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CALIBRATION OF QUARTZ ELECTRONIC STOPWATCHERS COMPARISON METHOD USING A DIGITAL CAMERA

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Abstract. Measurement of time intervals with low accuracy on intervals from a few seconds to several hours or days is relevant for some broad applications in various fields of activity. Such measurements are widely used in the technological processes of various enterprises during the preparation and quality control of the preparation of medicines, during the maintenance of technical equipment and mechanisms, chemical technological processes, etc. For such measurements, manual electronic quartz stopwatches are widely used, which, despite their not too high measurement accuracy, must guarantee users the accuracy of measurements within the tolerance established by the technical documentation, since the risks of using untested measuring equipment are quite high, or generally unacceptable especially in the medical field. The issue of calibrating quartz electronic stopwatches by various methods remains relevant for many of their applications. The article discusses the calibration of quartz electronic stopwatches by the method of comparison using a digital camera. A calibration scheme for stopwatches was developed and a calibration measurement model was created based on the developed calibration scheme. The contribution of each component of the measurement model to the calibration result and the corresponding uncertainties of the model components were determined. The measurement uncertainty budget was made based on the proposed stopwatch calibration model. The influence of the most significant influential values on the accuracy of measurement results was analyzed. The content of quantitative and qualitative correction indicators, which must be taken into account during calibration to achieve the highest accuracy of measurements, is revealed. The method of calibrating stopwatches described in the article can be used in calibration laboratories that have the appropriate equipment and standards.

Key words: Stopwatch; Time and Frequency; Matching method; Calibration; Uncertainty; Digital camera.

1. Introduction

It is widely known that time and frequency measurements are the most accurate measurements, and are used in various high-precision fields of science and technology. Uncertainties of time and frequency measurements can reach 10–17. At the same time, despite such high measurement accuracy capabilities, measuring time intervals with low accuracy, for example up to 1 second, at intervals from several seconds to several hours, or even days, are also relevant. Such measurements are widely used in the technological processes of various enterprises, for example, during the preparation and quality control of the preparation of medicines, during the maintenance of technical equipment and mechanisms, chemical technological processes, etc. For such measurements, manual electronic quartz stopwatches are widely used, which, despite their not too high measurement accuracy, must guarantee users the accuracy of measurements within the tolerance established by the technical documentation, since the risks of using untested measuring equipment are quite high, or generally unacceptable, especially in the medical field. To ensure the necessary reliability of the measurement results, most users choose the calibration procedure in accordance with the requirements of the standard [1]. The issue of calibrating quartz electronic stopwatches by various methods remains relevant for many of their applications.

2. Drawbacks

According to the [2], stopwatches can be calibrated by three main methods: the direct comparison method [3], the time base method [4], the totalize method [5]. Also, all these methods are described in the publication of the US National Institute of Standards and Technology [6], which is the most well-known and most comprehensive in this matter.

The direct comparison method is the simplest and represents a comparison of the time interval measured by a stopwatch with a reference interval that can be given by radio signals, a wired network, or simply another calibrated reference stopwatch. The advantage of this method is its cheapness (no costs for expensive equipment), and the disadvantage is the lowest accuracy, since the accuracy is affected by the human reaction, which can be several tenths of a second.

The time base method consists in determining the relative error of the quartz stopwatch generator using non-contact technologies, using inductive, acoustic or optical sensors. The advantage of this method is the speed of measurement (usually it takes several minutes) and its high accuracy, since it completely excludes human reaction. But this method is not suitable for all types of stopwatches, requires expensive specialized equipment and has a significant drawback – it lacks testing (testing of its start and stop) of the stopwatch. In addition, there are risks of the influence of the software, which relates the frequency of the quartz oscillator to the change of the stopwatch indicators.

