LINEAR ELECTRIC ENCODER™

PRINCIPLES OF OPERATION

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Abstract

The **Linear Electric Encoder** is the linear member of the novel Electric Position Sensing technology, which also includes angular displacement encoders.

The **Linear Electric Encoder** comprises a scale and a read-head that interact capacitively. The scale is a printed circuit strip on which a periodic pattern field transmitter is printed. The read-head is also a printed circuit substrate on which a conductive receiver pattern is printed. A typical read-head has a profile of 6mm including the processing electronics, and provides two outputs that are sinusoidal functions of the measured displacement.

The interaction area between the read-head and scale is typically 25mm by 60mm, resulting in the averaging of multiple transmitter periods. The averaging provides a high signal to noise ratio, mechanical mounting-error tolerance, and significant insensitivity to scale contamination.

The **Linear Electric Encoder** differs from sine/cosine optical linear encoders in the following aspects:

- The scale is electrically active
- The excitation is AC
- The period is typically two orders of magnitude longer
- The output is absolute

The outputs of the **Linear Electric Encoder** have a very low DC offset, low harmonic distortion, perfect amplitude matching, and high temperature stability, they can thus be digitized (interpolated) to provide submicron resolution and accuracy of 10 microns and better.

The long period of the Linear Electric Encoder provides several advantages, such as virtually no tradeoff between speed and resolution, and output signals of low frequencies, which are less prone to parasitic phase shifts and to PWM noise.

1. Principles of the **Linear Electric Encoder**

The electric field between the plates of a parallel plate capacitor is known to be nearly uniform when the separation between the plates is smaller than the smallest dimension of the plates. A variation of the parallel plate capacitor comprises two insulating substrates facing each other, patterned with conductive coating, (the feature size being commensurate with the plates separation). If one substrate is shorter it can move along the longer one to provide displacement dependent capacitance. This is the basis of Type-1 Electric Position Sensing, that is described below, and which is one of six possible configurations. \(^{[1]}\)

A Type-1 incremental **Linear Electric Encoder** includes a stationary scale and a moving read-head – as shown in **Figure 1**. A repetitive pattern of rectangular bars is printed on the scale (shown in a), where every four consecutive bars constitute a spatial period. The individual bars in each period are excited with four AC voltages shifted by 90 electrical degrees, such that the odd bars are excited with 0° and 180° - *in-phase* waveforms, and the even bars are excited with 90° and 270° – *quadrature* waveforms.

![Figure 1 - Incremental Type-1 Linear Electric Encoder](image-url)
The read-head receiving plate (shown in b) includes a sinusoidal pattern with a period that equals four scale bars, and is surrounded by a complementary pattern. The gap separating the sinusoid and the complementary pattern is as small as practical, while the separation between the scale and the read-head is typically in the order of the width of one individual bar.

![Receiver Plate Diagram]

**Figure 2 - Signal processing of the Linear Electric Encoder**

Synchronous detectors are essentially analog multipliers that multiply the output of the charge amplifier with square waves - which are in phase with the 0° and 270° excitation waveforms, respectively. The net result is that the outputs of the two low pass filters are DC voltages proportional to the sine and cosine of the read-head displacement relative to the scale. The fine period position, combined with the instantaneous values of the sine and cosine signals translates to the incremental position of the read-head.

In mathematical language, if the function \( h(x) \) represents the sinusoidal read-head pattern then the output signals, being proportional to the overlap between it and the respective excitation plates, would be proportional to:

\[
\int h(x)s_1(x)\,dx \quad \text{and} \quad \int h(x)s_2(x)\,dx
\]

Where \( s_1(x) \) and \( s_2(x) \) represent the respective in-phase and quadrature excitation plates. Therefore, as the read-head travels, the output voltages portray the cross-correlation functions of the read-head and scale functions.
2. Absolute Output Linear Electric Encoder

The Linear Electric Encoder can be adapted to provide an absolute output by providing a coarse mode, in addition to the previously described fine mode. While in the fine mode the full read-head travel includes many periods; in the coarse mode the output signals are also proportional to the sine and cosine of the read-head position, but the period length equals the full read-head travel. Although the scale of the absolute version can be switched between the two modes, the coarse mode is only needed on power turn on, to identify the position of the read-head within a fine period. The fine and coarse mode readings are combined to provide the absolute position of the read-head with a resolution and accuracy that are determined by the fine period length and fidelity, and the quantization depth of the processing electronics.

