OPTICAL ENCODER HEAD WITH IMPROVED LINEARITY

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Key words: encoder, optical scanner, Vernier scale, opto-sensors, interpolator.

Abstract: We present a high precision optical scanner, combining averaged optical sensors array with appropriate 10 um graduated scales on measurement - fix plate and Vernier sliced parallel scale on reading plate. The generated sine wave signals are at least 30dB less distorted by distributing and mismatching optical edges over a number of sine wave periods within a number of Vernier scaled periods. Reading plate which is positioned along optical array has a unit division smaller than those on a fixed scale - permit a far more precise positioned optically generated sine wave current. Position-like averaging of four generated signals was distributed over an opto-array and reading scale. Background of reduction as well as prototype is presented.

Good matching was found between mathematically analyzed optical scanner and measurement, where comparable measurements were performed on optical head having redistributed and fixed opto-edges.

Optični dekodirnik z izboljšano linearnostjo

Kjučne besede: dekodirnik, optični pretvornik, Vernierjeva skala, optični senzor, interpolator.

Izvleček: V članku predstavljamo optični dekodirnik z visoko točnostjo pretvorbe. Sestoji se iz polja optičnih senzorjev, namenjenih povprečenju signala ter iz fiksne in čitalne letve z 10 um rastrom in z Vernierjevo porazdelitvijo. Zgradba sistema omogoča periodično prerazporeditev optičnih robov znotraj periode sinusnega signala in znotraj Vernierjeve periode ter s tem zmanjšanje popačenja proizvedenih sinusnih signalov za 30dB. Čitalna letev ima raster zmanjšan v primerjavi z rastrom merilne letve kar posledično pomeni veliko boljše pozicioniranje in razpršen vpliv uklonskih pojavov. Princip delovanja in prototipni optični dekodirnik so opisani v članku.

Izdelana matematična analiza se dobro ujema z izsledki meritev. Poleg rezultatov meritev je podana primerjalna analiza sistemov z Vernierjevo porazdelitvijo - in sicer s konstantnim in s prerazporejenim rastrom.

1 Introduction

Accurate measurement of displacement is of prime importance in any computer controlled machine (CNC). The need to manufacture "something" requires the ability to move "something" with a very high level of accuracy. And for this accurate position sensors are needed, also called position encoders /4/.

Such encoders can be roughly split by the type of displacement they detect (rotary, linear) or by the quantity they detect (optical, magnetic) or by the type of output data they produce (incremental, absolute).

This work deals with linear optical incremental position encoders.

As this work deals with a very narrow field of research not much literature is available. Most information can be found in books about automatics and robotics /1, 2/. Our solution is also much differ from that in patents /10, 11/.

2 Optical encoder

An optical encoder (Figure 1) is typically composed of a light source (LED), the main scale with a built-in optical grating with period PM and the optical scanner that is composed of an optical sensor and a reading scale with a built-in optical grating with period PR /3/. The main and reading scales are glass plates on which a thin layer of metal (chromium Cr) is deposited and then a regular pattern is etched into this layer. If periods PM and PR are the same then as the scanner moves along the main scale the patterns on the main and reading scale overlap to a different degree, depending on the momentary position of the scanner. In short, as the scanner moves along the main scale the amount of light from the light source (LED) is modulated. Therefore the electrical signal produced by the photo sensor is also modulated. In our case the photo sensor is a reverse polarized photodiode and the signal is in the form of electrical current.

Real encoders use four such sensors placed apart Ľ of the grating period (PM, PR) so that they produce four signals that are 90° shifted between each other. Figure 2 shows the four ideal quadrature signals +A, -A, +B, -B that are produced by the four sensors. The two pairs of signals are amplified with a differential amplifier to remove the large DC components and suppress even harmonics to produce the signals A and B.

