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WAYS OF INCREASING THE ACCURACY OF THERMOPHYSICAL MEASUREMENTS.

1. INCREASING THE ACCURACY OF CONVENTIONAL METHODS

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New methods are described that increase the accuracy and speed of thermophysical measurements. Principles of the design of appropriate instruments and primary measuring transducers are presented, and their metrological evaluation is given.

A lecture on the title topic was presented by the author at the recent International Thermophysical School in Tambov [1]. The content of the lecture is published as an abstract [2] which, certainly, does not give a full idea of the strengths and metrological feasibilities of the new methods and devices for thermophysical measurements. In view of the great interest in the lecture and the numerous letters that were received by the author later as well as many wishes, it seems useful to present more complete information to experimenters in thermal physics the form of several articles with a detailed bibliography of our relevant works.

As is known from the information theory of measuring devices, the attainable accuracy of measurements depends both on the level (power) of the measuring signal, the useful signal-to-noise ratio, and on which parameter of the measuring signal (amplitude, phase, or frequency) contains useful information. The outstanding American physicist L. Brillouin was the first to consider the problem of physical measurements within information theory in his well-known book [3]; the monograph by Russian Prof. P. V. Novitskii can also be recommended [4]. It was found that at a preset level of the measuring signal and preset measuring time, the (averaged) amplitude modulation (amplitude measuring methods) contained the least information and, consequently, gave the greatest measurement error. Under the same conditions, time (or phase) modulation (pulse, pulse-phase, and phase methods of measurement) increases the amount of information (the measurement error is decreased accordingly) 2π times, if external noise obeys a normal distribution law. Finally, frequency modulation (frequency methods of measurement) has the highest informative value in comparison with the previous methods, and primary frequency transducers provide the highest accuracy of measuring some physical quantities. It is also known that the accuracy of measurement of a physical quantity increases with the time of measurement (the time of continuous averaging of the recorded parameter of the measuring signal), but this increase is not infinite, as it cannot reach the accuracy of the (reference) standard measure that is embedded in the measuring instrument. A normal electromotive force (emf) element with a relative instability of 10^{-4} (guarantted to four decimal places of emf) is ordinarily used in series-produced instruments; in series-produced phase, period and frequency meters measures of time intervals or frequencies are used whose stability is higher by two or more orders of magnitude. This is another important advantage of the frequency and phase methods of measurements over the amplitude methods. It should be noted that, other things being equal, for achievement of a preset accuracy of measurement, the frequency methods provide the shortest time of measurement (the fastest measurements), and the amplitude methods, the longest time (the slowest measurements).

In this connection, it is necessary to state that in contemporary experimental thermal physics the levels of accuracy and speed of measurement of thermal quantities and thermal properties are much lower in comparison with the levels achieved in other fields (for example, measurement of mechanical, electric, and acoustic parameters

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of compounds and many other physical quantities.) Analysis has shown that in experimental thermophysical studies, conventional amplitude methods that employ various kinds of measuring bridge are used, as a rule, which, as was stated above, give the worst results from the view point of accuracy. Phase methods of measurement are seldom used; frequency transducers of temperature and other thermal quantities are used sometimes, but they are ineffective, because they are based on the principle of electrical resonance, and in this case the accuracy of measurement of a physical quantity, for example, temperature, is determined not by the accuracy of measurement of frequency, which can be extraordinarily high, but by the quality of the resonance transducer. Experimenters often neglect this fact and in scientific papers they give underestimated measurement errors.

It should be noted that the accuracy of measurement of thermal properties is determined not only by the accuracy of measurement of the parameter of the appropriate sensor (for example, resistance of the thermistor, or emf of the thermocouple), but also by some other conditions connected with the peculiarities of thermal phenomena. Among these conditions we can mention the necessity to take account of thermal drift of the sensor, real conditions of thermal interaction of the sensor with the object of study, etc. Many authors have devoted their works to these matters; therefore, this problem will not be considered here, but our entire attention will be concentrated on the accuracy of measurement of the parameters of thermal sensors. The different methods will be comparatively estimated with measurement of temperature, its excessive value, and the rate of change as an example. At present, for this purpose thermocouples and thermistors are most widely used under ordinary conditions. In the former case temperature is inferred from the value of the thermal emf, i.e., only amplitude methods are used; in the latter case, temperature is found from the active resistance, its changes or contribution to the transfer function, and to the phase-frequency characteristic of a primary transducer with a thermistor as its component. Therefore, amplitude, phase, frequency, and other more complicated methods can be used in these cases. Thermistors seem preferrable as thermal sensors, especially when high accuracy of measurements is required; they are gradually replacing thermocouples, especially in view of the fact that in recent years great achievements have been made in obtaining high stability of time and in decreasing the technological scatter of parameters of manufactured semiconductor thermistors.

