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REFERENCE'S ACCURACY IN VIRTUAL FREQUENCY-TO-CODE CONVERTERS

S.Y. Yurish, N.V. Kirianaki and N.O. Shpak

Institute of Computer Technologies
Bandera str., 12, 290013, Lviv, Ukraine

Abstract: The methodology and experimental results of the researches for thermal instability of reference clock generator in microcontroller based frequency-to-code converters with virtual channel are described in the Paper. The temperature uncertainty of the frequency and time references, distribution laws and correlation factor of their errors were determined in the experiments. The maximum relative temperature error of the frequency reference is $\pm 11.5 \cdot 10^{-6}$, and the maximum temperature error of the time reference is $\pm 0.38 \cdot 10^{-6}$. The total relative error of the "measurement standard" in the microcontroller based frequency-to-code converters is equal to $\pm 10.9 \cdot 10^{-6}$. The obtained results are used at research of the limiting metrological characteristics for microcontroller based measuring instruments of frequency/time parameters with virtual measuring channel.

Keywords: frequency-to-code converter, quartz-crystal generator, temperature instability.

1   INTRODUCTION

One-chip microcontrollers together with novel program-oriented methods for frequency-to-code conversion are widely used in various measuring instruments, microsystems and smart sensors. Due to the program-oriented approach we have so-called virtual measuring channel. It is built on the virtual level, inside the programmable computing power and includes some virtual counters and references.

The maximum accuracy of such analog-to-digital conversion is determined by frequency stability of the built-in quartz-crystal generator. The system clock generator is a "base standard" in these converters.

The temperature instability of the quartz-crystal generator is one of the main components of parametric instability, which has the greatest density in comparison with other components. As it is known, the frequency deviation of non-temperature-compensated crystal oscillator from the nominal due to the temperature change is $(1 \div 50) \cdot 10^{-6}$ in the temperature interval $(-55 \div +125\ ^0\ Ñ)$ and the frequency range $5 \div 50$ MHz. In turn, the modern program-oriented methods of frequency-to-code conversion allow to receive the quantization error, commensurable with the temperature instability of the frequency (time) reference realised on the basis of such quartz-crystal generator. Therefore, the knowledge about more exact value of the reference's error is the necessary conditions for designing of accurate converters. However, no one from the microcontroller manufacturer does not ensure the user with such information.

The experimental researches of quartz-crystal generators have large complexity because of considerable amount of time consumed on the temperature characterisation. Due to a large scatter, appropriate to the real temperature characteristics of quartz-crystal generators, the experiment takes very important place at the designing and manufacturing the accurate frequency-to-code converters.

The methodology and experimental results of the researches for thermal instability of reference clock generator in microcontroller based frequency-to-code converters with virtual channel are described in the Paper. The temperature errors of the frequency and time references, distribution laws and correlation factor of their errors were determined in the experiments.

2   MEASUREMENT SET UP

The research of quartz-crystal generators in the working temperature range with the aim to determine the temperature instability of frequency is common for all varieties of quartz generators at its experimental investigations. The temperature instability of frequency in the whole working temperature interval from t_{min} up to t_{max} is determined as:

$$\frac{\Delta f}{f} = 2 \cdot \left(f_{max} - f_{min} \right) / \left(f_{max} + f_{min} \right) , \tag{1}$$

where f_{max} and f_{min} are the maximum and minimum values of the generator's frequencies in the working temperature range.

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The objectives of experiment were: (i) to determine the temperature instability of the frequency and time references of the embedded microcontroller; (ii) to determine the correlation factor of their errors; (iii) to determine the distribution laws for the temperature errors.

As an experimental sample the one-chip microcontroller from the MCS-51 (Intel) microcontroller family was selected, because its very wide distribution in measuring systems and instruments due to usability functional - logical architecture.

According to the proposed algorithm for frequency-to-code conversion, the frequency and time references were realised on the basis of the built-in quartz-crystal generator. The frequency reference has been realised as follows. The synchronisation signal of the internal system clock generator of the microcontroller through the output ALE was applied to the input of the external frequency divider by 3. Then the signal $f_{ALE/3}$ was applied to the input of the built-in microcontroller's timers/counter. As a quartz-crystal oscillator the 6 MHz resonator RG-05 was used. The time reference was realised by the following way. The required time interval was formed with the help of the delay subroutine. This subroutine was realised by the method of nested program cycles and combinations of precisely set up delays of smaller duration.

