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IMPROVING PERFORMANCE OF ENCODERS BASED SYSTEMS USING WAVELET TECHNIQUES

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Abstract – This paper aims at the accuracy improvement of low-cost encoders based systems. Calibration data together with the approximations and details of wavelet decomposition are used to obtain some important parameters of absolute encoders. Differential and integral non-linear errors are estimated and their values are used to increase measurement accuracy. An error compensated system can easily be obtained by including the encoder, a microcontroller and a memory with a code conversion table. Simulation and experimental results, obtained from a low-cost angular encoder, are used to validate the proposed characterisation method based on wavelet data processing.

Keywords: encoders, wavelet transforms, error compensation.

1. INTRODUCTION

Digital encoders are used for linear and angular displacement and position measurements. For high resolution measurements the mechanical accuracy of the encoder must be very high in order to minimize errors. For example a 12-bit full-range encoder (span=360º) corresponds to approximately 316 angular seconds resolution. As the resolution becomes lower the dimensional requests increase and the price of the transducer becomes higher (hundreds of dollars). It is also important to refer that even if incremental encoders are cheaper than absolute encoders, they are more sensitive to disturbing pulses (noise) and more affected by power failures. Considering the large number of applications of absolute encoder systems [1-3], this papers presents a microcontroller based system with calibration and error compensation capabilities that can be used to improve the performance of low-cost encoders based systems. A wavelet [4-6] based algorithm is proposed to extract the main error parameters of the encoder, namely its integral and differential non-linearity errors.

Basically, the wavelet analysis enables a windowing technique with variable-sized regions. The use of long time intervals, where a more precise low-frequency analysis is performed, enables the gathering of the encoder's INL error profile, and the use of shorter time intervals, where a more precise low-frequency analysis is performed, enables the gathering of the encoder's DNL error profile that is associated with the high-frequency information of encoder's characteristic. This information can easily be used to evaluate the main parameters of linear or angular encoders.

2. SYSTEM DESCRIPTION

2.1 Hardware

The system includes three main elements: an encoder, which could be linear or angular, a microcontroller [7-8] and a precision positioning device [9-11] required only for calibration purposes. The system can be used to evaluate encoder's characteristics in the calibration phase, and after, in the measuring phase, the evaluated errors for each position code can be stored in the microcontroller memory to improve measurement system accuracy.

In the calibration phase a mechanical rotary positioning device is used to generate a set of reference angles. For each reference angle the output from the encoder is taken and the errors for each digital code of the encoder stored in a memory for post-processing error compensation. The accuracy and resolution of the mechanical positioning device must be at least four times higher than the correspondent encoder's values. Figure 1 represents the system block diagram used during calibration phase. The calibration system includes the encoder, a manual or automatic precision rotary stage, a set of 8 pull-up resistors, a data acquisition board (NI-DAQ ATMIO-16E4) and a personal computer (PC).

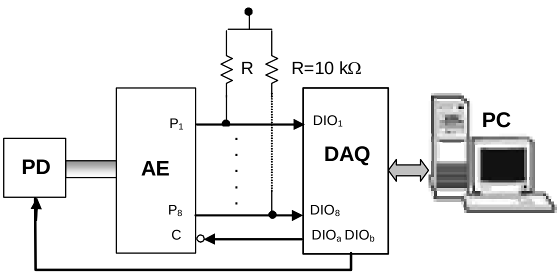

Fig. 1 Hardware block diagram of the calibration system (PD- positioning device, AE- angular encoder, DIO- digital input-output, DAQ- data acquisition board, PC- personal computer, C- AE select pin, R- pull-up resistors).

After calibration the main characteristic of the encoder are evaluated and the correction coefficients, stored in the microcontroller's memory, are used to provide error compensation during measuring phase. Figure 2 represents the hardware block diagram of the measuring system that includes mainly the encoder, a microcontroller (PIC16F877) and a transceiver (MAX233).

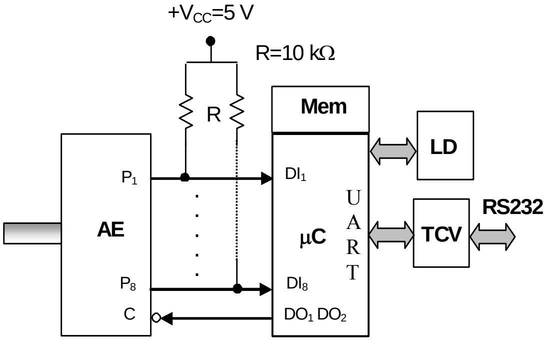

Fig. 2 Hardware block diagram of the measuring system (AE- angular encoder, DI_i- digital input, DO_i- digital output, UART- universal asynchronous receiver transmitter, TCV- transceiver, μC- microcontroller, LD- local display, Mem- memory C- AE select pin, R- pull-up resistors).

