A Novel Magnetic Linear Encoder Designed by Using the Slant Multi-Phase Filtering Model *

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A novel design model based on the slant multi-phase filtering model is presented. A magnetic linear encoder with sinusoidal output voltage waveform has been investigated, and the improved sinusoidal output waveform can be easily acquired. A minimum 6% of distortion factor, when the difference of slant phase is $\frac{2\pi}{3}$*, is observed. It is found that the Wheatstone bridge type sensor, made of NiFe(450A)/NiO(300A) bilayers deposited on Si (001) substrate, can enhance both output signal and thermal stability, and then can be widely used in the field of magneto-resistive sensor.*

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Thin film magnetic resistance sensors are extensively used to detect weak magnetic fields:[1−3] for example, in reading heads of magnetic data storage system, such as hard discs. They are also widely used to measure distance, linear and angler positions,[4] wheel speed of rotation,[5] and non-contact magnetic torque,[6] etc. In most of the AMR devices, thin films of ferromagnetic materials are used due to their miniature and high frequency response. Based on these advantages, magnetic linear encoders (MLE) can be used to detect a small displacement of a linear pulse motor (LPM) mover. As an actuator capable of moving directly, linear motors have been used in some fields. For example, a linear pulse motor has been used as a driving part of artificial hearts because its thrust/input power ratio is larger. Kikuchi *et al.*[7] designed a magnetic linear encoder with sinusoidal output voltage waveforms, which was formed by detecting gaps and bias gaps. By using this method, a distortion factor less than 10% of the sinusoidal output waveform was reached. However, in real operation it is very difficult to accurately adjust these gaps. For solving this problem, a new idea of slant multi-phase filtering (SMPF) theory has been put forward.[8] By using this new method, it is easier to reduce nth harmonic voltages, such as the odd harmonic that can be divided by three. The sinusoidal output voltage is obtained by designing the slant angle between the signal magnetic field and the MR element direction. Based on the SMPF model, a novel design of magnetic linear encoders is presented in this Letter.

The magnetic linear encoder (MLE) is schematically shown in Fig. 1. The MLE consists of a detective head and a set of the teeth-like patterns engraved on a soft magnetic substance such as iron plate. The detective head is the magnetic resistance (MR) sensor. The detective head detects the magnetic flux change produced by the teeth-like patterns. The MR sensor was set to face the LPM mover. By moving the LPM mover at a certain distance, detective gap d, from the MR sensor, the applied magnetic field, i.e. the bias field on the MR sensor, is changed. Figure 2(a) shows that the magnetic fields shot perpendicularly on the iron plate and the magnetic flux is concentrated on the teeth of the iron plate with higher magnetization. The magnetic field distribution above the iron plate in the horizontal plane of the MR sensor and the magnetoresistance change of the MR sensor are shown in Fig. 2(a). It indicates that the magnetic fields reach maximal value near the tooth edges.

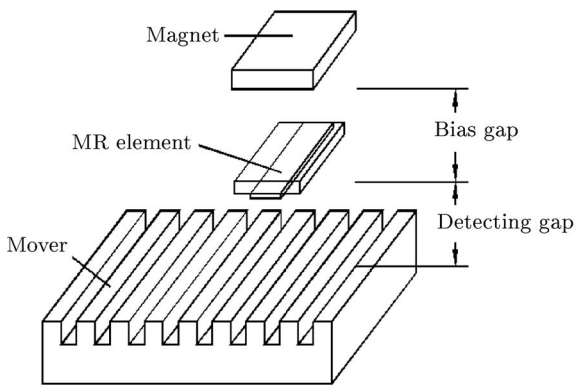


Fig. 1. Schematic of magnetic linear encoder (MLE). The MLE consists of a detective head and a set of teeth-like patterns engraved on a soft magnetic substance such as iron plate. The detective head consists of a MR NiFe (450 Å)/NiO(300 Å)/Si(001) bilayers thin film sensor and a magnet.

