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AN OPTICAL DISPLACEMENT METER BASED ON A LIGHT-TO- FREQUENCY CONVERTER

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Abstract: This paper proposes a contactless displacement measurement system based on a temperature compensated light-to-frequency (L/F) converter. The optical displacement sensor is represented by the L/F converter excited by a LASER beam. To compensate the temperature drift error of the displacement sensor, an additional temperature measurement system based on a temperature transducer is required. The processing of the data delivered by the sensors is on-line performed using a neural algorithm implemented on a Digital Signal Processor. The Artificial Neural Network architecture used in the present application is Multiple Inputs – Single Output (MISO) type, and the output of the network represents the displacement value after an on-line temperature correction. In the calibration phase of the displacement measurement system a closed-loop motorised linear actuator controlled by a plug-in-PC motion board is added to the system.
Keywords: Displacement Measurement, Optical Transducer, Error Compensation.

1. INTRODUCTION

Optical displacement systems are now recognised as being a simple and inexpensive answer to many typical demands of industrial manufacturing [1] [2]. Using various combinations of emitter-receiver optical devices, the developed displacement measurement system try to avoid several drawbacks such as poor resolution or the higher sensitivity to temperature and environmental noise. These external disturbances can strongly reduce the measurement accuracy.

Relating to temperature drift errors, they can be reduced by using a temperature transducer, close to the optical displacement sensor, and use its output signal to implement a temperature compensation method [3] [4]. Related the environmental noise, the external light intensity fluctuations represent one of the main noisy sources. The avoiding of this influence is performed using a witness optical sensor that is excited only the external light. Taking into account the elements for increasing the optical displacement system performance, the purpose of the paper is to present the performance improvement provided by an on line neural processing algorithm implemented using a Digital Signal Processor.

2. THE HARDWARE

The Displacement Measurement System is represented in the Figure 1 and includes several elements related with displacement sensing, the acquisition of the temperature information, the digital signal processing of the acquired information and a controlled actuator necessary for the calibration of the displacement system.

2.1. The optical displacement transducer

In what concerns to displacement sensing, the system includes an emitter-receiver transducer based on LASER-diode source (He-Ne, 670 nm, 4 mW) that excites a Texas Instruments light-to-frequency converter (TSL230). The TSL230 programmable light-to-frequency converter combines a configurable silicon photodiode and a current-to-frequency converter on a single monolithic CMOS integrated circuit. The output can be either a pulse train or a square wave (50% duty cycle) with frequency directly proportional to light intensity. The output is TTL compatible, allowing direct two-way communication with a microcontroller and is also compatible with Digital Signal Processor Kit (TMS320C31) used in the present application. The TSL230 programming includes the selection of sensitivity range (S_0 and S_1 inputs) and converter output frequency scaling (S_2 and S_3 inputs). Thus, assigning appropriates high (H) and low (L) voltage levels to the $S_0..S_3$ inputs, the TSL230 sensitivity can be increased up to 100 times and the output frequency can be divided up to 100 times.

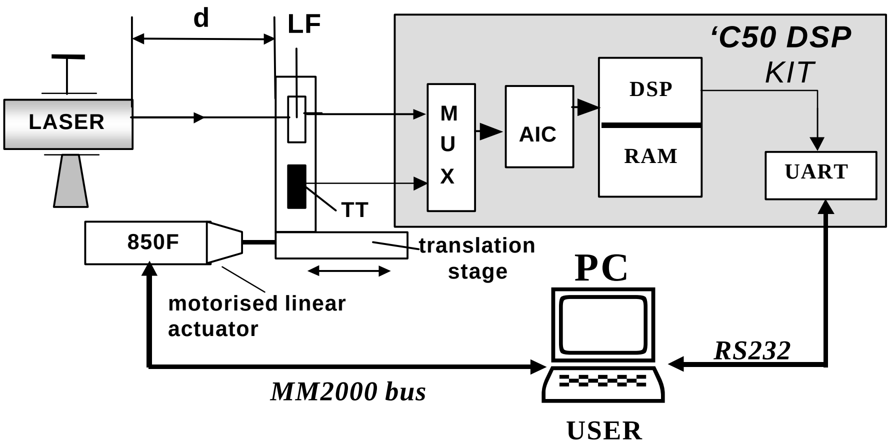

Figure 1. The Displacement Measurement System including the calibration components (LF- light-to-frequency converter, TT- temperature transducer, MUX- analogue multiplexer, AIC- analogue interface circuitry, UART- universal asynchronous receiver-transmitter).