2.2 Wavelet data processing

The characterization of the encoder is obtained by using wavelet techniques [12-14]. Valuable information can be extracted from the wavelet decomposition tree. The wavelet approximations represent the high-scale, low-frequency components, of the encoder transfer curve. The details of the wavelet decomposition represent the low-scale, high-frequency components, of the encoder's transfer curve. The wavelet approximation is used to extract the integral non-linear (INL) of the encoder and the details are used to extract other important data that includes quantisation and differential non-linearity errors of the encoder.

Based on the shape of encoder's transfer curve, the step profile of the Haar [15] function, also known as Daubechies 'db1', is used as mother wavelet. The analytical expression of this function is given by:

$$\psi(x) = \begin{cases} 1 & \text{if} \quad x \in [0, 0.5[\\ -1 & \text{if} \quad x \in [0.5, 1[\\ 0 & \text{if} \quad x \notin [0, 1[\end{cases} \tag{1}$$

For a continuous signal (s), discrete wavelet analysis coefficients are given by:

$$C(a,b) = \int_D s(x) \frac{1}{\sqrt{a}} \psi\left(\frac{x-b}{a}\right) dx \tag{2}$$

where D represents the function domain, in our application the angular range of the encoder, signal (s) represents the encoder characteristic and the coefficients a and b represent the position and scale coefficients of the wavelet decomposition, defined by:

$$a = 2^j, \; b = k \cdot 2^j \quad \text{where} (j,k) \in Z^2 \tag{3}$$

being a the decomposition level.

As an example, Figure 3 represents graphically the wavelet decomposition process for a decomposition level, number of details, equal to 4.

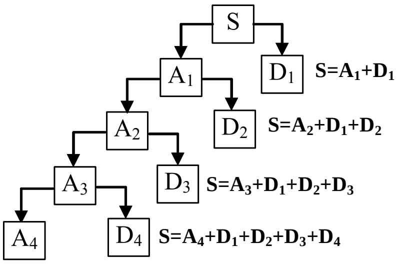

Fig. 3 Graphical representation of a wavelet decomposition process with a decomposition level equal to 4.

The level of wavelet decomposition that must be used to obtain encoder's parameters depends on the number of calibration points and on encoder's resolution (R), given by:

$$R = \text{span} / 2^n \tag{4}$$

where span represents the measurement range amplitude of the encoder and n its number of bits. In the next section the relation between the level of wavelet decomposition, encoder's resolution an number of calibration points will be established and confirmed by simulation results.

3. SIMULATION RESULTS

Some MATLAB functions were developed in order to evaluate the performance of the proposed wavelet based method. The main tasks of the simulation programs include the generation of an arbitrary encoder characteristic and the analysis based on wavelet decomposition. The parameters that can be adjusted in the transfer characteristics are: the span of the encoder, its resolution, differential and integral non-linear errors and input signal that represents the angular position used for calibration purposes. The wavelet analysis program includes some MATLAB built-in functions (e.g.: wavedec and wrcoef) and the simulator accepts a variable parameter (n_wav) that corresponds to the number of details considered in wavelet decomposition.

Figure 4 represents the simulated transfer characteristic and angular error of an encoder with INL and DNL errors equal to 2,5 LSB and 1 LSB, respectively. A 7-bit angular encoder with 8192 calibration angles (N_{CA}) uniformly distributed in the interval 0º-360º is considered. In this case, 1 LSB corresponds to an angular displacement of 2,8125º (span/2^n).

Figure 5 represents analysis results based on wavelet decomposition when one approximation and six wavelet detail functions are considered. The polynomial curve fitting of the wavelet approximation curve exhibits an INL error of 2,5271 LSB, which represents a relative deviation of 1,08 % from the true value. From the 6-detail curve a DNL error of 0,9844 LSB is obtained, which represents a relative deviation of 1,56 % from the true value. Considering the random nature of the generated characteristics and the effect of quantisation (Q) errors [16] the obtained results are quite acceptable and the computation processing load to evaluate the parameters is very low [15].

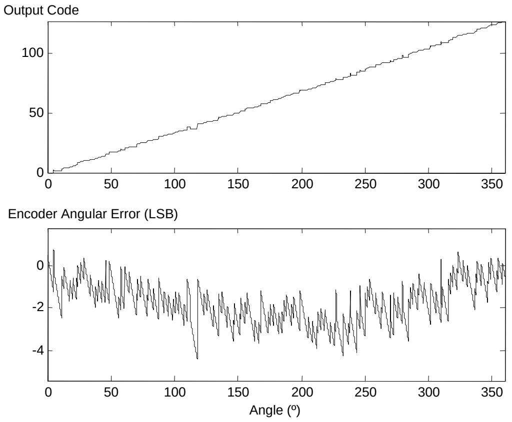

Fig. 4 Simulation results of output code and angular error of a 7-bit encoder using the following simulation parameters: INL=2,5 LSB, DNL=1 LSB, span=360º, number of calibration angles, N_{CA}=8192.