![Figure 3 - Conceptual coarse mode absolute Linear Electric Encoder](image)

Like the fine mode, the output signals of the coarse mode are also products of cross correlation between sinusoidal and rectangular patterns; however, the roles of the read-head and of the scale are reversed. Figure 3 is a conceptual illustration of the scale and read-head in the coarse mode. The scale includes a conductive strip that is split along its length by a sinusoidal gap. The two sections of the scale are excited with phase-opposing alternating voltages, whereas the read-head includes a rectangular conductive plate that is connected to the charge amplifier, as before. The read-head signal will be a sinusoid with a period that equals the scale length, but since the sine function is ambiguous and its amplitude may be affected by gap tolerance, etc., a complementary cosine signal is required.

Figure 4 illustrates a space division multiplex concept that simultaneously provides coarse-mode sine and cosine functions from the same scale. The bars are divided into two portions - the gap in the odd bars is position-modulated with a sine function, while in the even bars it is modulated with a cosine function. The sine and cosine bars are excited with the same frequency but in quadrature relation as before. In the coarse mode, the upper and lower portions are excited with phase-opposing waveforms. As before, the composite output of the charge amplifier is separated into its constituents by two synchronous demodulators fed with quadrature related switching signals and followed by two low pass filters.

![Figure 4 – Coarse/Fine Linear Electric Encoder](image)

The pattern of the read-head in Figure 1 is optimized to minimize the effect of variations in the uniformity of the air gap on the fine channel output signals. Such variations may result as the read-head moves along an imperfect mechanical guide. A first-order cancellation is inherent in the up-down symmetry of the pattern. Similarly, by making the pattern left-right symmetrical, the output is made insensitive to tilt in the cross axis.
Tilting the coarse-mode rectangular receiver plate (figure 3b) around an axis parallel to the travel axis would affect the balance of the upper and lower portions of the transmitter bars and, consequently, the balance of the sine and cosine outputs. To minimize this effect, the strategy illustrated in Figure 5 is used, where the sine and cosine transmitter bars are alternatingly mirrored relative to the centerline, as a result each two consecutive bars are compensating.

Figure 5 – Scale pattern for a tilt-compensated Linear Electric Encoder

3. A Long Period and its Implications

An optical system is not suitable to accurately generate repetitive patterns with a long period. This is because the accuracy of sinusoidal patterns generated is limited at least by gray scale non-linearity of the photographic media. In principle, generating a bi-level, pulse-width modulation approximation of the sinusoid could circumvent this limitation, but imaging the pattern would mold a heavy burden on the photodiode illumination and responsivity uniformity. Different constraints would limit the period length of sinusoidal patterns generated by diffraction.

Electrostatic fields are governed by different laws and can be accurately generated with virtually any period length. The electric field inside a parallel plate capacitor is uniform, except for edge fringing, which becomes smaller as the ratio of the gap to the plate dimensions diminishes. As a result, a patterned capacitor may not include features much smaller than the separation between the plates, and electric field patterns are limited to long rather than short periods.

A diffractive optical encoder will provide sinusoidal waveforms that, theoretically, may be interpolated indefinitely. However, in practice the following imperfections limit the interpolation depth:

- DC offset
- Amplitude mismatch
- Harmonic distortion

It can be shown that a DC offset in the sine and cosine outputs will result in an error term that repeats once per period length (electrical cycle), while an amplitude mismatch will result in an error that repeats twice per period length. Although these errors, and harmonic distortion as well, can be compensated to some extent, the sine and cosine signal currents are generated in two separate photodiodes and calibration can only be maintained over a limited temperature range. On the other hand, since the period length of the optical encoder is short, it still provides significant accuracy and resolution and the above imperfections are manifested only as subdivisional errors.

The Electric Linear Encoder differs from the Optical Linear Encoder in additional respects, the most notable of which being the period length, which is, orders of magnitudes longer (few millimeters versus few micrometers). To achieve resolution comparable to that of optical encoders much higher interpolation factor (quantization depth) is needed, and the sinusoidal outputs of the electric encoder must be significantly more accurate. Fortunately, the factors involved make that possible, as follows:

- The quality of the transmitting and receiving plates is dependent on an inherently accurate photolithographic reproduction process
- Fringe effects play a positive role by reducing harmonic distortion - attenuating higher spatial harmonics in the sinusoidally patterned field
- The dimensions of the interaction area between the read-head and scale are flexible. The read-head length can be maximized, depending on the application, to average many periods and improve accuracy.
• Prior to demodulation the output signals are AC coupled and share a common receiving plate and a processing channel. Consequently, they are closer to ideal in terms of DC offset, amplitude matching, harmonic distortion and signal-to-noise ratio, and are also stable over temperature.