The MR sensor is schematically shown in Fig. 2(b). It consists of four MR elements R_1, R_2, R_3 and R_4, made of NiFe(450 Å)/NiO(300 Å)/Si(001) bilayer films, in which the NiO thin film of 300 Å was de-

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posited on a Si(001) substrate of 0.5 mm thickness by rf sputtering at an Ar partial pressure of 0.5 mtorr without introducing O_2 gas. The NiFe thin film was deposited by vacuum evaporation. An Au layer was then deposited on the NiFe thin film as electrodes. The dimensions and the resistance of each MR element are 1000 μm×10 μm (length/width) and 1 kΩ, respectively. In order to reduce the even harmonic components, two groups of MR elements, (R_1, R_4) and (R_2, R_3), were set at a phase difference of p, where p is half wavelength of the periodic external H_{ext} produced by the magnets. Moreover, as the MR elements were set at a slant angle φ $\left(\varphi = \arcsin\left[\frac{2p}{3l}\right]\right)$ with respect to the normal direction of signal magnetic field H_{ex} (see Fig. 4), it is found that the sinusoidal waveform could be improved obviously and the third harmonic components of the sensor output are reduced largely.

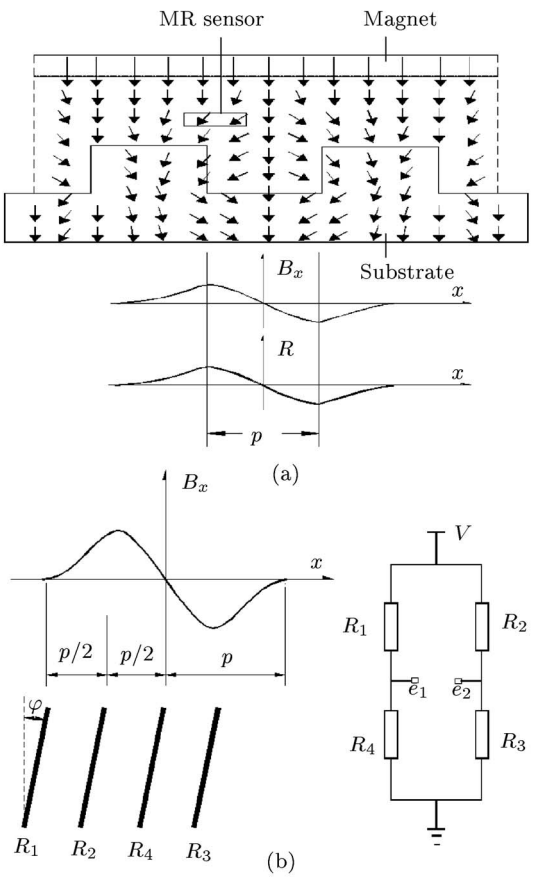


Fig. 2. (a) The magnetic flux-density distribution of the mover. The magnetic fields shot perpendicularly on the iron plate and the magnetic flux is concentrated to the teeth of the iron plate with higher magnetization. The magnetic flux distribution above the iron plate in the horizontal plane of the MR sensor and the magnetoresistance change of the MR sensor are also shown. Here p is half wavelength of the periodic external field H_{ext}. (b) Magnetic resistance (MR) sensor consisting of four elements R_1, R_2, R_3 and R_4. There is a phase difference of $p/2$ between the two MR element groups (R_1, R_4) and (R_2, R_3).

Figure 3 shows the output voltage V and distortion factor D_f vs the slant angle for the detecting gap, $d = 200\,\mu$m, and the half wavelength of a periodic H_{ex}, $p = 0.78$ mm. The distortion factor is defined in Eq. (1), where the output voltage waveform harmonics of 2nd to 7th are considered

$$D_f = \frac{\sqrt{\sum_{n=2}^{7} V_n^2}}{V_1^2} \times 100\%, \tag{1}$$

where V_n is the nth harmonic voltage ($n = 2, 3, 4\cdots$), and V_1 is a fundamental component.

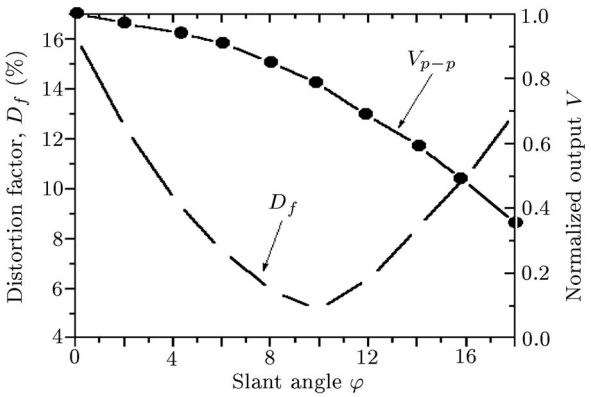


Fig. 3. Output voltage V and distortion factor D_f vs the slant angle for the detecting gap, $d = 200\,\mu$m and the half wavelength of a periodic H_{ext}, $p = 0.78$ mm.