The summation method is the most widely used in metrological laboratories. Its essence is that the operator simultaneously presses the start and stop buttons on the stopwatch and the frequency counter, ensuring the synchronous start of the stopwatch and the frequency counter, while a periodic signal of 1 kHz is constantly supplied to the frequency counter from the generator. The disadvantage of this method is the effect on the results of the operator's reaction measurements (although it is much smaller than in the direct comparison method) and the impossibility of simultaneous calibration of two or more stopwatches on the same reference equipment. Also, this method requires a significant amount of measurement time, as measurements must be made several times at each calibration point.

In [2] and [6], a digital camera is additionally used in the summation method to exclude the operator's reaction. At the same time, in [6], the use of the camera is considered only in the photography mode, which limits the accuracy of the method to the resolution of the stopwatch. In [2] it is suggested to shoot 2 short videos (at the beginning and at the end of the measurements) and make their storyboard. This method is the closest to the one proposed in this publication, it has a number of advantages, such as: eliminating human reaction, high accuracy (up to 10–7), testing the start and stop of the stopwatch. But it also has a number of significant disadvantages, namely: its implementation requires specific equipment (a counter), which is not commercially available, the accuracy of the method strongly depends on the shooting speed of the camera and requires a high-speed camera (240 or 420 frames per second), in the method the mathematical model of the measurement and the uncertainty budget are not given, and also, what is very important, this method does not provide for the determination of the presence and magnitude of the constant offset of the stopwatch time, which is due to the premature display of the first second by the stopwatch during measurement. Such an offset is not present in all stopwatches, but in a significant number of those that are commercially available. The mentioned shortcomings are eliminated in the method proposed in this article.

3. Goal

The purpose of the study is to study the method of calibrating quartz electronic stopwatches using a digital camera.

4. Applied Research Method

The considered method that combines the method of matching stopwatch readings with frequency counter readings and the method of matching stopwatch readings with a reference time scale using a digital camera. The combination of these two methods makes it possible to test the stopwatch, to determine the presence and magnitude of the permanent offset of the stopwatch time, which is caused by the premature display of the first second by the stopwatch during the measurement, and to determine the relative deviation of the stopwatch readings, which makes it possible to calculate the deviation and the expanded uncertainty of the measurement for any interval time in the range of its measurements.

To determine the permanent displacement of the stopwatch readings, it is enough to conduct a series of ten short, for example, 3 second measurements. This significantly reduces the time of using the reference equipment and enables the simultaneous calibration of an almost unlimited number of stopwatches. In addition, the tenfold measurement allows for a significant increase in the accuracy of such measurements, compared to threefold measurements, which are usually performed at long intervals, when using the matching method using an oscillator and a frequency meter. Also, the proposed method does not involve the use of expensive specific equipment, the necessary frequency meter, generator and frequency standard are available in almost every laboratory that deals with time and frequency measurements, and an ordinary digital camera is also not something special now.

The stopwatch Hitrax Kat.Nr.38.2014 manufactured by TFA Dostmann GmbH & Co. was chosen as the object of calibration for the research. KG (hereinafter referred to as a stopwatch).

Calibration was performed in two stages according to the calibration schemes shown in Fig. 1. The dashed line shows the process of simultaneously pressing the start (stop) buttons for measurements on the frequency counter and stopwatch. The lightning icon shows the process of video recording of the time scale and stopwatch displays.

The following reference and auxiliary tools were used for the research:

– cesium frequency standard Symmetricom 5071A with a time scale (output 5 MHz, relative frequency deviation is $5 \cdot 10^{-13}$, extended uncertainty of relative frequency deviation on the averaging interval from 1 s to $5 \cdot 10^{-12}$);

– frequency meter Agilent 53131A (frequency range from 0.1 to 225 MHz), used in pulse counting mode with manual control, with a reference signal from the frequency standard (relative expanded uncertainty $2 \cdot 10^{-9}$);

– the generator (synthesizer) HAMEG HM8134-2, was used under the reference signal from the frequency standard to supply the frequency meter with a periodic signal of 1 kHz (extended uncertainty 10^{-7});

– environmental parameters meter "Atmosphere-1" (measurement ranges: temperature is from 5 ^{o}C to 40 ^{o}C, humidity – from 10 % to 90 %, pressure – from 650 hPa to 1080 hPa, extended measurement uncertainties are: for temperature – 0.4 ^{o}C, for humidity – 0.3 %, for pressure – 0.8 hPa);

– a smartphone digital camera Samsung Galaxy M21 (SM-M215FZKUSEK) with a shooting frequency of 30 frames per second (used as auxiliary equipment).