The sensitivity of the light-to-frequency converter with temperature generates the idea of introducing in the system a temperature transducer (TT) and to use the temperature information to increase the accuracy of the displacement measurement system, compensating by software the temperature variation effect. To minimise the errors caused by LASER and external light intensity variations, a second light-to-frequency converter (LF2) together with an optical splitter (OS) are introduced. In this case the displacement optical transducer structure is presented in figure 2.

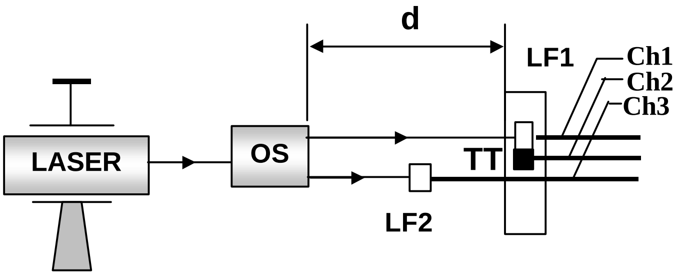

Figure 2. Optical displacement transducer with compensation of external influences.

The signals delivered by LF1, LF2 and TT are applied to an analogue multiplexer, and the light and temperature information stored in these signals are processed by the DSP ('C50) .

2.2. The temperature sensor

A SMARTEC temperature sensor (TT-SMT160-30) [5] represents the solution used for temperature measurement. The SMT160-30 output signal (Figure 3) is characterised by a duty-cycle proportional to the temperature.

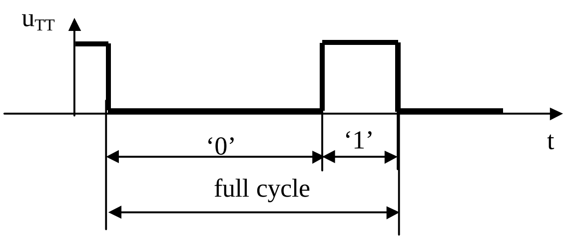

Figure 3. The SMT 160-30 output signal.

To be able to calculate the duty cycle, two measurements are processed. One is the time that a full cycle takes, the other one is the time the signal is high ('1'). Both times are measured using the Digital Signal Processor (TMS320C31-30MHz) timer facilities (TCLK0-TCLK1). To extract the temperature information the specifications from the data sheet of the sensor [6] relating the duty cycle (DC) with temperature (T) is used:

$$DC = 0.31924 + 0.00472 \cdot T(^\circ C) \quad (1)$$

The frequency of the output signal of the sensor lies between 1 and 4kHz. This means that at least in every ms a new measured value is available. This situation permits to measure multiple periods, n_T=2..100, and to use the calculation of the average to increase the accuracy of temperature measurements.

2.3. The Digital Signal Processor kit

A 16-bit floating point DSP TMS320C31 [7] running at 30 MHz has been programmed to acquire the LF converter and TT signals, coming from the transducers, and to process them. The TLC32040 AIC on the board provides a single-channel, input-output analogue interface with the following features: single-chip digital-to-analogue (D/A) and analogue-to-digital (A/D) conversion with 14 bits of dynamic range. The AIC interfaces directly to the ‘C50 serial port. The master input clock to the AIC is provided by a 10 MHz timer output from ‘C50. Using the A/D and D/A facilities of the TLC32040, the acquisition of the LF converter and TT signals is possible. The ‘C50 communicates with PC (Pentium II/350 MHz) using the XF and BIO pins through the RS-232 serial port. Using this facility the program associated to the present application is easily implemented on the main processing part of the system.

2.4. Controlled translation system

For the calibration of the displacement measurement system a PC controlled translation system is used. In the proposed system a Newport 850F series closed-loop motorised linear actuator [8] with 50 mm travel range, accuracy better than 0.06%, and bi-directional repeatability better than 1.0 μm, is used. The motorised linear actuator is controlled and driven by a Newport Motion Master 2000 board (MM2000). The MM2000 card “plug-in-PC” is a multi-axis point to point motion controller that can control up to four different axes using any combination of dc and stepper motors. In the present application, it controls only the 850F actuator (dc motor) which is connected to a universal interface box [9]. The key features of the motion controller are: velocity rates from 6E-2 to 1E+6 counts/s, high speed position retrieval (750us), programmable digital PID filters with 16-bit coefficients, and 256 μs sampling interval.