The signals in figure 2 are periodic; this corresponds to a movement of the scanner head with constant velocity along the main scale. One period of the signal corresponds to a movement of the scanner head equal to the grating period (PM, PR). The signals are not periodic in time but they are periodic in relation to the displacement along the main scale. The signals in figure 2 are also not pure sine/co-

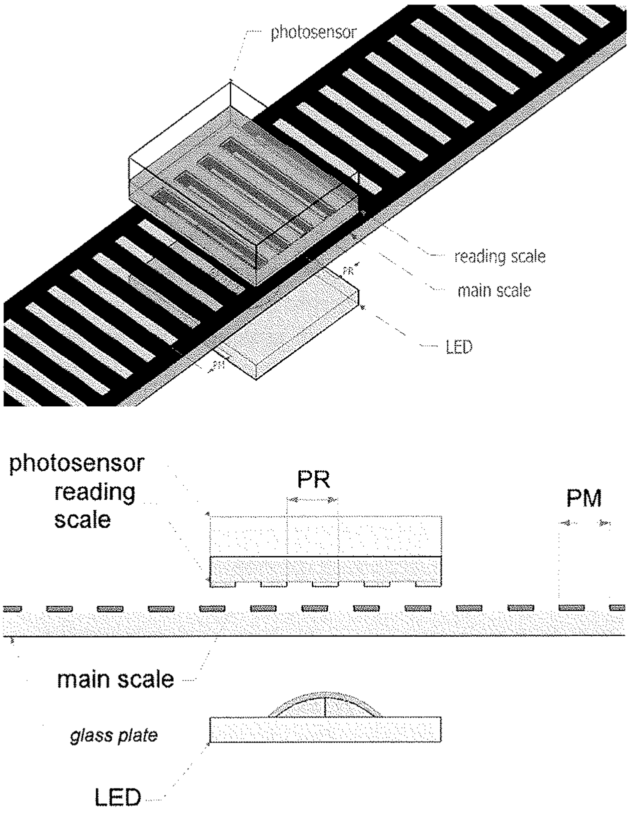


Fig. 1: Optical encoder.

sine in reality they are distorted and contain harmonic components.

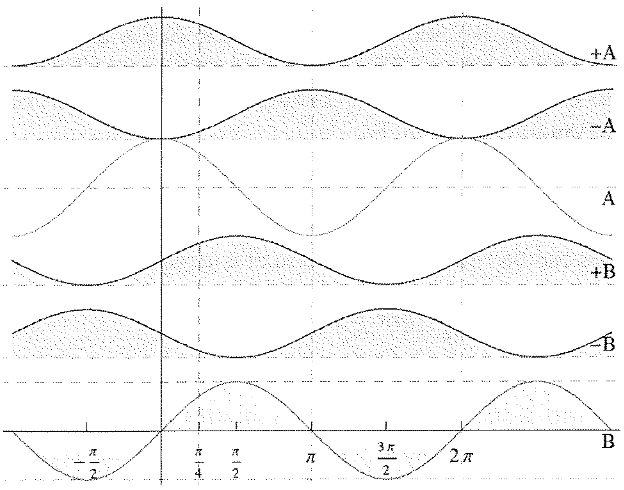


Fig. 2: Quadrature signals.

2.1 Interpolation

As we have seen the encoder produces two 90° shifted (quadrature) signals A and B as can be seen in figure 3. The two quadrature signals enable us to detect the position of the scanner head at all time just by measuring the values of signals.

The signals can be digitized directly so that the resolution of the encoder is determined by the grating period (PM, PR). Or interpolation can be used to increase resolution.

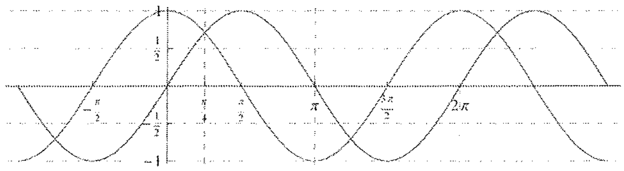


Fig. 3: Ideal signals.

If we have available two quadrature (sine/cosine) signals then we can by scaling and adding or subtracting of the two signals produce a new signal shifted by an arbitrary amount as is illustrated by the simple circuit in figure 4 and the two trigonometric formulas (1) and (2). We can produce a number of such shifted signals and make XOR operations on them (figure 5) to produce a quadrature signal with four times higher frequency which results in a four times higher encoder resolution.

$$\sin(x+\alpha) = \cos\alpha \sin x + \sin\alpha \cos x \qquad (1)$$

$$\cos(x+\alpha) = -\sin\alpha \sin x + \cos\alpha \cos x \qquad (2)$$

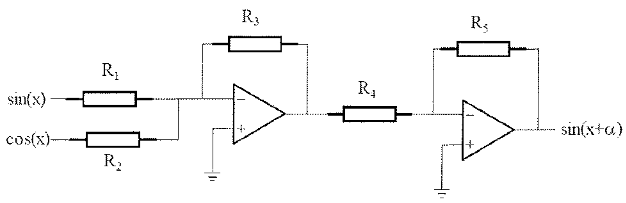


Fig. 4: Shifted signals.