For calibration, other reference and auxiliary equipment can be used, which can ensure the performance of the necessary functions and the accuracy of measurements. When using a frequency standard that does not have a visual time scale, a Ch7-15 synchro meter or similar equipment can be used.

During the first stage, the values shown in the Table 1 were obtained.

The deviation of stopwatch readings Δ_t is determined by the expression:

$$\Delta_{ti} = t_{swi} - t_{fi}. \qquad (1)$$

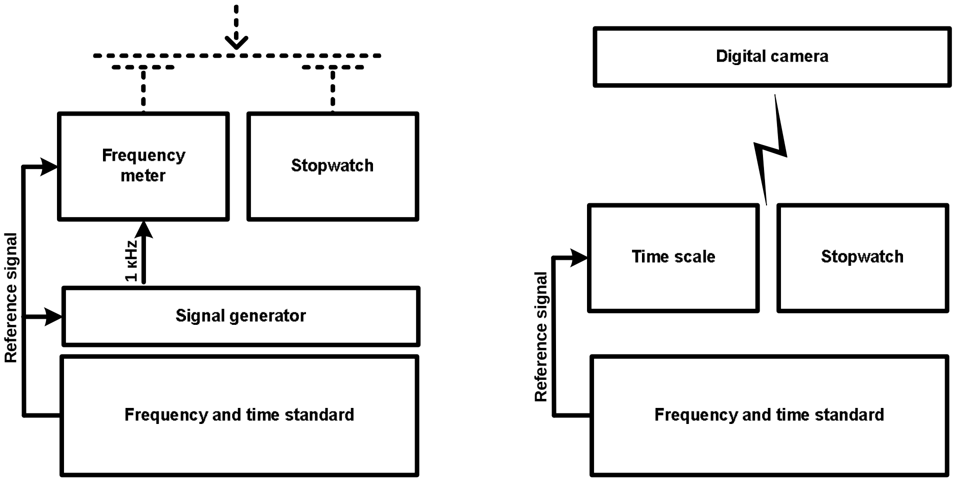
The constant bias of the stopwatch readings Δ_{tp} is determined by the expression:

$$\Delta_{tp} = \Delta_{tp}/10. \qquad (2)$$

The standard uncertainty of the constant bias of stopwatch readings $u(\Delta_{tp})$ is determined by the expression:

$$u(\Delta_{tp}) = \frac{S(\Delta_{tp})}{\sqrt{10}}, \qquad (3)$$

here $S(\Delta_{tp})$ is RMS deviation of stopwatch deviations Δ_{ti}. As can be seen from the Table 1, the constant bias in stopwatch readings is negligible and is most likely the result of operator response. However, it is not recommended to skip this stage, as there are frequent cases when the constant bias of the stopwatch readings can exceed 0.5 s.



a *b*

Fig. 1. Calibration scheme of stopwatches: a – determination of the constant displacement of stopwatch readings; b – determination of the relative deviation of stopwatch readings

Table 1. **Determining the permanent bias of stopwatch readings**

Frequency meter readings t_{fi}, s	Stopwatch readings t_{swi}, s	Deviation of stopwatch readings Δ_{ti}, s	Constant bias of stopwatch readings Δ_{tp}, s	The standard uncertainty of the constant bias of stopwatch readings $u(\Delta_{tp})$, s
3.073	3.10	0.027	–0.001	0.005
2.348	2.36	0.012		
2.464	2.46	–0.004		
2.174	2.17	–0.004		
2.004	1.99	–0.014		
2.051	2.03	–0.021		
1.714	1.71	–0.004		
2.681	2.67	–0.011		
2.280	2.27	–0.010		
2.667	2.69	0.023		