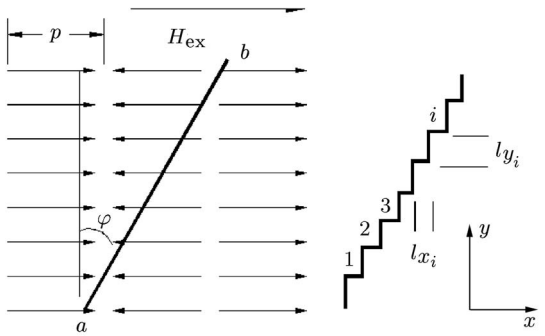


Fig. 4. The model of slant multi-phase filtering (SMPF). A slant MR element is equivalent to N steps. Each step consists of l_{x_i} and l_{y_i} segment.

In addition, the MR element slant angle φ is expressed by

$$\varphi = \sin^{-1}\left[\frac{\Delta\theta}{\pi}\frac{p}{l}\right]. \tag{2}$$

The model of slant multi-phase filtering (SMPF) of the MR sensor is shown in Fig. 4. The signal magnetic field (H_{ex}) is periodic and parallel to the direction of the x-axis. Here l is the MR element length. A slant MR element is equivalent to N steps. Each step consists of l_{x_i} and l_{y_i} segment. Suppose that $\Delta\theta$ is the phase difference between point a and point b, which is defined as slant phase difference:

$$\Delta\theta = \frac{\pi}{p}\Delta P = \frac{\pi}{p}\cdot l\sin\varphi, \tag{3}$$

where φ is the slant angle between MR element and the normal direction of signal magnetic field H_{ex}. In

the direction of the x-axis, every segment l_{x_i} is in the same direction of H_{ex}. Notice that the AMR effect is very small; the x component of output voltage, v_x, is nearly zero, where v_x is the sum output voltage of segment l_{x_l}. Therefore, it can be ignored. In the direction of the y-axis, the segment l_{y_i} is perpendicular to H_{ex}. The phase difference between l_{y_l} and $l_{y_{i+1}}$ is $\frac{\Delta\theta}{N}$, thus the multi-phase factor is $e^{i\frac{\Delta\theta}{N}}$. Then, we obtain the output voltage of slant MR element[8]

$$\begin{aligned} U &= \sum_{m=1}^{\infty} b_m \int_0^1 \sin m(\theta + \delta\Delta\theta) d\delta \\ &= \sum_{m=1}^{\infty} \frac{b_m}{m \cdot \Delta\theta} [\cos m(\theta + \Delta\theta) - \cos m\theta] \cos\varphi, \end{aligned} \tag{4}$$

$$u_1 = \sum_{m=1}^{\infty} \frac{b_m}{m \cdot \Delta\theta} [\cos m(\theta + \Delta\theta) - \cos m\theta] \cos\varphi,$$

$$\begin{aligned} u_4 = \sum_{m=1}^{\infty} \frac{b_m}{m \cdot \Delta\theta} &[\cos m(\theta + \Delta\theta + \pi) \\ &- \cos m(\theta + \pi)] \cos\varphi, \end{aligned}$$

$$\begin{aligned} e_1 = u_1 - u_4 = \sum_{k=1}^{\infty} \frac{b_{2k-1}}{(2k-1)\Delta\theta} &[\cos(2k-1)(\theta + \Delta\theta) \\ &- \cos(2k-1)\theta] \cos\varphi, \end{aligned} \tag{5}$$

where u_1 is the voltage output of R_1, u_4 is the voltage output of R_4, and e_1 is the voltage output of the three-terminal circuit. As a result, e_1 has no even harmonics that can be divided by two.