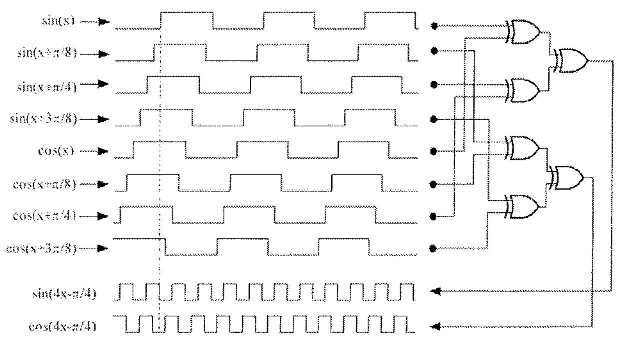


Fig. 5: Interpolation by factor 4.

One example of an integrated interpolation system is the IDS-EN400 /4/ which has a selectable interpolation factor 5, 10, 20, 25, 50, 100 and integrated signal conditioning circuitry.

The main emphasis of this work is the improvement of the quality of the quadrature signals to enable higher interpolation factors and higher encoder resolution. With the industry standard grating period (PM, PR) of 20μm, interpolation factors of 100 and more would enable resolutions in the nanometric range.

3 Improved encoder

The old scanning head (figure 6) was composed of four photodiodes (+A, -A, +B, -B) that produced the quardrature signals and an additional photodiode (RI) that generates the index signal which is used for absolute position encoding (for more information see /3/). Such a scanning head was basically described in Section 2. The spectral purity of such a scanning head is mainly determined by the diffraction and reflection of light by the two optical gratings in the main and reading scales. Without this the signals would have a triangular shape not sinusoidal.

We have used several techniques to improve the signal quality as described below.

3.1 Vernier (Nonius) pattern

In figure 7 we can see how two patterns with period P1=1 and P2=0.9 produce a third pattern which has a much larger period P=9 (9 is the least common multiple of P1 and P2). This new Vernier pattern corresponds with the movement of the scanning head along the main scale therefore we can place four photodiodes in one period of the Vernier pattern for generating the quadrature signals as depicted in figure 7.

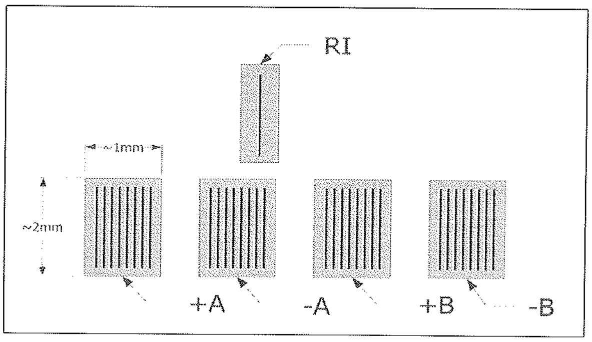
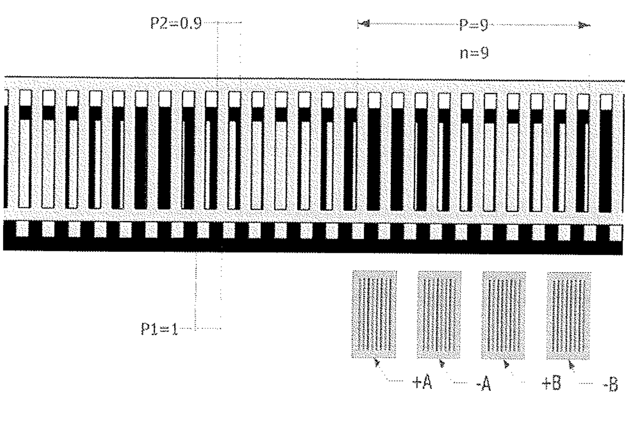


Fig. 6: Old scanning head.



Fig, 7: Vernier (Nonius) pattern.