First, we consider the possibility of increasing the accuracy of measurement of the parameters of sensors by conventional phase and frequency methods.

Phase Methods. They are as versatile as amplitude methods, since a phase meter can measure almost any physical quantity that can be measured by electrical methods. In this case the quantity measured can be transformed by a transducer into a phase shift or a time delay between two electrical (reference and measuring) signals. In this case the primary measuring transducer (sensor) is a phase-shifting circuit that switches on the thermosensitive element or a delay line that contains a radiator, a receiver of (ultrasonic, light, or radio) waves, and the object of study, through which sounding waves are transmitted.

If an a.c. bridge with a thermistor with resistance $R(t)$ connected to one of its arms is used as a primary transducer, then by analysis of the argument of the transfer function of the bridge circuit, it is possible to calculate the bridge arms in such a way that the increment of the phase shift $\Delta\varphi$ of electrical oscillations at the input-output of the circuit is minimal with changes in R, and the derivative $d\varphi/dR$ can be $1.5\cdot 10^{-2}$ rad/Ω. Series-produced digital phase meters measure phase shift with an error of 0.1 of an angular degree ($6\pi\cdot 10^{-4}$), which corresponds to relative measurement error $\delta R/R = 7\cdot 10^{-5}$. For example, for an STZ-14 thermistor it means that a series-produced phase meter can measure temperature with an error of $3\cdot 10^{-3}$ K. This measurement error can also be achieved by amplitude measurement, but then it is close to the feasibility limit of the method.

The relatively high error of series-produced digital phase meters (such as the F2-34) mentioned above can be explained by the fact that these phase meters are intended for measuring phase shifts over a wide frequency range. For our purpose we can restrict ourselves to one or several fixed frequencies, for example, 1 or 5 MHz. For these frequencies there are highly stable generators, comparators, precision radiometers, and metrological aids. When phase meters are used at a fixed frequency, use can be made of high-quality circuits, principles of phase multiplication, etc., which provides accuracy in measuring phase shifts that is higher by several orders of magnitude and does not make the circuit design more complicated or increase the cost. Such a phase meter can contain a built-in generator of a harmonic signal which is a reference signal for the meter and is simultaneously fed to the input of the primary measuring transducer. The phase meter measures the phase difference between the measuring signal from the output of the primary transducer and the reference signal. Optimal values of electrical parameters of the components of the primary measuring transducer that provide maximal sensitivity to any changes in the resistance of the thermistor are calculated for a given fixed frequency, and the thermal sensor is calibrated at the same frequency.

Researchers at our laboratory have suggested two versions of this phase meter [5, 6] for fixed frequencies of 1 and 5 MHz. These meters can measure phase shifts with an error that is not worse than $2\pi \cdot 10^{-5}$ ($3.6 \cdot 10^{-3}$ $^{\circ}$). These researchers have also suggested a method and a device for measuring changes in phase difference [7] with an error at the level $2\pi \cdot 10^{-7}$. Because of space limitations, these devices cannot be described in detail, and interested readers can write to the Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute" (15, P. Brovka Str., Minsk 220072, Belarus), and they will receive the necessary information. Here we describe the principle of one of the devices [5], which provides a substantial increase in the accuracy of measured phase shifts.

The phase shift $\Delta\varphi$ between two harmonic signals with frequency $f = \text{const}$ to be measured is expressed in the form

$$\Delta\varphi = \omega\tau_{\varphi} = 2\pi f\tau_{\varphi} , \tag{1}$$

where τ_{φ} is the time shift between them. For the case of a phase meter in which quantizing pulses are used whose frequency exceeds by a factor of n the frequency of the signal, expression (1) is written as

$$\Delta\varphi = \frac{2\pi f N_0}{nf} + \Delta\varphi_1 = \frac{2\pi}{n} N_0 + \Delta\varphi_1 , \tag{2}$$

where N_0 is the reading of the phase meter (digital code, whole number); $2\pi/n$ is a quantum of the phase; $\Delta\varphi_1$ is a neglected phase shift that does not exceed the quantum of the phase.

Further, an additional measuring signal is formed by feeding to a mixer signals that were obtained by multiplication of the frequency of the measuring signal by n and the frequency of the reference signal by $n-1$. This produces a signal whose frequency coincides with the frequency of the reference signal, but the phase difference between them appears n times higher because the frequency of the measuring signal was multiplied by n and the multiplied phase shift was transferred to the initial frequency. Then, with the integer number of periods neglected, the phase difference between the reference signal and the additional measuring signal is

$$\left\{n\Delta\varphi\right\} = \left\{2\pi N_0 + n\Delta\varphi_1\right\} = n\Delta\varphi_1 ,$$

where the braces { } mean subtraction of the integer number of periods, which is usually the case in measurements by a phase meter. It should be noted that the subtracted integer number of periods is N_0, if $0 < \Delta\varphi_1 < 2\pi/n$.