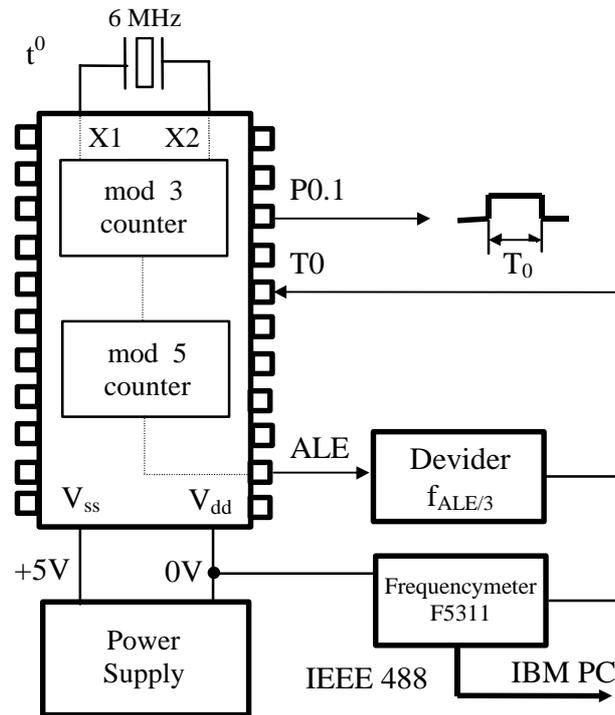The block diagram of the measurement system is shown in Figure 1.

Figure 1. Block Diagram of Measurement System.

For determination of the temperature frequency instability the quartz-crystal oscillator was cooled up to the temperature equal to the minimum temperature from the working temperature range and then was soaked in this point up to $25 \div 30$ minutes. After that the values of frequency on the output ALE and the duration of time interval on the output P0.1 were measured. The measurements of frequency were repeated in remaining points of the working temperature range through $5 \div 10\ {}^{0}C$ in all working interval from t_{min} up to t_{max}. The time of a normal temperature cycle with the temperature overfall of $50\ {}^{0}C$ should not be less than 15 minutes. The researched errors being random variables, the statistical processing of sample from 60 values was carried out for obtaining authentic eventual results. The abnormality of the values in the sample was checked on with the help of the Shovene criterion. The processing of experimental data was carried out on the IBM PC compatible computer with the help of the created software for statistical processing as well as the software package NUMERI. The accuracy of measurements is characterised by the following dimensions: the root-mean-square error of measurements σ, the probability error of measurements υ and the average error of measurements η. In this case

$$\sigma = \pm\sqrt{\frac{\sum \varepsilon^{2}}{n \cdot (n-1)}}, \qquad (2)$$

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where n is the number of measurements; ε is the deviation of separate measurements from their arithmetical average;

$$\upsilon = \pm \frac{2}{3}\sigma \tag{3}$$

$$\tag{4}$$

$$\eta = \pm 0.8\ \sigma$$

Finally, the results of measurements can be written as

$$f_x = \frac{\sum f_i}{n} \pm \sqrt{\frac{\sum \varepsilon^2}{n\ (n-1)}}\ , \tag{5}$$

where n is the number of measurements; ε is the deviation of separate measurements from their average.

The experimental research of the correlation dependence for temperature errors of the references was carried out at simultaneous measurement of frequency on the output $f_{ALE/3}$ of the external divider and the time interval T_0 on the output P0.1. At this, the temperature of quartz-crystal oscillator was varied from +18 ^{0}C up to +100 ^{0}C with the consequent cooling. The research of the correlation dependence was carried out also at change of the supply voltage V_{dd} in the range from + 4.7 up to + 5.25 V.

