# High resolution optical shaft encoder for motor speed control based on an optical disk pick-up

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# High resolution optical shaft encoder for motor speed control based on an optical disk pick-up

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Using a three-beam optical pick-up from a compact disk player and a flexible, shaft-mounted diffraction grating, we obtain information about the rotation speed and angular position of the motor's spindle. This information may be used for feedback to the motor for smooth operation. Due to the small size of the focused spot and the built-in auto-focus mechanism of the optical head, the proposed encoder can achieve submicrometer resolution. With high resolution, reliable operation, and low-cost elements, the proposed method is suitable for rotary and linear motion control where accurate positioning of an object is required.
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## I. INTRODUCTION

To achieve smooth operation as well as providing position indication, motors need a feedback signal containing information about the rotation speed. This is usually done through a shaft encoder, which monitors the rotation speed or the angular position of the motor. The shaft encoder may be optical, magnetic, or mechanical in nature. A commonly used motion control device for motors, the optical encoder[1–4] uses a light-emitting diode or a laser source to generate a beam of light, a patterned cylinder to reflect the beam, and a photodetector to monitor the variation of the reflected light. The lines or scale-marks on the cylinder serve as the counting target; their period is limited by the beam spot size. Despite the low resolution of the patterned cylinder, this device is usually suitable for measuring the average velocity over a relatively long period, and exhibits reasonable performance in applications involving high-speed motors. However, this method does not have sufficient accuracy for monitoring the instantaneous velocity or angular position of the shaft when the motor turns slowly. For such low-speed applications that demand tight speed control and position prediction (e.g., magnetic tape drives, optical scanners, and monochromators) an encoder with very fine resolution is desirable.

A variety of optical position encoders have been studied to increase the resolution of the motor rotation control, using either a diffraction grating with variable pitch,[5,6] or a pseudorandom position encoder,[7] or an interferometric position controller.[8] Although submicrometer resolution has been achieved, the cost and complexity of these approaches have limited their range of applications. In this article we describe a cost-effective, reliable, high-resolution shaft encoder implemented with a three-beam optical head from a commercially available CD player and a flexible diffraction grating. The proposed scheme enables both absolute and incremental position sensing with submicrometer resolution.

## II. SYSTEM CONFIGURATION

### A. The three-beam optical pick-up

A high-resolution optical encoder must be able to accommodate the vibration and wobble of the spindle. A three-beam optical pick-up[9,10] is a reliable device used in CD players for following data marks along a given track. As shown in Fig. 1, the module is designed to split the laser beam into three beams, focus them on the flexible grating, and detect the reflected signals which will be used as servo signals and data signals. The diffraction grating placed in front of the laser diode diffracts the laser beam into three beams, forming one center spot and two secondary spots. The objective lens that focuses these beams onto the flexible grating also collects them after reflection. A beamsplitter directs the reflected beam toward a detector set which includes three detectors with the center one divided into four subdetectors (the quad-detector). An astigmatic lens is used to generate the sum signal (SUM) and the focus error signal (FES) on the quad-detector.[9–12] These signals from the quad-detector are used for auto-focusing and, in the case of a CD, data-reading. The secondary detectors each generate a SUM signal, A and B, which are used to generate the tracking error signal (TES) derived from (A-B). The actuators on which the objective lens is mounted use the FES and TES to maintain focus and follow tracks in an optical disk. The pick-up is designed to read a disk through its 1.2 mm thick substrate; therefore, we had to insert a cover glass with a thickness of 1.2 mm in front of the flexible grating to eliminate spherical aberrations.

To implement the optical head in the proposed shaft encoder, the FES obtained from the quad-detector is used for auto-focusing to ensure that the beam is continuously fo-

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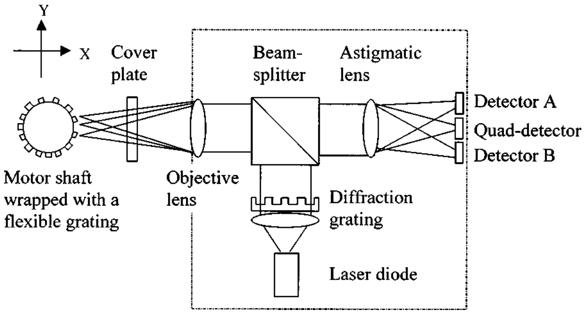

FIG. 1. The module of a three-beam optical pick-up (dashed line) includes a laser diode with λ = 0.78 μm, a diffraction grating yielding three beams, an objective lens of 0.45 NA for focusing and collecting these beams, an astigmatic lens, and a detector set for detecting the focus error signal and the groove-crossing signal. The design of the objective lens demands a cover plate of 1.2 mm between the flexible grating and the objective lens. For clarity the secondary beam paths are only drawn in the end of the objective lens and the detector set.

cused onto the flexible grating. The SUM signal derived from the quad-detector is assigned to generate an index signal to carry information about the absolute position. Signals A and B from each secondary spot obtained through the secondary detectors are related to the groove crossings; therefore, they are used for monitoring the shaft rotation speed and providing the incremental position indication.