This phase shift is recorded by the counter of a second phase meter with capacity n. If the readings of this counter are N_1, then

$$\left\{n\Delta\varphi\right\} = n\Delta\varphi_1 = \frac{2\pi}{n} N_1 + \Delta\varphi_2 . \tag{3}$$

If the frequency of the first additional measuring signal of the previous channel is multiplied by n and the frequency of the reference signal, by $n-1$, with integer periods neglected, the phase difference between the reference and the new measuring signal is

$$\left\{n^2\Delta\varphi_1\right\} = \left\{2\pi N_1 + n\Delta\varphi_2\right\} = n\Delta\varphi_2 , \quad 0 < n\Delta\varphi_2 < 2\pi .$$

Continuing to form additional measuring signals $m-1$ times in a similar way, one can obtain the phase shift of the $(m-1)$-th signal relative to the reference signal with account of the readings N_{m-1} of the counter of the respective phase meter

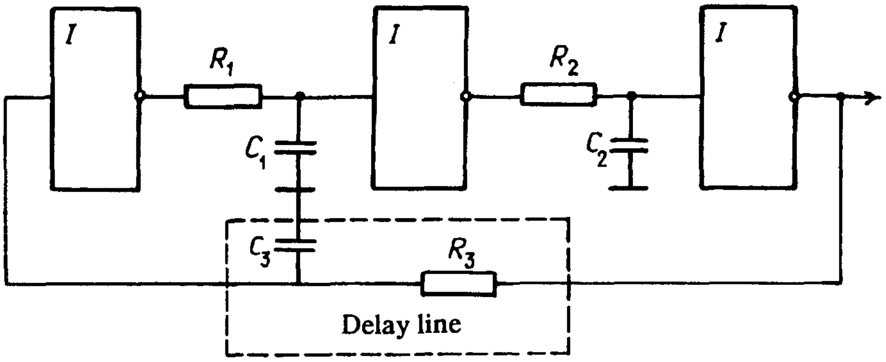

Fig. 1. Temperature sensor.

$$\left\{n^2 \Delta\varphi_{m-1}\right\} = n\Delta\varphi_m \tag{4}$$

and the *m*-th additional signal

$$\left\{n^2 \Delta\varphi_m\right\} = n\Delta\varphi_{m+1}\,, \tag{5}$$

where $\Delta\varphi_{m+1}$ is the residual phase shift, which is neglected in the phase meter of channel *m*.

Using successive substitutions and omitting the braces, since it is assumed that $0 < \varphi_1 < 2\pi/n$, we obtain the measured phase shift

$$\Delta\varphi = \frac{2\pi}{n} N_0 + \frac{2\pi}{n} N_1 \frac{1}{n} + \frac{2\pi}{n} N_2 \frac{1}{n^2} + \ldots$$

$$\ldots + \frac{2\pi}{n} N_{m-1} \frac{1}{n^{m-1}} + \frac{2\pi}{n} N_m \frac{1}{n^m} + \frac{\Delta\varphi_{m+1}}{n^m}$$

or

$$\Delta\varphi = \frac{2\pi}{n} \sum_{i=0}^{m} N_i \frac{1}{n^i} + \frac{\Delta\varphi_{m+1}}{n^m}\,, \tag{6}$$

where N_i are readings of the *i*-th phase meter; *n* is the frequency multiplication factor; $i = 0, 1, 2, \ldots, m$; *m* is the number of additional measuring signals; $\delta\varphi = \Delta\varphi_{m+1}/n^m$ is the error in measurement of the phase shift.

Since it was assumed that the neglected phase $\Delta\varphi_{m+1}$ was positive and did not exceed $2\pi/n$ (which is ensured in the device by circuit engineering means), the maximal error in the measured phase shift is

$$\delta\varphi_{\max} = \frac{2\pi}{n^{m+1}}\,. \tag{7}$$

In an implemented prototype phase meter, $n = 10$, $m = 4$ and, consequently, $\delta\varphi_{\max} = 2\pi \cdot 10^{-5}$. This phase meter, together with a primary transducer in the form of an a.c. bridge with a thermistor, for example, an STZ-14 used as one of its arms, can measure temperature with an error of 10^{-4} K.

