as shown in figure 5. In this arrangement, the pickup head is fixed in position and the mirror is driven by a micro-linear stage. The displacement of the stage is measured by an SIOS laser interferometer (model number MI 5000E, made by SIOS Co., Germany). A National Instruments USB-6009 data acquisition interface is used to acquire the FES and stage displacement signals. Readouts of the interferometer are then plotted against the FES output from the pickup head. Figure 6 shows the calibrated S-curve having the linear range of about 5 μm.

4.2. Accelerometer performance test

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 is known as the comparison method. The present study applies the same calibration approach to characterize the performance of the developed accelerometer using an ultralow-frequency accelerometer (PCB Piezotronics Inc., model number 393B31, sensitivity 11 V$/g$) as the reference.

Figure 7 provides a schematic illustration of the experimental setup employed for the comparison calibration test. In this arrangement, the *Z*-axis movement of a nanopositioner (model number PI-762.3L, Physik Instrumente (PI) Co., Germany) was used to provide the excitation force, and an LVDT (linearly variable differential transducer) was embedded in each axis for measurement. During the calibration experiment, a FFT analyzer (model number 3560C, Bruel & Kjaer, Denmark) was used to generate excitation signals, which were then amplified by a power amplifier to drive the nanopositioner. The optical accelerometer and the reference accelerometer were positioned on the top of the nanopositioner. The output signals of the two accelerometers were then acquired and analyzed by the same FFT analyzer.

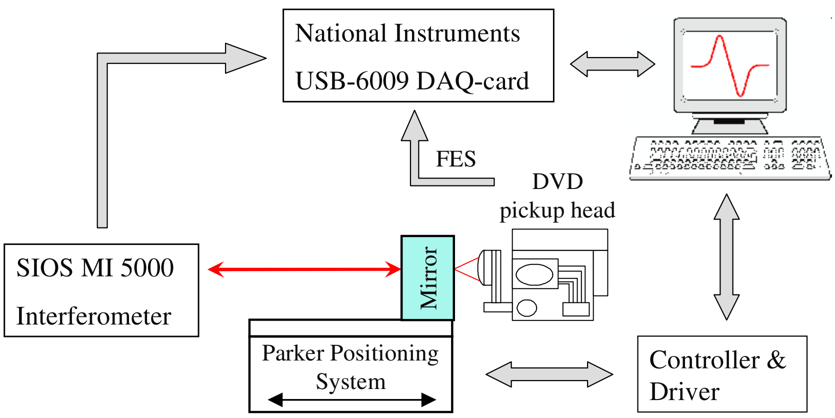


Figure 5. Schematic illustration of the measurement setup for S-curve calibration.

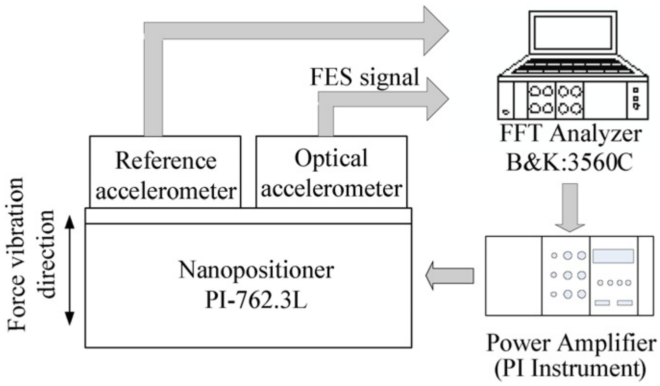


Figure 7. Schematic illustration of the experimental setup for accelerometer calibration.

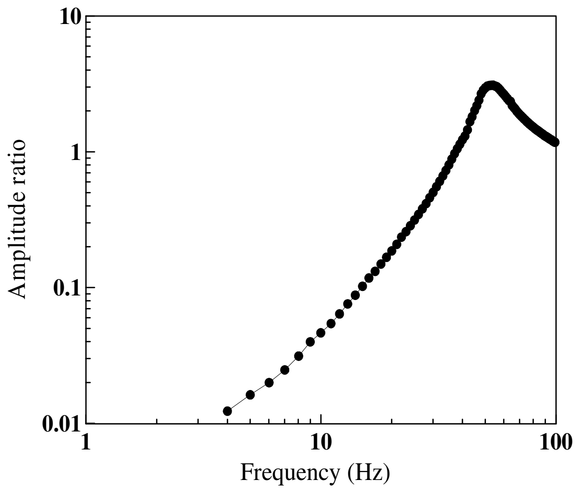


Figure 8. Resonance frequency response in a log–log plot.

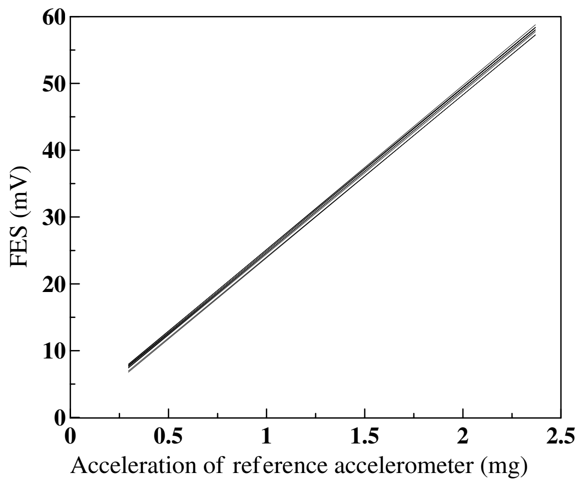


Figure 9. Nine tests of acceleration response at 5 Hz.