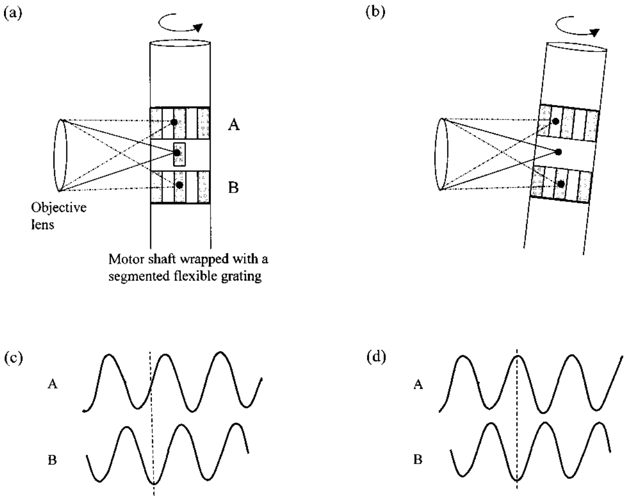

FIG. 2. The flexible grating, which serves as a line counting target, may contain three arrays for incremental and absolute encoders. The center array with index marks is used to generate the index signal for reference position. The other two strips with continuous grooves are used to provide groove-crossing signal for detectors A and B. The black dots indicate the position of the focused spots. (a) The two secondary spots are arranged to shift 1/4 (or odd multiples of 1/4) of the grating period with respect to each other to introduce a 90° phase shift in the groove-crossing signal. (b) Due to shaft runout, the relative position of the secondary spots on the grating introduces the change of the phase difference between signals A and B, which is used to indicate the direction and amount of the runout. (c) The corresponding groove-crossing signal for (a) shows a phase shift of +90° between signals A and B (the positive sign indicates signal A is leading signal B). (d) The corresponding groove-crossing signal for (b) shows a phase shift of +180° between signals A and B.

### B. The flexible grating

To generate an index signal for the reference position and the groove-crossing signal for the relative position, the flexible grating may be divided into two strips separated by a region that contains index marks as shown in Fig. 2(a). The index signal read by the central spot then serves as an absolute position indicator. The output signals A and B from each secondary detector yield sinusoidal functions of time corresponding to the position of the focused spot on the grating. With proper alignment of the two secondary spots as illustrated in Figs. 2(a) and 2(c), signals A and B show a 90° phase shift between them (the so-called ''push–pull'' readout). This phase shift can be used to extract direction information about the rotation and to remove the effect of motor runout in the direction perpendicular to the optical path (the *Y* direction in Fig. 1). Owing to shaft runout, the relative position of the two focused spots on the gratings is changed, which implies a shift of phase between signals A and B as illustrated in Figs. 2(b) and 2(d). The direction and the amount of runout is then obtained by detecting the change of the phase shift between signals A and B. For the case illustrated in Fig. 2, the increase of the phase shift from +90° to +180° (the positive sign represents signal A is leading signal B) indicates the shaft tilt is following the direction of the rotation. The change of 90° in phase, equivalent to the 0.25 grating-period, can be used to extract the amount of tilt by geometric calculation once the separation between focus spots A and B is known. In conventional optical encoders, a reticle or mask is added to introduce such a phase shift. Electronic processing of these sine waves generates zero-crossing signals, which further increase the resolution, and yield digital signals suitable for interpolation. The auto-focus mechanism of the actuator (defocus tolerance is ±0.6 mm) is used to correct for the wobble in the direction parallel to the optical path (the *X* direction in Fig. 1).

### C. Experimental setup

The experimental setup of the proposed system shown in Fig. 3 comprises a motor with the flexible grating mounted on its shaft, and a three-beam optical pick-up designed for CD-ROM players. The flexible grating is a commercially available plastic grating with a period of 1.1 μm, coated with a thin layer of gold to increase its reflectivity. Referred to Fig. 1, the optical pick-up contains a laser diode operating at a wavelength of 0.78 μm, a diffraction grating for generating

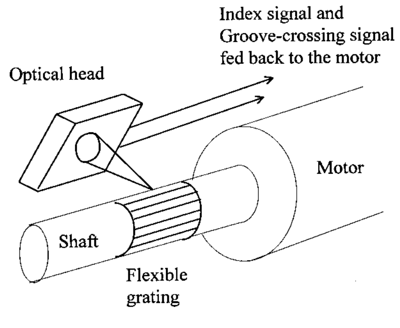

FIG. 3. Experimental setup of the proposed optical encoder. A three-beam optical head and a 1.1 μm period flexible grating are implemented to provide the focus error signal (FES) and groove-crossing signal (SUM, A, and B). These signals can be fed back to the motor for controlling the rotation.