3. THE SOFTWARE

The control, communication, and data processing for calibration, testing and measurement phases represent the main components of the software. The DSP is used in the present application for on-line computation of the distance, between the emitter and receiver, taking into account also the additional information regarding the temperature and the level of the external light intensity. Considering the strengths of the Artificial Neural Network (ANN) [10] a neural structure is designed to model the characteristic $d=d(f_{LF}, DC_{TT})$, where d is the distance between the LASER source and the light-to-frequency converter (Figure 1), f_{LF} is the frequency of the digital signal delivered by LF converter and the DC_{TT} is the duty cycle of the signal delivered by TT. In the final proposed solution, Figure 2, the complexity of the used ANN architecture is increased to model the $d=d(f_{LF1},f_{LF2}\ DC_{TT})$ characteristic, where f_{LF1} and f_{LF2} represent the frequencies of the signals delivered by the LF1 and LF2 sensing elements.

3.1. Communication and processing software

As presented in the hardware description, a set of three signals is acquired using the AIC of the DSP kit. The f_{LF1} and f_{LF2} computation is performed using the DSP functions included in ‘C50 Assembly. The duty-cycle of the signal received from TT channel is also calculated based on DSP timers (Timer0 and Timer1). The timer starts at the moment the input changes from logical ‘1’ to ‘0’. When the signal goes from ‘0’ to ‘1’ the timer content is stored (TC_1). At the end of the period, when the signal changes from ‘1’ to ‘0’ again, the timer content is stored once more (TC_2). Considering the TC_I values stored in the DSP memory the calculation of the duty cycle is performed.

The calculated f_{LF1}, f_{LF2} and DC values are sent from DSP to the PC, via RS232, where they are stored in the ANN training files. At the same time, using the 850F-MM2000 capabilities, the value of the displacement of the translation stage are sent to the PC and are used afterwards in the ANN training phase. The 850F control and data acquisition is performed in LabVIEW. Thus, two low level drivers in a LabVIEW sequence structure are provided, one to send commands and another to receive responses to MM2000. They are called SendCmd.vi and ReadResp.vi. Among the commands that are sent to MM2000 for controlling the linear actuator, the following deserve special mention: DH to define the home position of the actuator axis, and 1PA±nn or 1PR±nn to define the new absolute or relative position of the actuator axis. The choice of the + or – signal is associated with forward or backward movements.

3.2. The ANN architecture and training

The neural structure used in the present application is a Multilayer Percepton Network (MLP) with two inputs and one output in the LF-TT case and three inputs and one output for the LF1-LF2-TT case, used as final solution in the proposed system. In both cases the network number of layers is three, the hidden layer includes a number of the neurons in the interval I_{hidden}=[5;25]. Referring to the hidden neuron activation function, in the present work a tansignoid function is used. The ANN output neuron is characterised by a linear activation function.

Regarding the network training, the establishment of neurons weights and biases W1,b1, W2, b2 is performed using a Backpropagation algorithm, Levenberg Marquardt. The implementation of the software used for ANN design is made in MatLab, using several specific ANN training functions such as tansig(), trainlm(), simuff(). The input training matrix includes the frequency values from the optical transducers (LF1, LF2) and the temperature values associated with temperature transducer (TT). Tests were made in the temperature range, T=[20;90], where the temperature coefficient of output frequency is several times greater than the value indicated in TI data sheets. In these conditions, the DCs of TT signal for several values of the temperature are stored in a file and used together with LF output frequencies, to train the ANN. The set of distance values $d_{j,}$, used as target vector during ANN training phase, are established by using the 850F-MM2000-displacement system.

After the ANN design, the W1, b1, W2, b2 are stored in the DSP block memory for neural processing of the values obtained on the output of the frequency and duty-cycle calculation blocks. Thus, in the measurement phase using the DSP basic functions, such as multiplication and addition, the current displacement value d is found out.

4. EXPERIMENTAL RESULTS AND FINAL REMARKS

To design the ANN associated with the distance value extraction, a data set is determined for various positions of the translation stage. The imposed values of the distance between the emitter and the receiver of the optical distance transducer are included in the interval I_d=[0;50] (mm). For d values included in I_d the measured values of f_{LF1} corresponding to the signal delivered by operational sensor are included in the I_f interval I_f=[3;8] kHz. Sum squared error (SSE) evolution during ANN training phase and displacement transducer modelling errors are represented in Figure 4.

