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Estimation of quantization steps of time interpolator in view of temperature changes

Abstract

This paper presents a method of limiting the effect of ambient temperature drift on the measurement uncertainty of a time counter (TC). A change in ambient temperature causes a change in the TC transfer function, i.e. the widths of quantization steps to be exact. Recalibration is a procedure that is then required, but it disturbs the measurement process. However, with the knowledge of the current ambient temperature and having the set of transfer functions identified at different temperatures, it is possible to determine and use the most adequate transfer function and virtually eliminate the temperature impact. For this purpose, three interpolation methods were studied: the nearest neighbor method, linear and polynomial interpolations. A newly evaluated transfer functions were tested in interpolating TC to select the best interpolation method.

Keywords: time-digital conversion, two-stage interpolation, multi-edge coding in independent coding lines, time counter, time digitizer.

1. Introduction

Most of contemporary methods for precise time-to-digital conversion are the methods based on the use of discrete delay lines [1]. In these methods, the width of quantization step depends on the propagation time of a single delay element used to build the delay line. The shorter the delay, the narrower the quantization step, making the result more precise. An improvement in precision requires the change of integrated circuit in which the converter has been implemented to the newer one, which is not always possible, and is usually linked to additional expenses. Therefore, more advanced time-to-digital conversion methods are advised. They include, among others, methods based on the independent coding lines [2] and the multi-edge coding [3]. These methods allow to achieve narrow quantization step (even below 1 ps) and high precision (up to 6 ps) [6, 7]. Such high precision of measurement is difficult to maintain at a constant level for a long time due to drift of supply voltage and ambient temperature. Changes in supply voltage are effectively eliminated by applying low-noise LDO regulators. However, reduction of the temperature drift is a more complicated problem, to which this paper has been dedicated.

One way to it is eliminate the temperature influence is based on closing the converter in a hermetic housing and holding the device at the certain temperature. Another solution is to calibrate the converter before every series of measurements at given temperature. However, this solution extends significantly the converter's dead time. The solution that we propose is a method based on the selection of proper transfer function predetermined for the current ambient temperature.

2. Method

Determination of TC transfer functions for all potential ambient temperatures is practically impossible, however, an evaluation of interpolated transfer function based on a set of predetermined characteristics can be applied relatively easy. For example, assuming that the TC transfer functions for temperatures of 20°C and 30°C were precisely evaluated, then it is possible to calculate accurately the resultative function for 25 C. Method of determining of such transfer function is described further in this paper.

3. Experimental study

Our studies were performed with the use of precise TC with two stage time interpolation method involved [4]. In the first interpolation stage (FIS) a four-phase clock (FPC) was applied, while in the second interpolation stage (SIS) we have used a time-to-digital converter based on multi-edge coding in independent coding lines [5]. Since the transfer function of the TC depends on widths of quantization steps in FIS and SIS we investigated their behavior in view of temperature changes. During all tests, the TC was placed in a thermal chamber PL-2J (*Espec*) and powered by a power conditioner 1750XP (*Helion*). The use of a conditioner made it possible to eliminate disturbances from the power grid. A diagram of the measurement setup is presented in Fig. 1.

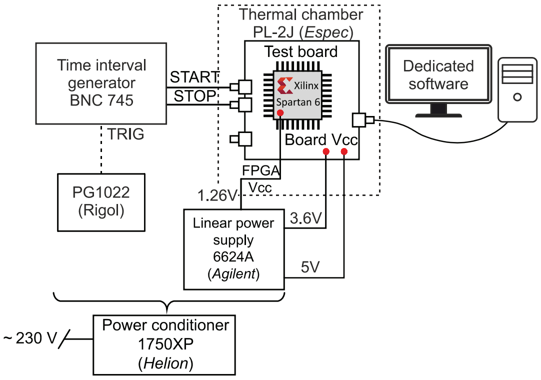

Fig. 1. Measurement setup for testing of time counter at different ambient temperatures

The detailed results of temperature studies of the counter have been presented in paper [6]. The transfer function of the counter was determined at the following ambient temperatures: −10°C, 10°C, 25°C, 40°C, 60°C. It is worth noting that the processing range of SIS is determined by FPC widths, so a change in the width of FPC segments changes the width of the SIS active processing range.

Figure 2 presents the widths of FPC segments and the widths of SIS quantization steps for an example segment 0 of FPC for temperatures mentioned above. Based on obtained results, one can observe that the widths of FPC segments 0 and 2 decreases while the segments 1 and 3 increase along with the ambient temperature. This changes the widths of SIS active processing range. This effect is caused by changes in propagation times of elements used to build the FPC generator [6]. It can also be observed that the measurement range of SIS is narrower with the temperature increase, and the range begins either in the delay line (smaller number of quantization step before active range). It is caused by the extension of propagation time of delay elements used to build the delay line.