The practical implications of the long period, and the associated low signal frequencies are:

• No index position is needed, even in the incremental version, since a resilient mechanical stop with a travel that is contained in a pitch length is sufficient to identify the end period, from which the absolute position can be determined
• Reduced dynamic errors and parasitic phase shift
• Reduced sampling rate without missing cycles at high speeds
• Reduced sensitivity to adjacent PWM interference, which occupies a separate spectral region
• Essentially no conflict between high speed and resolution – as shown below

The accuracy required from the coarse channel increase with the number of fine channel periods over the length of the scale, i.e., as the scale becomes longer and the fine channel periods become shorter. To minimize this requirement the modification shown schematically in Figure 6 is used, where there are several coarse mode cycles along the length of the scale. To avoid ambiguous reading, their amplitude is linearly modulated and the position dependent vector sum of the coarse mode sine and cosine is computed and used to identify the coarse cycle. However, the magnitude of the vector also depends on the gap between the read-head and the scale - which could lead to serious errors. This error is compensated based on the fact that the magnitude of the corresponding fine channel vector, for a given gap, is constant along the entire length of travel. It can thus serve as a measure of the gap for correcting the coarse mode signals.

4. Signal-to-Noise ratio

The noise model of the Linear Electric Encoder is shown in Figure 7, where $C_f = 10\text{pF}$ is the feedback capacitance of the charge amplifier, $C_s$ is the receiving plate capacitance to the excitation plates, and $C_p$ is its parasitic capacitance to a grounded shield layer on the back of it. In a 25x60mm read-head the area of the sinusoidal fine channel receiver plate is 7cm². The optimal distance between the receiver and transmitter plates varies in accordance with the period length, for a 4mm period length it will be taken as 1mm, which will result in $C_s = 5\text{pF}$. The shield plate is an inner layer in a printed circuit board, at a distance of typically 0.5mm separated by glass-epoxy with a dielectric constant of is 4.5, which results in $C_p = 45\text{pF}$. 

![Figure 6 – Amplitude -modulated coarse-mode pattern](image)

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![Figure 6 – Amplitude -modulated coarse-mode pattern](image)
Figure 7 – Noise model for the Linear Electric Encoder

The dominant noise source is the front stage of the charge amplifier. The voltage gain of an ideal charge amplifier is \(-C_s/C_f\) - the ratio of the source capacitance and the feedback capacitance, assuming an infinite feedback resistance. In practice, a 10MΩ resistor is used and its effective value is increased by feeding the output voltage to it through a resistive voltage divider (not shown) which makes its affect on the frequency response negligible.

The total amplifier output voltage noise density is given by \([2], [3]\)

\[
\frac{4kT/R_f + in^2}{\omega cf^2} + e_n^2 \left[1 + \frac{C_s + C_p}{C_f}\right]^2 \quad [V^2/Hz]
\]

4kT/Rf (in Figure 7) is the thermal (Johnson) noise of the feedback resistance, where k=1.38x10^{-23} and T=300º. For R_f =10MΩ its value amounts to 1.6x10^{-27} [A^2/Hz]. For a FET input stage, in^2 is typically of the order of 10^{-28} [A^2/Hz] and is negligible in comparison with the thermal noise - which at the operating frequency of 10kHz, will result in output noise density of 4x10^{-15} [V^2/Hz].

For an amplifier with a voltage noise source of e_n=10nV/√Hz and the above capacitance, the noise density of the second noise source will be: 3.6x10^{-15} [V^2/Hz]. The overall output noise density at 10kHz will, therefore, be ~ 8x10^{-15} [V^2/Hz].

If the cut-off frequency of the low-pass filters in Figure 2 (and consequently, the bandwidth of the encoder output signals) is f_0 then the amplitude-modulated signal at the output of the charge amplifier will occupy the frequency range f_c ± f_0. The random noise integrated in this 2f_0-wide frequency range will be shifted to the base band by the synchronous demodulation and will set the limiting resolution of the sensor. For f_0 =1kHz the noise bandwidth will be 2kHz, and the RMS noise at the preamplifier output will be 4µV.

If the carrier wave is square we should add the noise contributions in the frequency intervals around the third and fifth harmonics as well. However, due to the decreasing contribution of the thermal noise, and the lower respective gains (1/3 and 1/5, in accordance with the Fourier coefficients) of the synchronous demodulator, the added noise would be negligible.
The signal voltage at the output of the charge amplifier is: \(-V_s C_s /C_f\) and for an excitation voltage \(V_s = 5V\) peak-to-peak, will be 2.5V peak-to-peak. The maximum value of the demodulated (full-wave rectified) signal will be 1.25V, and its ratio to the RMS noise will be \(\sim 3 \times 10^5\).