Of course, a sensitive element of the capacitance, inductance or, in general, impedance type can be used instead of a resistor. The phase-shifting circuit can be of a resonance type, and then sensitivity to changes in the reactive component of the transducer impedance will increase *Q* times (*Q* is the quality of the resonance circuit) in comparison with the indicated active resistance $\delta R/R = 7 \cdot 10^{-5}$. A phase method in which ultrasound is used as a source of information about the average temperature of the part of the medium sounded or about the excess temperature gives high accuracy of thermophysical measurements [8]. At our laboratory this method has been used

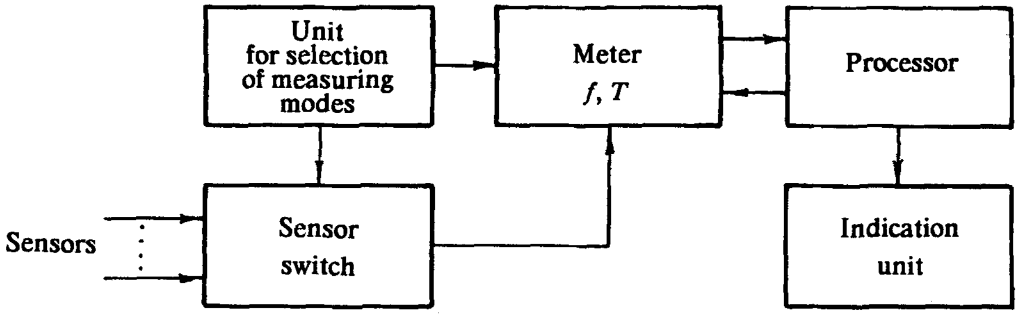

Fig. 2. Block diagram of the instrument.

for a long time both for body [9-14] and surface [15] ultrasonic waves, for waves in wires (for example, in the heated filament method [16-18]), etc. Especially high accuracy can be achieved if the medium studied or a wire sensor is a component of an acoustic resonator (interferometer). Readers interested in this promising trend are referred to our works [19-25].

Frequency Methods. Frequency transducers that are based on electrical resonance are known and widely used in many fields. For almost all physical quantities that can be measured by electrical methods, corresponding frequency transducers have been developed. When frequency methods are used, the physical quantity measured is inferred either from the measured frequency or from the difference between the frequency of the signal from the output of the primary transducer and the frequency of a reference generator (the differential method). Measurement of frequency is a most accurate procedure, but, as was shown above, the accuracy of measurement of a physical parameter is determined by the quality of the frequency transducer and the stability of its frequency. Therefore, autogenerator sensors with increased frequency stability are of interest.

At our laboratory frequency transducers that are based on the principle of a generator with delayed feedback have been studied for some years. A strength of these generators is that the frequency of the electrical oscillations is mainly determined by the parameters of the feedback circuit and depends rather weakly on the parameters of the active elements used and the supply voltages. Therefore, they are highly stable.

A version of the developed temperature sensor [26] is shown in Fig. 1. It is a generator of rectangular pulses by inverting CMOS elements with a delay line in the feedback circuit and thermistor, for example, an STZ-14, as a component. Laboratory studies of a fabricated frequency transducer have shown that the temperature-to-frequency conversion for an STZ-14 thermistor with a resistance of 1.5 kΩ is 700 Hz/K. At a constant temperature, the relative instability of the frequency of the sensor is 10^{-5}. Because of the characteristics of the generator just mentioned, it can be used to measure temperatures with a resolution of at least 0.001 K for a measurement time of 1 sec. Temperature is a linear function of frequency in the temperature interval within 30 K, and this interval can be shifted towards higher or lower temperatures by matching elements.

Similar generators have been developed for sensitive elements of the capacitance and inductance types and for acoustic delay lines and can be used for thermophysical and other measurements. A measuring instrument based on a generator with delayed feedback has also been developed [27, 28].

A block diagram of the instrument is shown in Fig. 2. The operation of the instrument can be described as follows. Under control of a unit for selection of measuring modes, a sensor is connected to a frequency or a period meter (an f- or a T-meter) through a sensor switch. The frequency or period is measured, depending on the value of the developed frequency. The processor calculates the physical quantity from the measured frequency or period and inputs the result to the indicator; it also controls the frequency and period meters and the indication unit. In a self-contained version of the instrument, the power supply is a storage battery and a recharging circuit. The instrument can also be supplied by a 220-V a.c. line. Frequencies are measured by a conventional method. The period meter is based on an interpolation circuit in order to obtain the highest number of discharges with the shortest time of measurement.

Thus, a generator with delayed feedback substantially increases the accuracy of measured parameters of thermal sensors and can be recommended to thermal physicists for a wide use.

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