The actual encoder uses a main scale with the grating period (*pitch*) of 20µm and we chose a reading scale period of 19µm to produce a Vernier pattern with a period of 380µm. Inside this 380µm we could place four photodiodes with maximum width of 95µm but the semiconductor technology chosen limits the width to 83µm. These dimensions are illustrated in figure 8. The two square shaped transmittances of the main and reading scales interact to create the Vernier pattern (380µm) which corresponds to the intensity of the light that falls on the photodiodes. As the scanning head moves 20µm the Vernier pattern moves 380µm. This movement of the pattern is detected by the four photodiodes placed 95µm apart to produce the 90° shifted signals. The "chopped" shaped of the Vernier pattern as seen in figure 8 is averaged (filtered) by the width of the photodiodes.

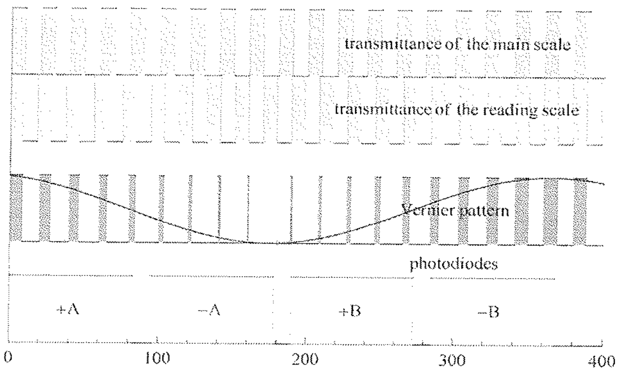


Fig. 8: Scanning cell.

This filtering can be simply described if we assume that each narrow strip of the diode produces the same small current i_n the only difference being that, as the pattern moves across the photodiodes, the currents i_n are shifted/delayed depending on the position of the strips that are producing them. Therefore we can find the total photodiode current i_D by summing all these small currents i_n over the photodiode width W,

$$i_D(x)=\frac{1}{W}\int_0^W i_n(x-\tau)d\tau \qquad (3)$$

This can be rewritten in the form of a convolution integral,

$$i_D(x)=\frac{1}{W}\int_{-\infty}^{\infty}(u(\tau)-u(\tau-W))i_n(x-\tau)d\tau \qquad (4)$$

where $u(\tau)$ is the unit step function. The impulse response of the linear system which is defined by (4) is $h(x)=\frac{1}{W}(u(\tau)-u(\tau-W))$. The frequency response is obtained by applying the Fourier transformation,

$$H(j\omega)=\int_{-\infty}^{\infty}h(x)e^{-j\omega x}dx=e^{-j\frac{W\omega}{2}}\left(\frac{\sin\left(\frac{W\omega}{2}\right)}{\frac{W\omega}{2}}\right)$$

and the amplitude response,

$$|H(j\omega)|=\frac{\sin\left(\frac{W\omega}{2}\right)}{\frac{W\omega}{2}} \qquad (5)$$

This is the typical $\frac{\sin x}{x}$ response which has periodic zeroes and these zeroes can be moved to a suitable place with the right selection of the photodiode width W. Please note that here x is displacement not time and $\omega = {}^{2\pi}\!/_{x}$.

Figure 9 shows an example where $W = {}^{380\mu m}\!/_{3} = 126.66\mu m$ therefore the first zero of the amplitude response is at the third harmonic. This arrangement would remove the third, sixth, ninth ... harmonic component. The disadvantage is that not all four photodiodes would fit in one Vernier period (380µm). Therefore we did not choose this option. Although the chosen $W = 83\mu m$ doesn't completely remove any higher harmonics it still suppresses them to some extent.

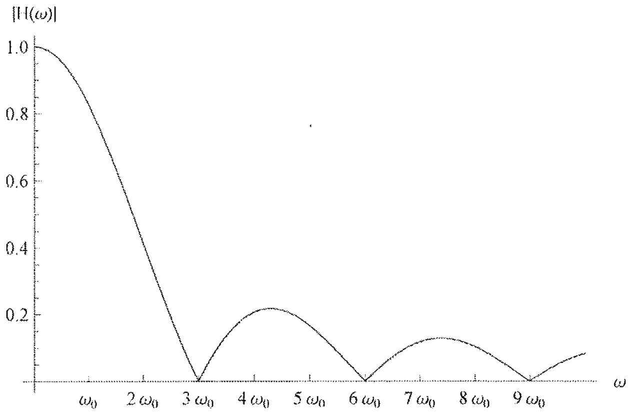


Fig. 9: Amplitude response ($W = \frac{1}{3}$ period).