It is known that a random Gaussian noise will exceed 3.3 times its RMS value for only 0.1% of the time, it practically will never exceed 4 times its RMS value. The dynamic range of the signal can therefore, be safely taken as \(3/4 \times 10^5 \sim 7 \times 10^4\) - which is equivalent to 16 bit.

5. Electrical interface, signal processing, resolution, and speed

The Linear Electric Encoder operates from a DC supply of +5V with a current consumption of only 5mA. This unusually low current is a result of the low loading of the scale capacitance, the low excitation frequency (10kHz), and the CMOS processing circuitry.

The sine and cosine output signals are typically 2V peak-to-peak, each provided as a complementary pair to minimize differential ground, and other common mode noise pickup. After the differential signals are digitized they are converted to a digital representation of the displacement. The conversion algorithm is based on an Arc-tangent look-up table that covers only one octant. This is based on the fact that a full sinusoidal waveform comprises 8 mirrored and/or inverted repetitions of the same pattern. This can be shown to be equivalent to extra 3 bits in the binary angle representation (where the first bit represents 180º) of the output-computed angle. An n-bit A/D converter provides n-2 functional bits (excluding the sign bit and the LSB). The resolution of the output binary angle will, therefore, be n+1 bits. The full conversion algorithm can be found in [4].

In accordance with the above, a scale with a period of 4mm combined with a 12 bit A/D converter will provide a resolution of \(4/2^{13}\)mm, or \(\sim 0.5\mu m\), while a 14 bit A/D converter will provide a resolution of \(\sim 0.1\mu m\).

The maximum read-head speed for 1kHz cut-off filters and 4mm pitch would be 4m/Sec - independent of the selected resolution. It is notable that increasing the excitation voltage will improve the signal-to-noise ratio and enable increased resolution, while increasing the excitation frequency and filter cut-off frequency will enable virtually, unlimited maximum speed.

6. Construction and Accuracy

The scale and read-head substrates are produced by standard printed circuit technology. The scale thickness varies between 0.2mm to 0.5mm and the standard fine period pitch is 1, 2, 4, or 8mm. Standard scale width is either 25mm or 10mm. The corresponding read-heads - which include all of the processing electronics, have a profile of 6mm, and a length of 60mm and 40mm, respectively.

Present day technology enables a minimum period length of about 0.5mm and the accuracy of the reproduced patterns using the new Laser Direct Imaging (LDI) technology is in the order of a few microns. However, the overall accuracy of the encoder is influenced by several additional factors:

- Averaging of many periods
- Attenuation of higher harmonics in the pattern by field-fringing
- Mechanical variations of the printed circuit following copper etching.

The resulting measurement accuracy is typically 10µm or better, depending on the scale length.

7. Environmental Tolerance
The output of the Electric Linear Encoder is surprisingly stable against various factors, such as temperature, humidity, contamination, mechanical vibrations, and electrical interference. This is a result of several factors:

- The large read-head and scale interaction area
- The symmetrical geometry of the receiver pattern
- The low bandwidth of the output signals

Temperature induced variations in the processing circuit, as well as in the air gap, equally affects the sine and cosine signals - but not their ratio. As a result, the operation of the encoder is basically temperature independent. The only temperature effect, which is not self-compensated, is the longitudinal expansion of the scale. However, it was found that a 0.2mm thick scale, properly bonded to a substrate, assumes its temperature expansion coefficient, for all practical purposes. This is the ideal situation in many applications, since it guaranties zero differential expansion relative to other machine elements. In applications where thermal expansion should be minimized, the scale should be bonded to a stable substrate.

The Electric Linear Encoder is significantly insensitive to deposited dust particles, due to the averaging over a large interaction area. The effect of both dust and moisture deposition, is further diluted with increased air gap.

The Electric Linear Encoder is inherently insensitive to magnetic fields. It is also virtually immune to electric fields due to the fact that the receiver plate is electrically shielded by the peripheral area and by the scale transmitter elements.

8. Wireless Read-Head and other Electric Encoders

Another version of the Electric Linear Encoder is under development, whereby two scales face each other, one serving as a transmitter and the other as a receiver. The coarse and fine signals are generated in response to a passive, patterned, dielectric plate “read-head” that moves between the stationary scales.

In addition to linear encoders, the new Electric Position Sensing technology is applied to rotary encoders, with similarly unusual properties. Figure 8 illustrates the different versions that are obtainable. The digital versions are obtained by digitizing and processing the analog outputs, to provide the desired output formats.

Figure 8 – Versions of Electric Position Sensors
References

1. Patent application.
4. www.netzerprecision.com

**Note:** The Linear Electric Encoder® is a registered trademark of Netzer Precision Motion Sensors, Ltd. For more information, please refer to [www.netzerprecision.com](http://www.netzerprecision.com).