Table 2. **Determination of the relative deviation of stopwatch readings**

Showing timelines				Relative deviation of stopwatch readings	The relative standard deviation of stopwatch readings due to the camera's shooting frequency
S_{X1}	S_{S1}	S_{X2}	S_{S2}	σ_t	$w(\sigma_t)$
25.07.2022 19:02:09.767 (68,529.767 s)	25.07.2022 16:42:09.000 (60,129.000 s)	26.07.2022 14:24:51.800 (13,8291.800 s)	26.07.2022 12:04:49.000 (129,889.000 s)	$-2.91 \cdot 10^{-5}$	$8.28 \cdot 10^{-7}$

To conduct the second stage, two videos lasting a few seconds each were recorded (hereinafter referred to as the first and second measurements). The first video was taken on the first day of observation, and the second video was taken on the second day of observation. For convenience, the stopwatch scale has been switched to clock mode. Free video to jpg converter 5.0, produced by Digital Wave Ltd., was used to obtain photos from recorded videos.

The results of the second stage of measurements are shown in the Table 2.

Relative deviation of stopwatch readings σ_t is determined by the expression:

$$\sigma_t = \frac{S_{X2} - S_{S2} - (S_{X1} - S_{S1})}{S_{S2} - S_{S1}}, \tag{4}$$

here S_{X1} is stopwatch time scale readings at the first measurement, s; S_{X2} is stopwatch time scale readings at the second measurement, s; S_{S1} is time scale readings of the standard at the first measurement, s; S_{S2} is time scale readings of the standard at the second measurement, s.

The readings of the time scale are recorded in the format indicating the date, hours, minutes and seconds, the readings of the same scales in seconds are displayed in brackets, starting from the first second of the first day of observations.

As can be seen in the Table 1 time-scale readings are displayed with three decimal places in seconds, although in the photographs themselves (Fig. 2) the time scale readings are displayed with an accuracy of only one second. Records of fractions of seconds in the Table 2 appeared due to the fact that in Fig. 1 shows not just photos taken at any moment in time, but photos from a timed video, where the distance between each photo (frame) is 1/30 s.

In Fig. 2, *a* there is a photo in which the stopwatch time scale readings changed (from 19:02:08 to 19:02:09), in Fig. 2, *b* shows a photo in which the display of the benchmark time scale changed (from 16:42:08 to 16:42:09), in Fig. 2, *c* shows a photo in which the stopwatch time scale readings changed (from 14:24:50 to 14:24:51), in Fig. 2, *d* shows a photo in which the display of the benchmark time scale has changed (from 12:04:48 to 12:04:49). In the upper left corner of the photos, the serial number of the day of observation and, through a space, the serial number of the frame are placed.

In Table 2 shows the time scale of the standard from the photos shown in Fig. 2, *b* and Fig. 2, *d* without fractions of seconds, and from the photos shown in Fig. 2, *a* and Fig. 2, *c* are displays of the stopwatch time scale with fractions of seconds calculated by the expression:

$$t_{ps} = \frac{(N_{KS} - N_{KX})}{30}, \tag{5}$$

here t_{PX} is fractions of a second that are added to the stopwatch time scale readings; N_{KS} is the sequence number of the frame on which the change in the time scale readings of the standard occurred; N_{KX} is sequence number of the frame on which the stopwatch time scale readings changed. The relative standard uncertainty of the deviation of the stopwatch readings due to the camera shooting frequency is calculated by the expression:

$$w(\sigma_t) = \frac{I_v}{\alpha \cdot (S_{S2} - S_{S1})} \tag{6}$$

where I_v is the variability interval when using six times the time scale readings in the expression (4), I_v = 0,2 C, since the variability interval for each reading is $\frac{1}{30} s.$, and for six readings: $6 \cdot \frac{1}{30} s. = 0,2 s.$; α is selected coefficient, $\alpha = \sqrt{3}$, since it is assumed that the distribution law of the variability interval I_v is uniform.