In order to evaluate the number of details that must be considered in the wavelet decomposition, the INL and DNL errors, obtained from wavelet analysis, were estimated for a number of detail wavelet functions varying between 1 and 10. The relative error obtained for INL, represented in Figure 6, shows that results are acceptable for a number of wavelet detail functions lower than 8. The best result is obtained for a number of wavelet detail functions (N_{WF}) equal to 7, which correspond to:

$$N_{WF} = \log_2\left(\frac{N_{CA}}{2^n}\right) \qquad (5)$$

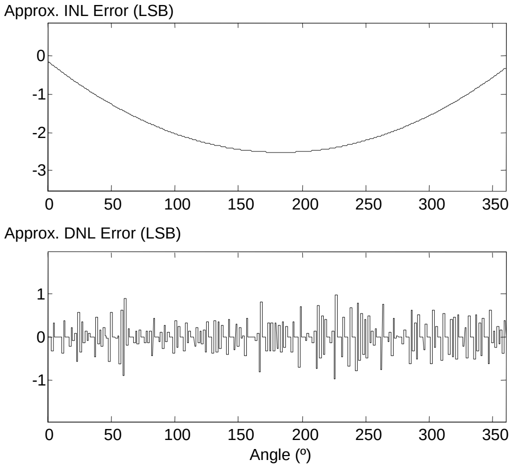

Fig. 5 Simulation results of the INL and DNL of a 7-bit encoder using the following simulation parameters: INL=2,5 LSB, DNL=1 LSB, span=360º, N_{CA}=8192.

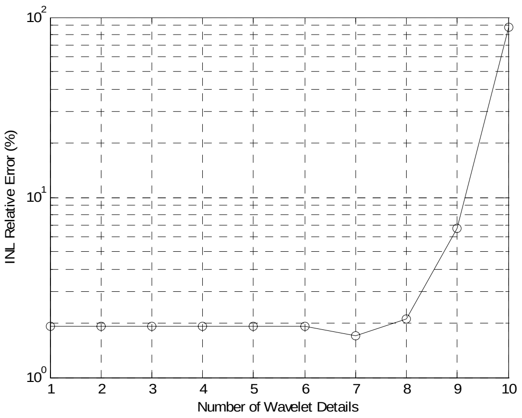

Fig. 6 Simulation results of the INL of a 7-bit encoder for a number of wavelet decomposition functions varying between 1 and 10 (the remaining simulation parameters assume the following values: INL=2,5 LSB, DNL=1 LSB, span=360º, N_{CA}=8192).

The relative error obtained for the DNL is represented in Figure 7. Again it can be confirmed that the results are acceptable for a number of wavelet detail functions lower than 8 and the errors are particularly low for a number of wavelet details lower than 5.

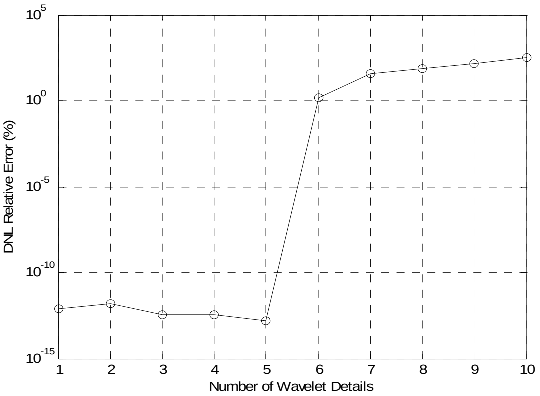

Fig. 7 Simulated results of the DNL of a 7-bit encoder for a number of wavelet decomposition functions varying between 1 and 10 (the remaining simulation parameters assume the following values: INL=2,5 LSB, DNL=1 LSB, span=360º, N_{CA}=8192).

Simulations were also performed in order to evaluate the repeatability of the method. Figure 8 represent the histogram data of the INL evaluation when 256 random encoder characteristics with INL=2,5 LSB and DNL=1 LSB are generated. The mean values and standard deviations obtained for the INL and DNL were: mean(INL)=2,5900 LSB, mean(DNL) =1,1577, std(INL)=0,0952 LSB and std(DNL)=0,2073 LSB. The represented results were obtained for a number of wavelet decomposition functions equal to 3.

As referred the polynomial interpolation of wavelet approximation function corresponds to the INL error of the encoder and it is also possible to obtain the global effect of others errors, including

DNL and quantisation error, by subtracting the approximation function from the encoder characteristic.