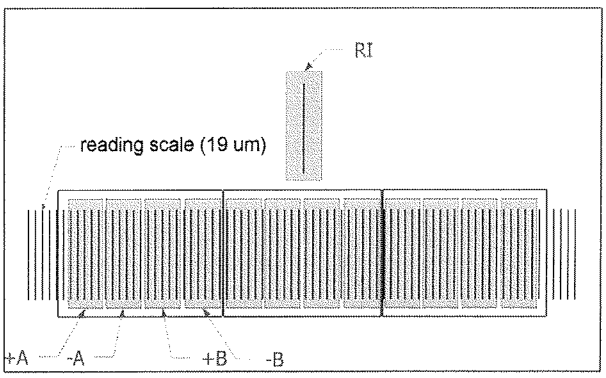


Fig. 10: Vernier distributed scanning head.

As shown in figure 8 four photodiodes were placed in the 380µm period so that a scanning cell was created. The whole scanning head contains 16 such cells (figure 10 shows only 3 cells). This was done to average out various unwanted effects like defects in the main and reading scale patterns or uneven illumination of the scanning head...

3.2 Shifted scanning cells

We could see in section 3.1 that by adding together shifted signals a favorable filter function was created therefore we tried this approach by shifting the scanning cells (figure 11) in the scanning head to remove the third harmonic component.

Let's write the combination of shifted signals as

$$g(x) = f(x) + f(x-a) + f(x-2a)..$$

Then by applying the Fourier transformation,

$$F[g(x)] = F[f(x)] + F[f(x-a)] + F[f(x-2a)]...$$

$$G(j\omega) = F(j\omega) + F(j\omega)e^{-ja\omega} + F(j\omega)e^{-j2a\omega}...$$

$$H(j\omega) = \frac{G(j\omega)}{F(j\omega)} = 1 + e^{-ja\omega} + e^{-j2a\omega}...$$

We get the frequency response $H(j\omega)$ of a system that adds signals that is shifted by x = a.

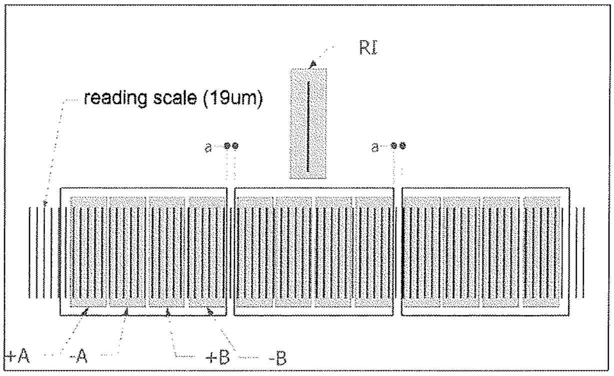


Fig. 11: Scanning head with shifted cells.

Our scanning head has 14 scanning cells and we wanted to remove the third component therefore $14a = {}^{380\mu m}\!/_{3}$, so we have to shift each cell by about 9 µm. The resulting filter function is shown in figure 12.

3.3 Rotation of the scanning head

We have also investigated the influence of scanning head rotation (figure 13) on the generated signals and discovered that this has a similar effect of shifting the signals as shown in equations (3)-(5) and a $\frac{\sin x}{x}$ filter function is created.

If for example the scanning head is rotated so that the upper edge of the scanning head is 6.66 µm (1/3 of the main scale period) left or right from the lower edge then the third harmonic component is removed similar as in figure 9.

4 Results

For comparison the harmonic components of the old scanning head (figure 6) were first measured (figure 14). As expected the largest is the third harmonic which is only 27dB smaller than the fundamental component.