3   EXPERIMENTAL RESULTS

The results of experimental researches for errors of frequency and time references are shown in Figure 2 and 3 accordingly.
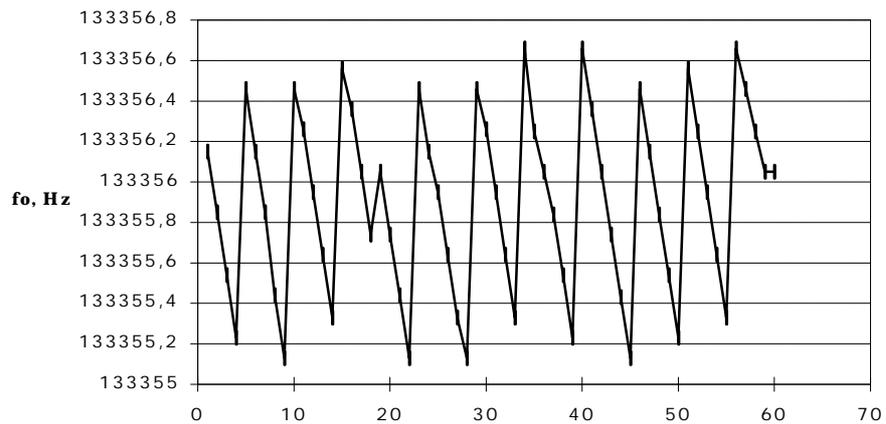
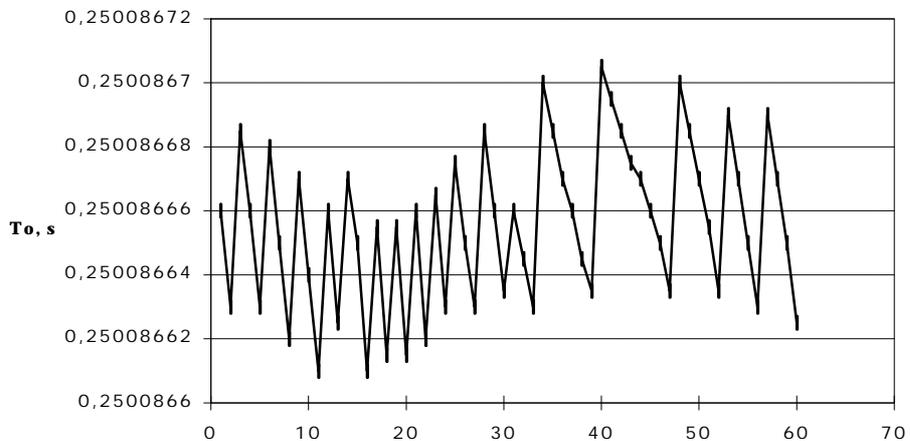

Figure 2. Frequency Reference Error at t = 20 ^{0} C.

Figure 3. Time Reference Error at t = 20 ^{0} C.

The frequency changes of an output signal of the quartz oscillator during time interval from 1 ms up to 10 s are stipulated by a thermal noise of a quartz oscillator and elements of the circuit as well as by fluctuations of other parameters. At the short average time, the main destabilising factor is the thermal noise of the quartz oscillator.