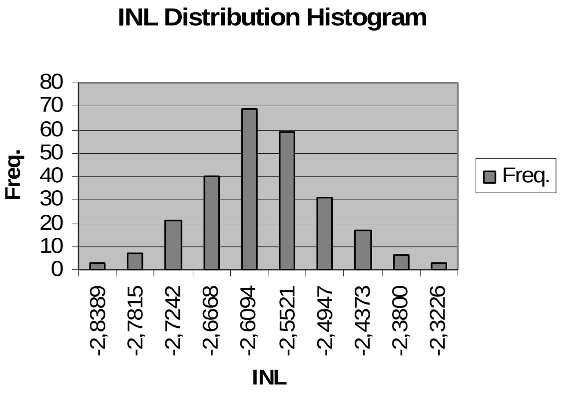

Fig. 8 Histogram data of the INL results for a set of 256 randomly generated encoders characteristics with INL=2,5 LSB and DNL=1 LSB.

The DNL error amplitude and distribution over the encoder's codes can also be obtained from the information contained in the wavelet decomposition function. Acceptable results, in terms of maximum amplitudes of INL and DNL errors, are achieved even when a single detail wavelet decomposition and a low number of calibrations angles are used.

4. EXPERIMENTAL RESULTS

In order to obtain experimental results, a low-cost absolute encoder [17] was selected. The main characteristics of the encoder are: 8-bit Gray code with 128 absolute states, maximum rotation speed of 120 rpm and the capability to retain last position in the event of a power failure. Manufacturer doesn't specify any information about INL or DNL errors so one of the testing purposes is to obtain those parameters using the test set up represented in Figure 1.

Figure 9 represents the experimental calibration data for a number of 512 calibration points uniformly distributed over the encoder's position range (0º-360º). The selected number of calibration points (N_{CP}) corresponds to an average value of 4 calibration measurements per encoder code. The positioning device was adjusted for an increment equal 0,7º between successive calibration points and for each angular position a set of 100 acquisitions was made and the integer mean value evaluated. This procedure was very important because it minimises measurement noise effects particularly disturbing for calibration angles near encoder's code transitions.

Figure 10 represent the INL and DNL evaluation results when a number of wavelet details equal to 2 were considered. The evaluated INL and DNL errors are respectively 0,6 LSB and 1,1 LSB, respectively. The low-cost encoder, selected for testing purposes, exhibits some missing codes and a non-monotonic characteristic.

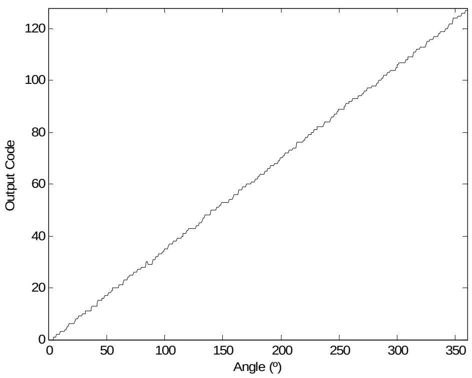

Fig. 9 Experimental calibration data of the tested encoder (N_{CP}=512).

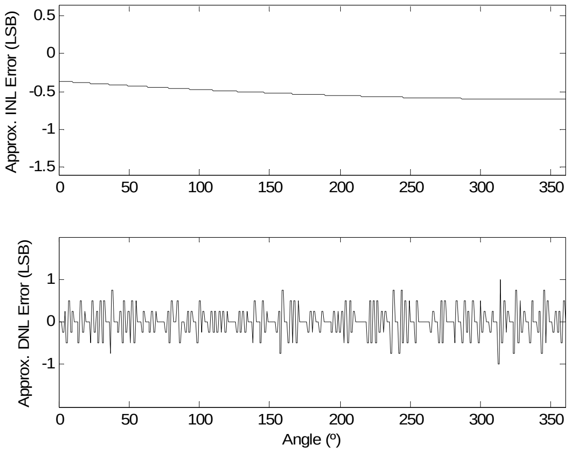

Fig. 10 Experimental results of INL and DNL errors of the tested encoder.

5. CONCLUSIONS

Simulation and experimental results show that wavelets can be used to extract the main errors of absolute encoders. Results from calibration of an encoder stored in the memory of a microcontroller can be easily used to improve the performance of low-cost encoders based systems.

The system concept can easily be adopted and extended to a set of different encoders connected to the same shaft or displacement target. In this case, data processing together with calibration data from the multiple sensors can be used to correct individual encoder errors and to increase the accuracy of the overall system. An interleaving of 2^b different encoders with properly adjusted offsets can be used to increment the encoder's number of bits by a term equal to b [18].

Finally it can be referred that the main characteristics of an encoder can be obtained with a single detail wavelet decomposition, which means a low computational load easily supported by a low-cost microcontroller. However the error compensation procedure can only be performed if the number of wavelet details is selected according to encoder's resolution, which means an increasing in data processing load.

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