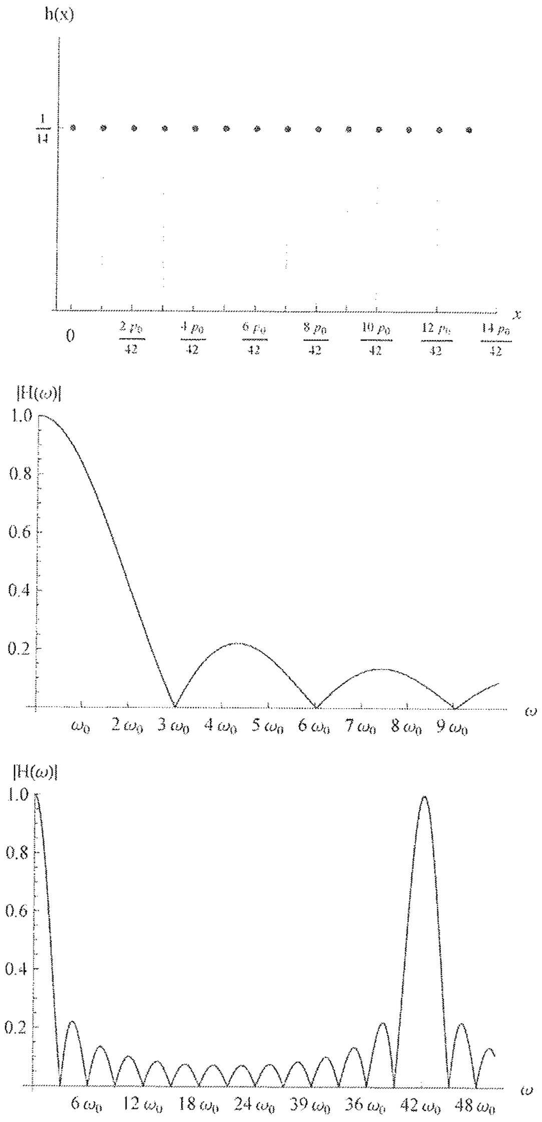


Fig. 12: Amplitude response (shifted cells).

Figures 15 and 16 show harmonic components of the distributed Vernier scanning head (figure 10) and the scanning head with shifted cells (figure 11). The Vernier distributed scanning head has the second and third harmonic 52dB below the fundamental component. For the scanning head with shifted cells only the second component can be seen 56db the third component is suppressed as predicted.

Figures 17 and 18 also show harmonic components of the two improved scanning heads. Here rotation was used to further suppress the second and third component. For the scanning head with shifted cells (figure 18) all harmonic components are below 60db.

In figures 15-18 the black line shows the FFT of the differential signal and the grey line shows the FFT of the single ended signal.

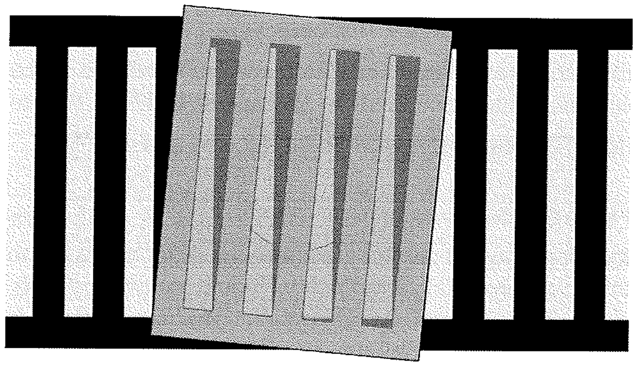


Fig. 13: Scanning head rotation.

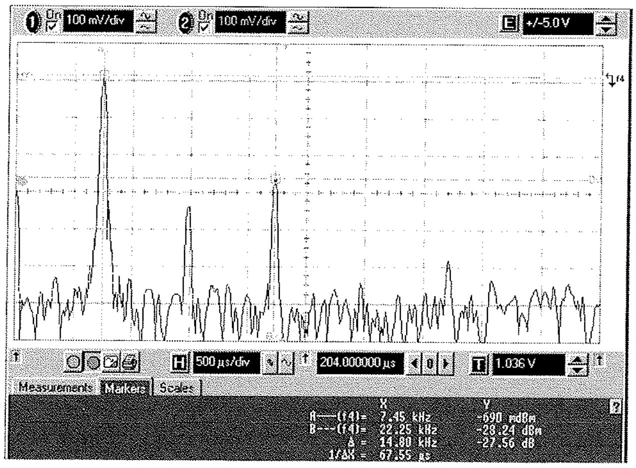


Fig. 14: Old scanning head.