The described method of calibrating stopwatches can be used in calibration laboratories that have appropriate equipment and standards. Interlaboratory comparison (ILC) are one of the forms of experimental verification of the activity of laboratories, in particular calibration ones, with the aim of determining technical competence in a certain type of activity. The successful results of conducting ILC for the laboratory are a confirmation of competence in conducting certain types of measurements by a specific specialist on specific equipment [7–9].

a b c d

Fig. 2. Photographs of the time scale readings of the standard and the stopwatch

In [10] presents the results of ILC calibration of the HS-45 electronic stopwatch manufactured by Citizen Watch Co., Ltd (Japan) at points from 30 s to 3600 s. The comparison of the results obtained during the calibration of the time meter by ten laboratories took place according to the radial scheme during 2016. The deviations of the results obtained by each laboratory were determined and the correctness of the obtained results was assessed taking into account the uncertainty of the measurements using the criterion of functioning statistics for the selected time intervals. One of the components of the general uncertainty of the stopwatch calibration was the correction caused by the operator's error when he pressed the stopwatch "start"/ "stop" button, which reached 0.004 s.

5. Evaluation of Calibration Uncertainty

For evaluation of the uncertainty of the stopwatch calibration, the recommendations [11–12] were applied. The mathematical model of measurement has the form:

$$E_{tXi} = \Delta_{Xi} + \Delta_{tp} + \Delta_S + \Delta_f + \Delta_g + \Delta_{Xd}, \qquad (7)$$

here E_{tXi} is measured deviation of stopwatch readings; Δ_{Xi} is the deviation of the stopwatch readings, which is determined by the expression:

$$\Delta_{Xi} = \sigma_t \cdot t_i, \qquad (8)$$

here t_i is time interval at which the stopwatch is calibrated (calibration point); Δ_{tp} is correction due to the constant bias of stopwatch readings; Δ_S is correction due to deviation of the reference time scale (from the frequency standard calibration certificate); Δ_f is correction due to the deviation of the frequency meter readings (from the calibration certificate); Δ_g is correction due to the deviation of the generator frequency from the nominal value (from the calibration certificate); Δ_{Xd} is correction due to the bias of stopwatch readings (from the stopwatch specification).

The standard uncertainty of the deviation of stopwatch readings $u(\Delta_{Xi})$, determined by the frequency of camera shooting for the ***i***-th measurement interval, is calculated by:

$$u(\Delta_{Xi}) = w(\sigma_t) \cdot t_i, \qquad (9)$$

Table 3. **The uncertainty budget for the deviation of stopwatch readings** E_{tXi}

Quantity x_i	Estimation x_i, s	Standard uncertainty $u(x_i)$, s	Distribution	Sensitivity coefficient c_i	Contribution to uncertainty $u_i(y)$, s
Δ_{Xi}	Expression (8)	Expression (9)	uniform	1	$u(\delta_{Xi})$
Δ_{tp}	Expression (2)	Expression (3)	normal	1	$u(\Delta_{tp})$
Δ_S	From the calibration certificate	$u(\Delta_S) = U/2$	normal	1	$u(\Delta_S)$
Δ_f	From the calibration certificate	$u(\Delta_f) = U/2$	normal	1	$u(\Delta_f)$
Δ_g	From the calibration certificate	$u(\Delta_g) = U/2$	normal	1	$u(\Delta_g)$
Δ_{Xd}	0	Expression (10)	uniform	1	$u(\Delta_{Xd})$
E_{tXi}	$\sum x_i$				U