The histograms of their distributions are shown in Figure 4 and 5. The check of the distribution laws according to the χ^2 criterions has shown, that the distribution laws of the references errors are close to the Gaussian.
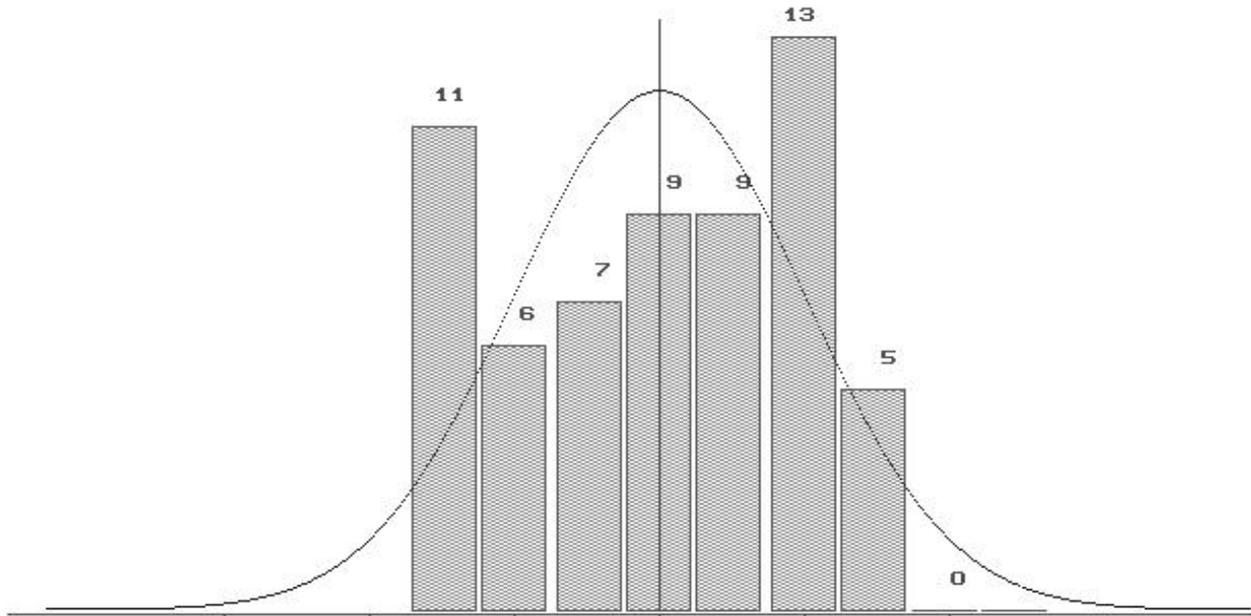

Figure 4. Histograms of Distributions for Frequency Reference Error.
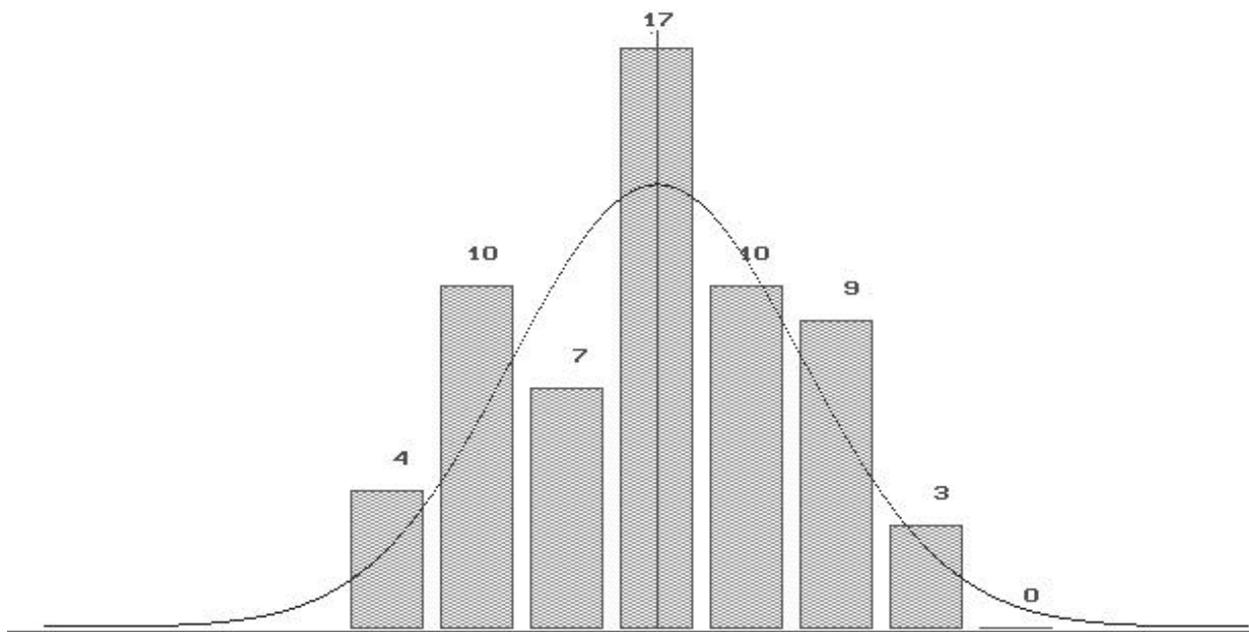

Figure 5. Histograms of Distributions for Time Reference Error.