By assuming $(2k-1)\Delta\theta = 2\pi$, where $2k-1 = 3k'$, $k' = 1, 2, 3\cdots$ and $0 \le \Delta\theta \le 2\pi$, then $\Delta\theta = \frac{2\pi}{3k'}$. For $k' = 1$, $\Delta\theta = \frac{2\pi}{3}$. Substituting it into Eqs. (3) and (5), we have $\sin\varphi = \frac{2}{3} \cdot \frac{p}{l}$, $\varphi = \sin^{-1}\left[\frac{2p}{3l}\right]$ and

$$\begin{aligned} e_1 = \Big\{ &\frac{3b_1}{2\pi}\left[\cos\left(\theta + \frac{2\pi}{3}\right) - \cos\theta\right] \\ &+ \frac{3b_5}{5\pi}\left[\cos\left(5\theta + \frac{10\pi}{3}\right) - \cos 5\theta\right] \\ &+ \frac{3b_7}{7\pi}\left[\cos\left(7\theta + \frac{14\pi}{3}\right) - \cos 7\theta\right]\Big\} \cos\varphi. \end{aligned} \tag{6}$$

As expressed by Eq. (6), e_1 has no even harmonic components and odd harmonic components can be divided by three, therefore e_1 is sinusoidal and it is easier to improve output waveform by adjusting slant angle φ. The reason is that not only the sinusoidal distortion induced by the nonlinearity of sensor but also the distortion induced by non-sinusoidal signal magnetic field can be reduced by using the SMPF method. However, only the sinusoidal distortion induced by the nonlinearity of sensor can be reduced by adjusting the detecting gap d. As shown in Fig. 3, over the range of small φ, the distortion factor D_f of the sensor is rapidly decreased with increase of φ, but the output voltage $V_{p\text{-}p}$ is slowly decreased. In fact, $V_{p\text{-}p}$ reaches the maximum at $\varphi = 0$ and D_f reaches the minimum at $\varphi = 10°$, corresponding to the best sinusoidal output. As is described above, for $\Delta\theta = \frac{2\pi}{3}$ the sensors have sinusoidal output (see Eq. (6)). Then, according to $\varphi = \sin^{-1}\left[\frac{2p}{3l}\right]$ (Eq. (3)), with the data of $p = 0.78$ mm, and $l = 3$ mm, a theoretical value $\varphi = 9.85°$ is calculated, which is in good agreement with the experimental value $\varphi = 10°$. In fact, the output voltage waveform produced by the MLE has been confirmed to be sinusoidal.

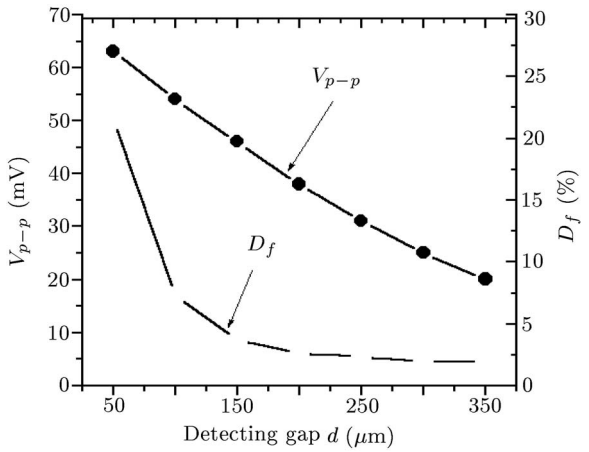


Fig. 5. Dependence of output voltage $V_{p\text{-}p}$ and distortion factor D_f on detecting gap d when the bias gap is 2 mm and the slant phase difference $\Delta\theta = \frac{2\pi}{3}$.

In summary, a novel design of magnetic linear encoder based on the slant multi-phase filtering (SMPF) model has been investigated. Based on this theoretical model, the output voltage waveform of the magnetic linear encoder has been improved, and is better than that obtained by using the conventional methods. Based on SMPF theory, the sinusoidal output waveform can be easily acquired when the slant phase difference $\Delta\theta$ is varied. In addition, the distortion factor is nearly independent of the detecting gap as the slant phase difference $\Delta\theta$ is set to be $\frac{2\pi}{3}$. Moreover, the installation and the adjustment of sensor based on the SMPF theory are easier. These results can be widely used in the field of magneto-resistive sensors.

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