4.2.1. Resonance frequency measurement. The resonance frequency of the current optical accelerometer is obtained by using the experimental setup of figure 7. The FFT analyzer was used to output a swept sine waveform signal to the power amplifier, which was then supplied to the nanopositioner, causing it to vibrate in the Z-axis direction. The FFT analyzer records the amplitude ratios of the nanopositioner and the optical accelerometer at every 1 Hz increment. The amplitude ratio indicates the ratio of Z to Y, where Y is the displacement of the nanopositioner measured by the LVDT and Z is the relative displacement between the seismic mass displacement measured by the FES signal and the displacement of the nanopositioner.

The corresponding result is presented in figure 8. It can be seen that the first resonance frequency of the optical accelerometer is 53 Hz. It is found that the damping ratio ξ of the current optical accelerometer is 0.17.

The Q factor can be defined as $Q \approx 1/2\xi$; it can be calculated that the Q factor is 2.94. Comparing the current work and the previous work [23], the Q factors are 2.94 and 276.7 for the current optical accelerometer and the previous optical accelerometer, respectively.

4.2.2. Low-frequency acceleration response measurement. As stated previously, the optical accelerometer developed in the present study is designed to measure movements of the Earth's crust. Therefore, the present experiments employed a sine waveform with a constant frequency of 5 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 9. As shown in table 1, based on the nine sets of experimental data, the averaged slope is 24.36 mV/mg and the averaged standard deviation is 1.625 mV. The measurement error is determined as the product of the averaged standard deviation and the slope inverse.

4.2.3. Frequency response measurement. Using the same experimental setup, the FFT analyzer was used to output swept sine waveform signals with frequencies in the range of 3–30 Hz. The acceleration signals of the reference accelerometer and the optical accelerometer are simultaneously recorded at every 1 Hz. The corresponding results are presented in figure 10. It can be seen that the acceleration results obtained using the optical accelerometer

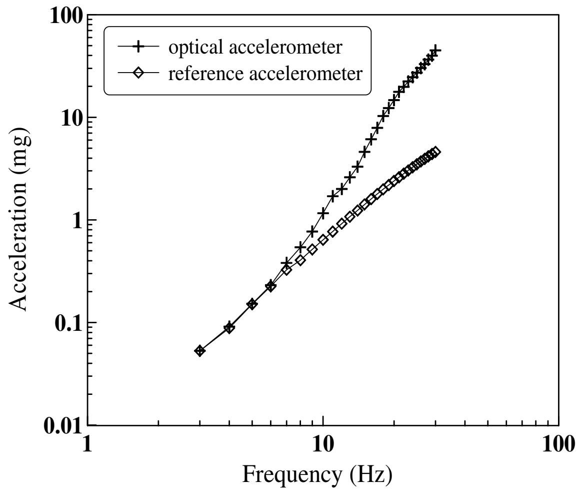


Figure 10. Frequency response in a log–log plot.

Table 1. Calibration results.

Data	Standard deviation (mV)	Slope (mV/mg)	Error (mg)
1	1.457	24.266	0.060
2	1.519	24.455	0.062
3	1.765	24.298	0.073
4	1.769	24.327	0.073
5	1.647	24.414	0.067
6	1.526	24.382	0.063
7	1.772	24.335	0.073
8	1.620	24.420	0.066
9	1.554	24.359	0.064
Average	1.625	24.362	0.067

are in good agreement with the reference accelerometer when the operating frequency is less than 6 Hz.

In practice, the operational frequency range (f_m) of an accelerometer is defined as $0 < f_m < 0.2f$, where f is the natural frequency of the device. In our optical accelerometer, shown in figure 8, f is 53 Hz. Thus the highest frequency that can be effectively measured by the optical accelerometer is 10 Hz. Although the current optical accelerometer has larger frequency response than the reference accelerometer for the frequency range above 6 Hz, a correlation function can be fitted to compensate for the errors.

As mentioned above, in the design of the structure, the moving part of the VCM is employed as the seismic mass and the spring that can simplify the design and manufacturing process compared with previous research [23]. Additionally, the suspension wires act as the spring that can increase the sensitivity. From the experimental results we can obtain that the optical accelerometer in this paper has a sensitivity of 24.362 V/g. Compared to the previous work where the sensitivity was 12.3 V/g, the current optical accelerometer is useful at low-frequency vibration since it has the higher sensitivity.

5. Conclusions

In this paper, an economical and highly sensitive optical accelerometer using a commercial optical pickup head is proposed. In the proposed design, the moving part of the voice coil motor (VCM) built in the DVD pickup head is used as the seismic mass which combines with the optical system of the DVD pickup to form an accelerometer. This system not only reduces the design and manufacturing process but also obtains a good measurement effect. Experimental results have shown that the accelerometer has a sensitivity of 24.362 V/g. It is useful at low-frequency vibration.

Acknowledgment

The financial support provided by National Science Council of ROC (NSC95-2221-E-002-230) is greatly appreciated.

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