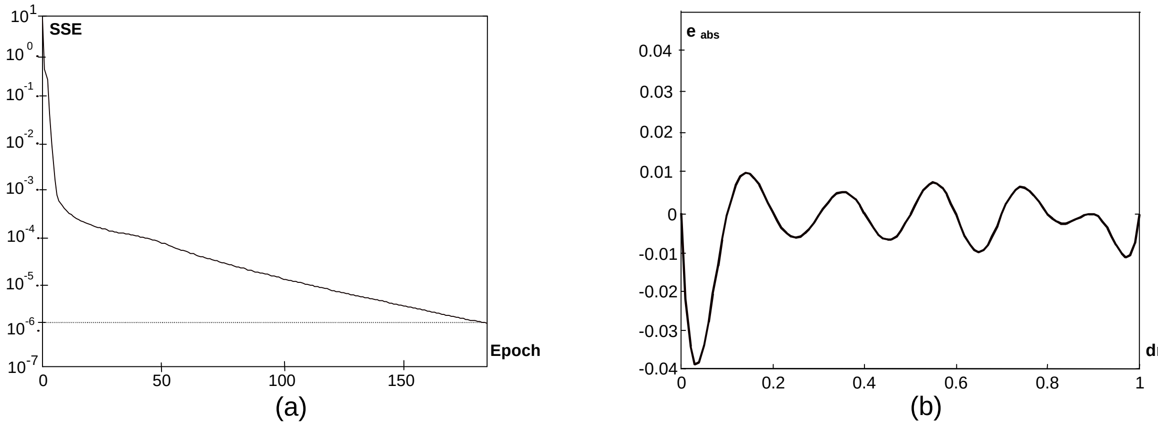

Figure 4. Training and transducer errors: (a) SSE evolution during ANN training phase; (b) displacement transducer modelling error as a function of the normalised distance after ANN training phase.

From previous graphs, it can be stated that the absolute error (e_{abs}) versus normalised distance d_n, for approximation of displacement transducer characteristics, presents a maximum of 0.04 and that the SSE, considered as the training control parameter, decreases to a minimum of 9.75E-7 after 186 epochs.

Taking into account the temperature information and frequency values of the signal delivered by LF2, the distance measurement errors are reduced to a value less than 10%, from the e_{abs} maximum level, when the setting of the LF1 and LF2 were S0=H, S1=L, S2=H, S3=H.

Analysing the LF converter characteristics versus distance, it can be underlined that for a small distance, d<2 cm, the optical transducer is characterised by a higher sensitivity, more than 100 Hz/mm and a good linearity. For a distances more than 2 cm the LF converter response has a non-linear dependence versus distance. The modelling of the LF converter characteristics for the entirely distance range, up to 50 mm, requires a number of neurons, in the hidden layer, greater than 15 and the implementation of the network using DSP requires more memory space and higher computation resources. Dividing the displacement range in two intervals, characterised by Id1(d<20 mm) and Id2(d>20 mm), ANN models the

LF converter characteristics for each Idi with only 9 hidden neurons. In this case, the number of epochs for ANN training in Id1 case is strongly reduced to 15 and the modelling of the LF converter, in Id1 interval, implies the usage of a simple ANN easily implemented with the DSP kit.

An important observation obtained from the experimental part of the work is related with the influence of the incidence angle, α, of the LASER beam with the LF converter active surface. Varying the α in I_α=[-5° ,5°] the fluctuation of f_{LF} are important, being required a constant α with $\alpha \rightarrow 0°$, in LF setting-up.

5. CONCLUSIONS

An optical displacement meter designed mainly to measure displacements less than 20mm has been proposed. As the main strengths of the present work it can be mentioned the diminishing of the external disturbance factors by including in the system additional sensors for temperature and external light fluctuation measurements. A second important element of the work concerns the implementation of frequency and duty cycle calculation, and of a neural modelling procedure implementation using a DSP. The usage of graphical programming to control the closed loop dc motor, via MM2000, enables an easy and user friendly implementation of system calibration. Others advantages of the measurement system are the immunity to noise, galvanic insulation and capability to make remote measurements.

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