During the next test we verified the precision of TC at the aforementioned ambient temperatures. For this purpose, a measurement of reference time interval (50 ns) was performed in two cases. In the first case, the TC was calibrated before measurement in each ambient temperature, while in the second one, the calibration was performed only once at the temperature of 25°C. Test results are presented in Fig. 3.

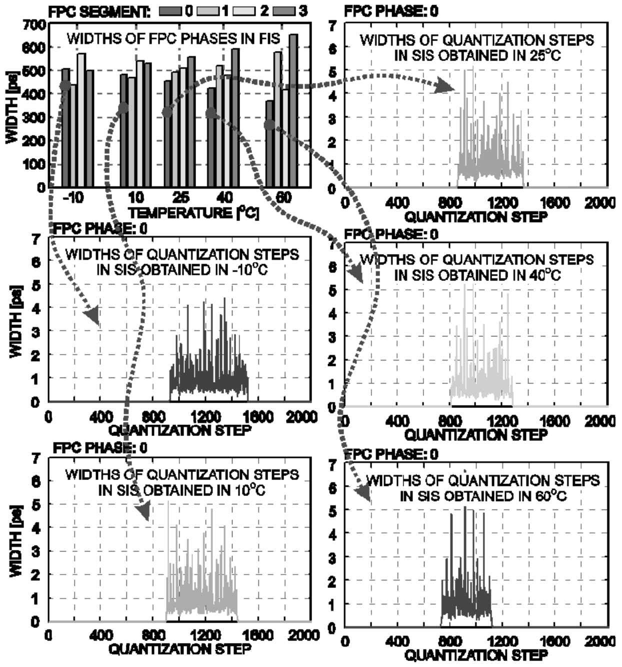

Fig. 2. Widths of FPC segments, a) at different ambient temperatures, b) related widths of SIS quantization steps

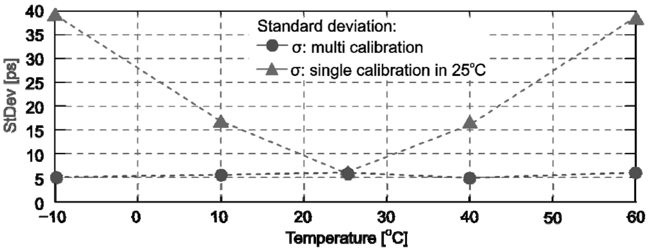

Fig. 3. Precision of time counter at different ambient temperatures

As it could be expected, if the calibration is performed at each temperature, the precision keeps a constant level of about 6 ps. However, in the second case, when the TC is calibrated once (at 25°C), its precision is deteriorated proportionally to a discrepancy between the current ambient temperature and the calibration temperature. The gradual precision deterioration arises from the maladjustment of processed transfer function to the current ambient temperature. The test confirmed the hypothesis posed in the introduction that ambient temperature drift deteriorates measurement precision.

Interpolation of the widths of quantization steps to obtain the transfer function corresponding to the current ambient temperature was performed using the Matlab (*MathWorks*) environment and the transfer functions collected earlier for different temperatures. Each transfer function was treated as an interpolation node, and the interpolation was performed with a resolution of 1°C between nodes. Thus 71 different transfer functions were obtained for temperature range from −10°C to 60°C. To determine these new transfer functions three different interpolation methods were applied, i.e. the nearest neighbor method, linear and polynomial (3rd order polynomial) methods. Figure 4 presents achieved interpolated widths of quantization steps. The widths of two example channels, no. 860 and no. 980, were distinguished. Channels were selected so that the width of one of them (860) reached zero at certain temperatures, while the width of the other one (980) was greater than zero regardless of temperature.

Interpolation nodes are marked with the blue points, while the red points represent results of the interpolation process. Based on results, it can be seen that the smoothest transitions between interpolation nodes are obtained by using the polynomial interpolation. However, this interpolation may result in false step widths. For example, within the range from −10°C to 10°C, the channel 860 should keep a zero width, but it does not keep. In addition, within the range from 10°C to 20°C, the width of this step is equal to an incorrect negative value. These effects are also noticeable for other steps, but they do not occur in cases of the other two tested interpolation methods. In linear interpolation, sharp transitions between nodes are visible, however there are not jumps in value as in the case of nearest-neighbor interpolation.