Although the frequency and time references are realised with the help of the same internal system clock generator of the microcontroller, the temperature error of the frequency reference is higher. It is stipulated by that, the required reference frequency f_0 is formed by two internal and one external frequency dividers,

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introducing the contributions to the resulting error of the frequency measure. As a result of experiments, the rigid inverse correlation of errors for frequency and time references with the correlation factor $\rho = -0.981 \pm 1.291 \cdot 10^{-6}$ was detected. The correlation dependencies at heating and cooling are shown in Figure 6.
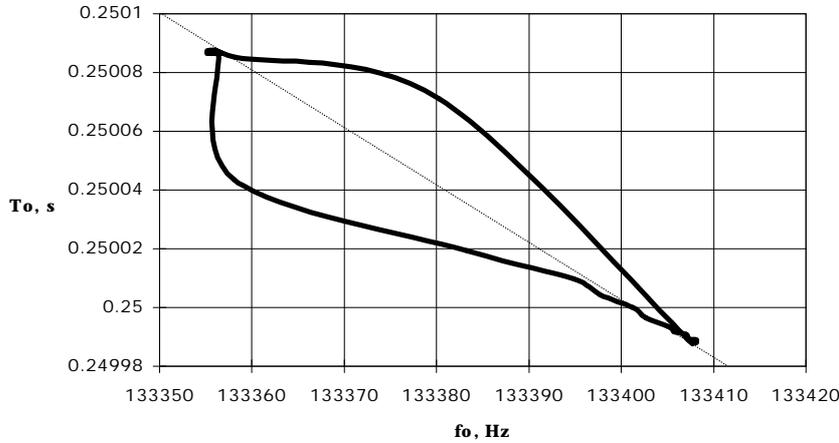

Figure 6. Correlation Dependencies at Heating (2) and Cooling (1).

The thermal instability of frequency for the quartz-crystal generator is $\Delta f/f = 11.5 \cdot 10^{-6}$. The dimensions of measurements accuracy at P = 97 % are shown in Table 1.

Table 1. Measurement accurasy dimensions.

	Frequency reference	Time reference
Result of measurement	133355.892 ± 0.468 Hz	$(250086.655 \pm 0.0246) \cdot 10^{-6}$ s
υ	± 0.312	$\pm 0.0164 \cdot 10^{-6}$
η	± 0.374	$\pm 0.0197 \cdot 10^{-6}$
Dispersion	0.219	0.0006

4   CONCLUSIONS

The experimental researches of the temperature errors for frequency and time references realised on the basis of the built-in microcontroller's quartz-crystal generator have allowed to determine the extreme accuracy of the "measurement standard", which cannot be exceeded for the given technical implementation independently on the used method of conversion. The maximum relative temperature error of the frequency reference is $\pm 11.5 \cdot 10^{-6}$, and the maximum temperature error of the time reference is $\pm 0.38 \cdot 10^{-6}$. As these errors are rigidly and negatively correlated, for finding the total error of the measure they should be added algebraically with allowance for the correlation factor ρ. Then the total error of the "measurement standard" in the microcontroller is equal to $\pm 10.9 \cdot 10^{-6}$.

The further improving of stability for the built-in quartz-crystal generator of the embedded microcontroller can be received by used of oven-controlled crystal oscillator. Besides, the temperature stability of frequency can be increased by frequency control of the quartz generators, as it is realised in the microcontroller of MSP430 family (Texas Instruments).

The obtained results are used at research of the limiting metrological characteristics for microcontroller based measuring instruments of frequency/time parameters with virtual measuring channel.

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AUTHORS: Head of R&D laboratory, IFSA Vice President, Dr. Sergey Y. YURISH, IFSA President, Ass. Prof. Dr. Nikolay V. KIRIANAKI, Director of Institute of Computer Technologies, Dr. Nestor O. SHPAK. Institute of Computer Technologies, Bandera str., 12, 290013, Lviv, Ukraine, Phone Int. +380 322 97 16 74, Fax Int. +380 322 97 16 41, Http://members1.infostreet.com/syurish E-mail: syurish@mail.icmp.lviv.ua