Table 4. **The uncertainty budget of stopwatch calibration**

Quantity x_i	Estimation x_i, s	Standard uncertainty $u(x_i)$, s	Distribution	Sensitivity coefficient c_i	Contribution to uncertainty $u_i(y)$, s
Calibration point 30 s					
Δ_{Xi}	-0.0009	0.00002	uniform	1	0.00002
Δ_{tp}	-0.0006	0.0051	normal	1	0.0051
Δ_{Xd}	0	0.0058	uniform	1	0.0058
E_{tXi}	–0.0015				0.0154
Calibration point 600 s					
Δ_{Xi}	–0.0175	0.0005	uniform	1	0.0005
Δ_{tp}	–0.0006	0.0051	normal	1	0.0051
Δ_{Xd}	0	0.0058	uniform	1	0.0058
E_{tXi}	–0.0181				0.0154
Calibration point 900 s					
Δ_{Xi}	–0.0262	0.0007	uniform	1	0.0007
Δ_{tp}	–0.0006	0.0051	normal	1	0.0051
Δ_{Xd}	0	0.0058	uniform	1	0.0058
E_{tXi}	–0.0268				0.0154
Calibration point 3 h					
Δ_{Xi}	–0.3147	0.0089	uniform	1	0.0089
Δ_{tp}	–0.0006	0.0051	normal	1	0.0051
Δ_{Xd}	0	0.5774	uniform	1	0.5774
E_{tXi}	–0.3153				1.1549
Calibration point 1 day (clock mode)					
Δ_{Xi}	–2.5179	0,0715	uniform	1	0.0715
Δ_{tp}	–				
Δ_{Xd}	–				
E_{tXi}	–2.5179				0.1430

Table 5. **The results of stopwatch calibration**

Time interval t_i	The resolution of the stopwatch d_e, s	Measured deviation of stopwatch readings E_{tXi}, s	Expanded uncertainty U, s
30 s	0.01	–0.001	0.015
600 s	0.01	–0.018	0.015
900 s	0.01	–0.027	0.015
3 h	1	–0.315	1.155
1 day (clock mode)	–	–2.518	0.143

The standard uncertainty of the correction due to the discreteness of the stopwatch readings $u(\Delta_{Xd})$ is calculated by:

$$u(\Delta_{Xd}) = d_e / \alpha, \qquad (10)$$

here d_e is stopwatch resolution at the calibration point. The uncertainty budget for stopwatch deviations is shown in Table 3.

The uncertainty contribution is defined as:

$$u_i(y) = u(x_i) \cdot c_i. \qquad (11)$$

The expanded uncertainty U of stopwatch calibration is calculated:

$$U = k \cdot \sqrt{u^2(\Delta_{Xi}) + u^2(\Delta_{tp}) + u^2(\Delta_S)} + \\ + k \cdot \sqrt{u^2(\Delta_f) + u^2(\Delta_g) + u^2(\Delta_{Xd})}, \qquad (12)$$

here k is coverage factor ($k = 2$), which defines the interval, with a confidence level that is approximately equal to 95 %, assuming that the distribution is normal. The uncertainty budget of stopwatch calibration is given in Table 4. In Table 4 deliberately omitted corrections Δ_S, Δ_f, Δ_g, since the estimation of their values and associated uncertainties is several orders of magnitude less than that of other values of the uncertainty budget. At the calibration point 1 day corrections Δ_{tp}, Δ_{Xd} are not taken into account, since the calibration point is specified for the clock mode.

The results of stopwatch calibration are given in Table 5.

6. Conclusions

The presented method allows you to calibrate electronic stopwatches with sufficient accuracy, is economically beneficial, allowing you to significantly save the time of using reference equipment, does not require funds for the purchase of specific equipment, allows you to perform calibration at any point of the stopwatch measurement range, including at long intervals, allows simultaneous calibration of an almost unlimited number of stopwatches. The method can be used not only to calibrate electronic stopwatches, but also any devices with a time scale.

7. Gratitude

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8. Conflict of interest

The authors state that there are no financial or other potential conflicts regarding this work.

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