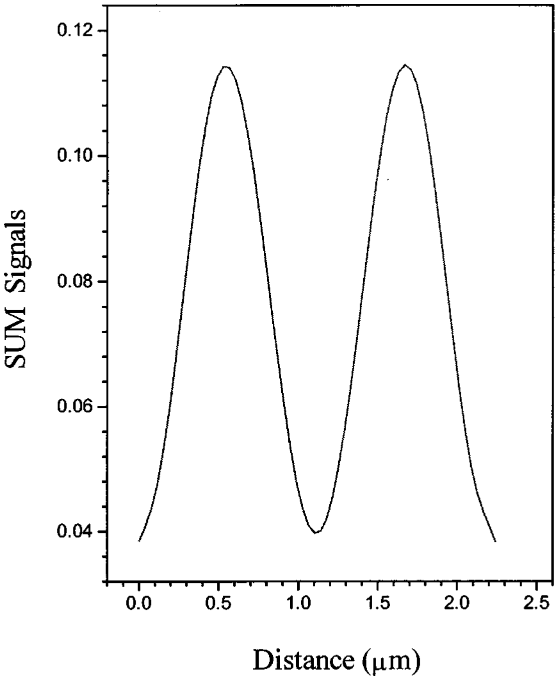

FIG. 4. Simulated results of the readout signal (SUM, A, or B) for the specific optical pick-up and the trapezoidal flexible grating used in the experiment. The sinusoidal curve is related to the position of the focused spot on the flexible grating.

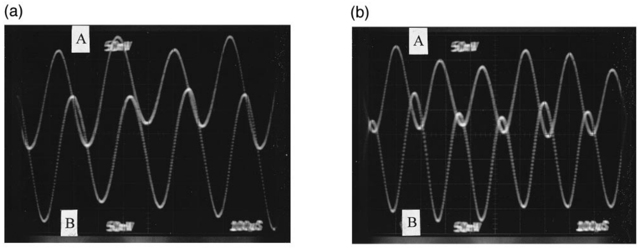

FIG. 5. Measured groove-crossing signals for event 1 with average rotation rate of 14 rpm (the corresponding average linear velocity is 5.9 mm/s). The abscissa is the time axis and the ordinate is the signal level. (a) The time period of the sine waves is 240 $\mu$s (the corresponding velocity is 4.6 mm/s) and the phase difference between signals A and B is 90°. (b) Recorded at another point during the same revolution, the time period of the sine waves is changed to 180 $\mu$s (the corresponding velocity is 6.1 mm/s) and the phase difference between signals A and B is shifted to ~160°.

the three beams, an objective lens with a numerical aperture of 0.45, and a quad-detector and two secondary detectors. To gain insight into the performance of the system, we use a general purpose diffraction modeling software DIFFRACT[13] to simulate the SUM signals (A or B), which serve as the groove-crossing signals. Figure 4 shows the simulated SUM signal for the specific optical pick-up and the trapezoidal flexible grating used in these experiments. Although the short-period flexible grating is not the optimum one for the optical pick-up, the sinusoidal curve corresponding to the position of the focused spot on the grating shows the feasibility of using this short-period grating as the counting target.

## III. EXPERIMENTAL RESULT

A dc brushless motor used in magnetic tape drives was tested with the proposed speed-monitoring scheme. In the magnetic tape application, the motor runs slowly (~5 rpm) during fine searching for a desired track which demands tight control of the motor rotation. With our flexible grating, we achieved a resolution of ~23 000 cycles per revolution (c/r) which is 46 times higher than the resolution offered by the built-in optical encoder. Two events with different average rotation speeds were tested for comparison: Event 1 with 14 rpm (the corresponding average linear velocity is 5.9 mm/s) and event 2 with 4 rpm (the corresponding average linear velocity is 1.7 mm/s).

For event 1, Fig. 5 shows groove-crossing signals from detectors A and B where the abscissa is the time axis and the ordinate is the signal level. Recorded at two different points during one revolution, the period of the sine wave in Fig. 5(a) is 240 $\mu$s (the corresponding velocity is 4.6 mm/s) and the phase shift is +90° while the period in Fig. 5(b) changed to 180 $\mu$s (the corresponding velocity is 6.1 mm/s) and the phase shift is +160°. The variation of the period of the sine waves corresponds to the variation of the rotation speed; the shift in the relative phase between signals A and B indicates the direction and the amount of shaft runout. Defects or dust particles gathering on the flexible grating may result in the variation of the amplitude of the signals as observed in Fig. 5. This can be eliminated by protecting the grating with a 1.2 mm thick substrate, as is done in optical disks.