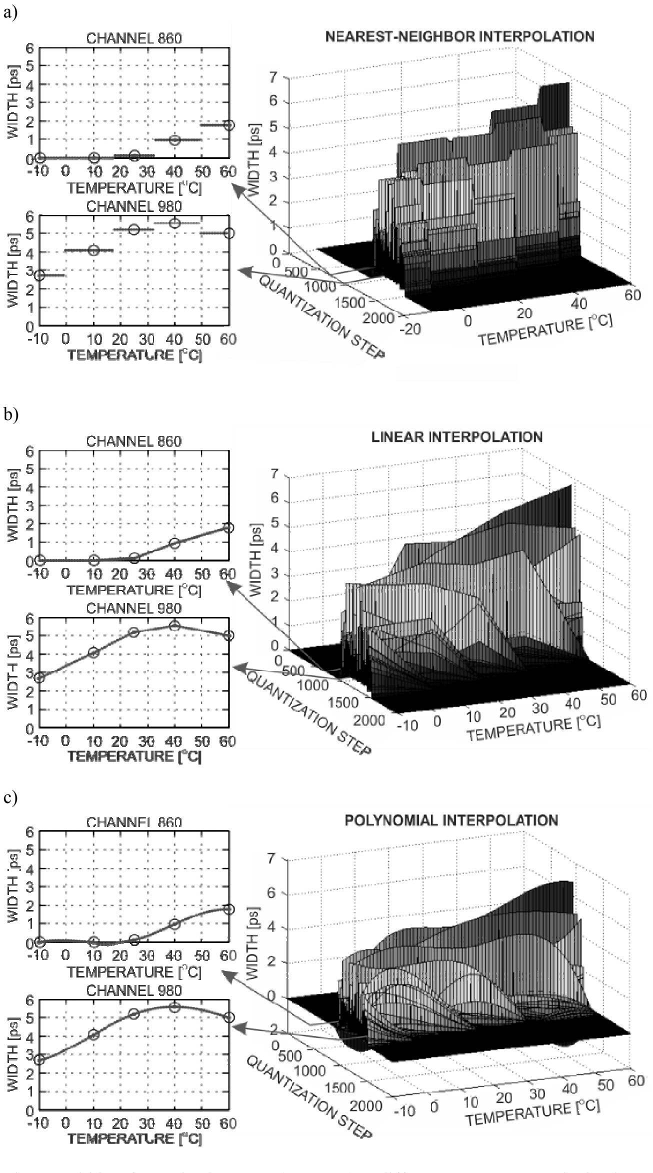

Fig. 4. Widths of quantization steps (860, 980) at different temperatures, obtained as results of the a) nearest neighbor interpolation, b) linear interpolation, c) polynomial interpolation

To assess the correctness of interpolated quantization steps and to determine the best interpolation method we performed next measurement session in which the interpolated transfer functions were used. Each interpolated transfer function was additionally calculated based on either five nodes (corresponding to all tested temperatures −10°C, 10°C, 25°C, 40°C, 60°C), or three nodes (−10°C, 25°C, 60°C). The obtained TC precision, achieved as the standard deviation of 2000 measurements of an example time interval (50 ns), for the cases mentioned above are shown in Fig. 5.

The original characteristic of TC precision (Fig. 2) has also been included to allow determining the ambient temperature range in which the applied interpolation methods give the best results.