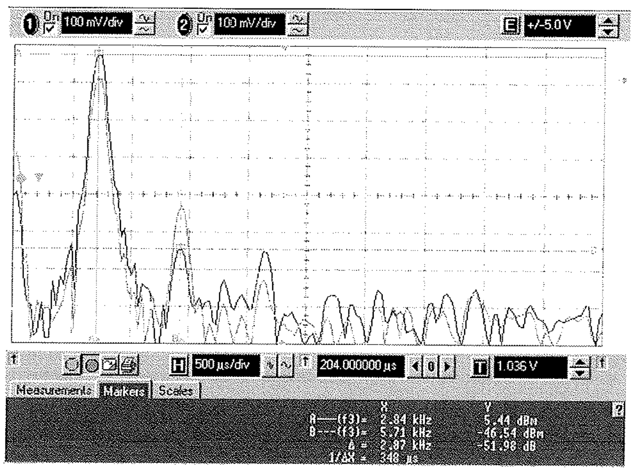


Fig. 15: Vernier distributed scanning head.

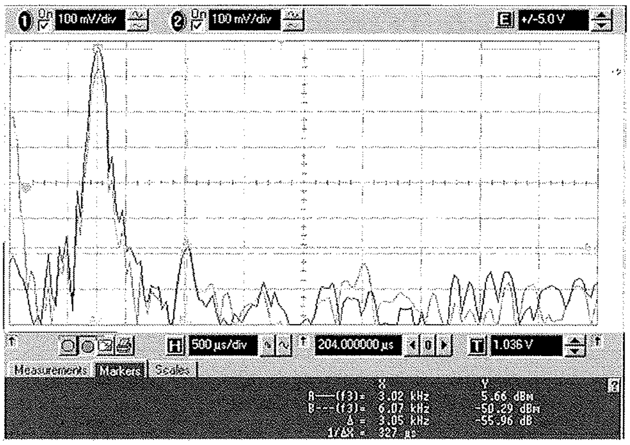


Fig. 16: Scanning head with shifted cells.

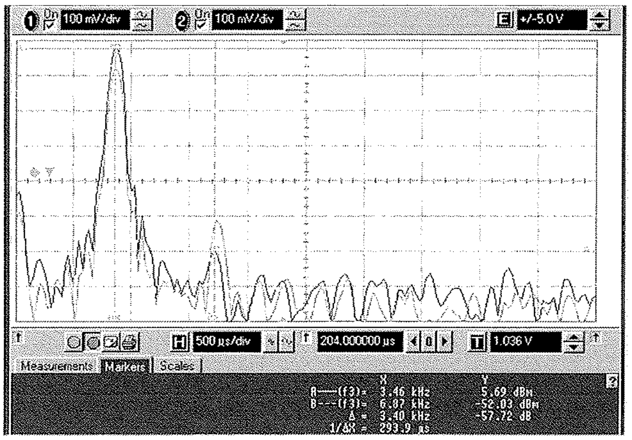


Fig. 17: Vernier distributed scanning head (rotated).

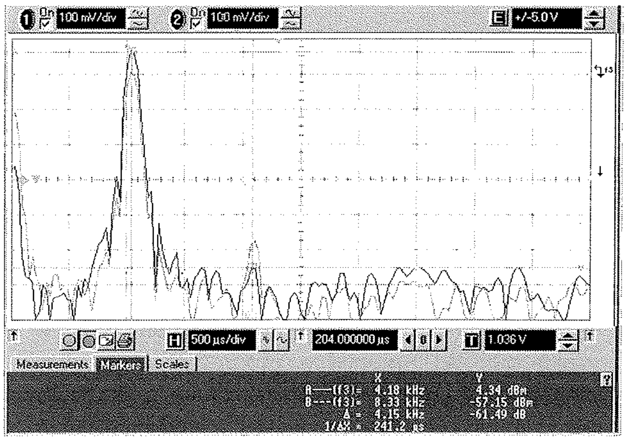


Fig. 18: Scanning head with shifted cells (rotated).

5 Conclusions

The aim of this work was to improve the scanning head of a linear encoder already used in the industry /5/. As shown in section 4 the improved scanning heads have the harmonic components suppressed by about 30db compared to the old scanning head. Furthermore with the introduction of multiple scanning cells into a single scanning head the influence of various unwanted effects were reduced like for example defects in the main and reading scale patterns or uneven illumination of the scanning head. Also by manufacturing all the photodiodes on a single chip diode matching was improved.

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