Further processing of the groove-crossing signals by means of a time interval analyzer (TIA) reveals detailed information about the rotation rate. Figure 6 shows the measured values of the instantaneous velocity versus time during event 1, where the variation of the rotation speed is monitored while the focused spot crosses 100 grooves. During the measurement period, the instantaneous velocity varies from 5.1 to 6.5 mm/s, and the average speed is 5.7 mm/s. Although the variation is small, which implies a smooth rotation, the proposed system accurately measures the instantaneous velocity of the motor.

Figure 7 shows variations of the rotation speed for event

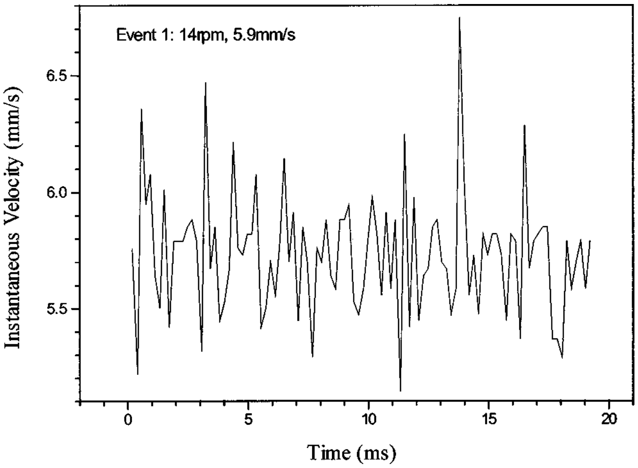

FIG. 6. Measured instantaneous velocity vs time for event 1. The results are recorded while the focused spot crosses 100 grooves. The instantaneous velocity varies from 5.1 to 6.5 mm/s and the average is 5.7 mm/s during the measurement period.

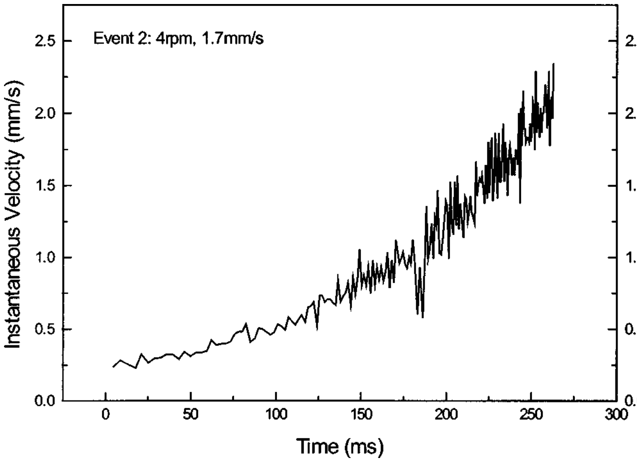

FIG. 7. Measured instantaneous velocity vs time for event 2 with an average rotation rate of 4 rpm (the corresponding average linear velocity is 1.7 mm/s). The results are recorded while the focused spot crosses 200 grooves. The instantaneous velocity varies from 0.22 to 2.2 mm/s and the average is 0.8 mm/s during the measurement period.

2 covering a range from 0.22 to 2.2 mm/s over 200 grooves. The average speed during the measurement period is 0.8 mm/s. This measurement indicates that the instantaneous velocity varied substantially over one rotation cycle of the motor. With the rotation speed varying greatly within one revolution, the measured instantaneous velocity with submicrometer resolution enables one to trace the rotation and to control the motor, if necessary. With conventional encoders having lower resolution, the oscillations are averaged out, and the instantaneous speed and the angular position measurement will not be accurate.

## IV. DISCUSSION

A high-resolution optical shaft encoder is presented to monitor the rotation behavior of the motor based on a three-beam optical pick-up and a diffraction grating. By monitoring the groove-crossing signal and the index signal, all information about the instantaneous velocity, the rotation position, and the reference position of the motor is detected and can be used as feedback signals for motor control. With the small size of the focused spot ($\sim$1 $\mu$m) on the line-counting target, the auto-focusing mechanism of the optical head, and the zero-crossing detection method, submicrometer resolutions are achievable. In our experiment where a 1.1 $\mu$m period grating was used, the variation of the rotation speed and the shaft runout were monitored. With cost-effective, reliable, and high-resolution elements, the proposed encoder is applicable to a wide range of motion control and monitoring systems.

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