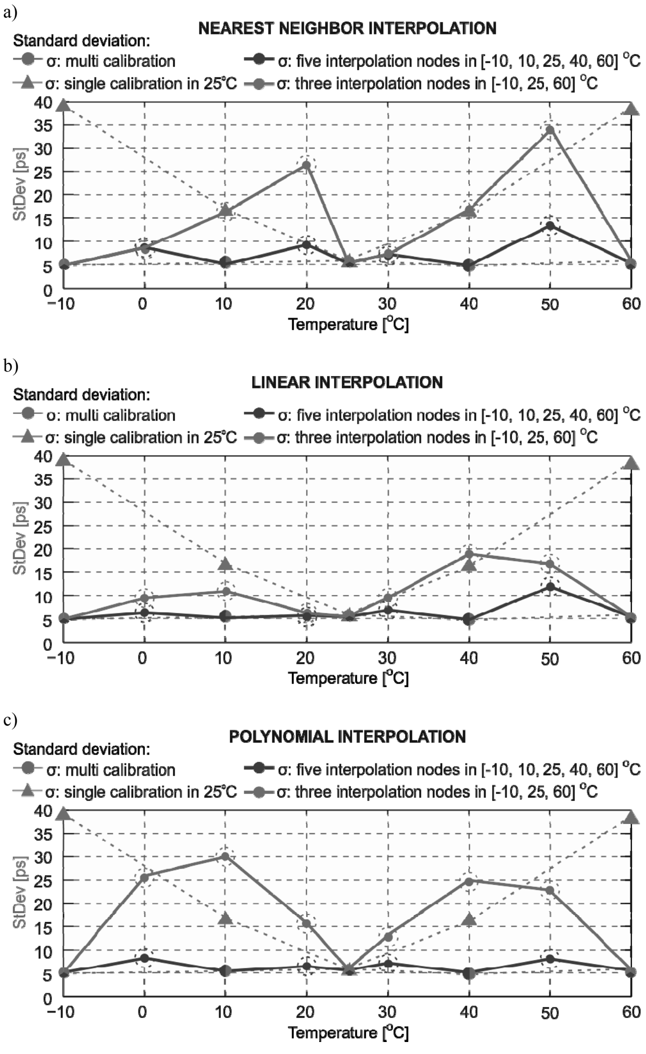

Fig. 5. Precision of TC at different ambient temperatures. The transfer function of TC calculated based on a) the nearest neighbor, b) linear, c) polynomial interpolations

In the first considered case (five interpolation nodes applied), the measurement precision for the time intervals between node points is only a slightly worse than the precision at the nodes (discrepancy <15 ps) nearly regardless of the interpolation method applied. The lowest measurement uncertainty is obtained for the polynomial interpolation.

In the second case (three interpolation nodes applied), differences in measurement precision between the applied interpolation methods were more significant than in the first case. For small divergences from the calibration temperature the measurement result may be burdened with an error even greater than in the case without any interpolation. The worst precision is observed for the nearest neighbor interpolation method (Fig. 5a) while the best one is obtained again with the polynomial interpolation.

At a small divergence of ambient temperature and the temperature at which the counter was calibrated, the result of measurement will be burdened with a greater error than in the case where no interpolation would be applied. Moreover a large measurement uncertainty is obtained despite the use of polynomial interpolation. The results obtained for linear interpolation can be considered to be acceptable, because the obtained characteristic of measurement uncertainty is better than the characteristic of a counter calibrated only once over nearly the entire tested temperature range.

4. Conclusions

The results of conducted studies show that it is possible to nearly eliminate the effect of temperature drift on the precision of time counter through the matching of its transfer function to the current ambient temperature. The valid transfer function can be interpolated on the basis of predetermined characteristics saved in the time counter memory. Obtained results show that the polynomial interpolation method provides the highest measurement precision, i.e. below 9 ps over the entire tested temperature range from −10°C up to 60°C. However, the use of this type of interpolation may result in false values of quantization channels, even with an imaginary, negative width. If only three predetermined characteristics are saved in the counter memory, the linear interpolation should be used, providing the precision not worse than 20 ps.

A certain drawback of the presented method of eliminating temperature drift is the necessity of keeping processing characteristics in the counter memory for every ambient temperature within the range in which the counter can operate. Storage of only several such characteristics, as interpolation nodes, can solve this problem, while the needed characteristics are then computed during measurements.

5. References

[1] Carbone P., Kiaei S., Xu F., Eds.: Design, Modeling and Testing of Data Converters, (Springer-Verlag, Berlin, Germany, 2014).

[2] Szplet R., Jachna Z., Kwiatkowski P., Różyc K.: A 2.9 ps equivalent resolution interpolating time counter based on multiple independent coding lines. Meas. Sci. Technol., 2013, 24.

[3] Wu J., Shi Z.: The 10-ps wave union TDC: Improving FPGA TDC resolution beyond its cell delay. IEEE Nucl. Sci. Symp. Conf. Rec., Dresden, Germany, Oct. 2008, pp. 3440–3446.

[4] Szplet R., Sondej D., Grzęda G.: Interpolating time counter with multi-edge coding, Joint UFFC, EFTF PFM Symp., Prague, Czech Republic, Jul. 2013, pp. 321–324.

[5] Szplet R., Sondej D., Grzęda G.: High-Precision Time Digitizer Based on Multiedge Coding in Independent Coding Lines, IEEE Trans. Instrum. Meas., 65, (8), Aug., 2016, pp. 1884-1894.

[6] Sondej D., Szplet R.: A study of the effect of temperature changes on the interpolating time counter, Measurement Automation Monitoring, vol. 61, no. 7, Jul. 2015.

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Ryszard Szplet was born in Poland in 1964. He received the MSc degree in electronic engineering, the PhD and Habilitation degrees in applied sciences from the MUT, Warsaw, Poland, in 1989, 1997 and 2013 respectively. In 2000/2001 he spent a one year research stay at the University of Oulu, Finland. Since 1990, he has been with the MUT, where he has taught digital microelectronics and worked on the development of methods and instrumentation for precise time measurements and generation.

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