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Development of Noise Measurements. Part 4. Problems and Methodology

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Abstract: Succession of problems in measuring the parameters of noise processes has been settled following the experience of thermal noise study. An effect of uninformative noise signals on the result of measuring integral characteristics and possibility of optimizing the duration of measurement in the input circuit has been scrutinized. The methods of increasing the interference immunity of means of measuring the integral characteristics of noise signals have been analyzed. *Copyright © 2013 IFSA.*

Keywords: Thermal noise, Flicker noise, Shot noise, Integral characteristics of noise signals, Duration of measurement.

1. Introduction

Evolving the method of research on the electrical noise of substances of different phase-states (liquid, solid or gaseous) and linear sizes, starting with macro-sizes and finishing with nano-sizes, requires to interpret the noise phenomenology as the fact that is determined by interaction within the limits of the substance itself and that between the substance and a measuring device. It highlights the need for the distinct understanding of both research subjects and methods. For example, with studying the electrical noise of a carbon nanotube (hence CNT) of the electric resistance 12.6 kOhm [1], a nanotube could remain in the superconductive state [2], and the value of resistance (12.9 kOhm according to [3]) is supposed to be determined by the resistance of nanotube contacts with bringing-in wires. It means that the measured noise could be referred to nanotubes just theoretically actually characterizing their contact areas.

Beside the need for awareness of monitored object noise-characteristics, some metrological experience is necessitated. This is the experience in manufacturing and exploiting noise thermometers with sensitive elements whose materials are used for research on information parameters by means of noise peculiarities. Apart from, the availability of metrological support for the very noise thermometers when the main monitored parameter is electric noise characteristics (voltage, current, power) could be adopted for the nanometrological assistance of metrology and industry efforts of nanotechnology exactly while studying electrical noise of different substances [4] as well as components of manufactured wares of nanoelectronics [5].

2. Objectives of the Work

Development of metrologically correct methodology of investigating the integral characteristics of noise signals is a main target.

3. Methodology of Investigating the Integral Characteristics of Noise Signals

Research methodology is first of all the methodology of measurements that includes the following aspects:

a) Assurance of the increased interference resistance due to the low amplitude value of the measured signals;

b) Separation of the bandwidth for intended investigations;

c) Predetermination of the general length of an experiment, particularly while undertaking low-frequency research on *1/f* noise with regulation of a basic reasonable error of method;

d) Selection of the methods of processing the gained signals (particularly, application of the high-speed Fourier transformation that includes the differentiation of a signal into frequency spectra; separation of interference frequency, for instance, the frequency of feeding power with its multiple frequencies; and their elimination from the re-formed signal);

e) Selection of optimal noise-characteristics research methods in terms of quality and negative issues;

f) Choice of methods apt to characterize the researched materials by known informative quality, durability, reliability, uncertainty and other parameters.

The research of integral characteristics of noise signals appearing in sensitive sensor elements enables comprehensive studying into physical nature both of noise processes occurring in substance, and non-noise substance parameters and characteristics. Exactly such an approach to noise research most completely renders its significance for modern electronics. Hereby the improvement in the means of measuring techniques, development of new conceptions of conducting the gauges themselves, automatization of a measuring process, implementation of interference-resistant technologies of gaining the output signals and etc. pose essential requirements to the methodology of measuring noise characteristics. Theoretical and experimental research in the area of measuring the integral characteristics of noise signals reveals the chain of problems, namely:

- Durable measuring caused by random nature of a noise signal;
- Influence of uninformative noise signals in the input circuit on the results of measurement;
- Low level of a noise signal;
- High requirements to interference-resistance of the measuring means.

Durable measuring period stipulated by random nature of the measured signal. The measured signal is mainly noise voltage or current. Each of them has a nature of homogeneous continuous random fluctuations concerning the average that is up to zero and constitutes a random ergodic stationary process. Studying it, any moment of time can serve as starting point. Measuring the parameters of a stationary process within any period of time, we should receive the same values of its characteristics.

Such integral characteristics of a random process as the mean of a square (variance in statistical investigations), mean square value (standard deviation) and spectral density of a noise signal tend to be measured in the first place. Since a noise signal is a random process, the true value could be gained during the infinite time of averaging. Any restriction on the averaging time leads to the appearance of a methodic measurement-error. In the ideal case, if there are no other noise signals except the measured one in the measuring circuit, the standard deviation of a noise signal variance σ [6] could be calculated as:

$$\sigma \approx \frac{1}{\sqrt{t\Delta f}}, \tag{1}$$

where t is the time of measurement, Δf is the bandwidth of a noise signal.

The results of modeling the dependence of the standard deviation of a noise signal variance on the time of averaging at the different values of the bandwidth Δf are notified in the Fig. 1.

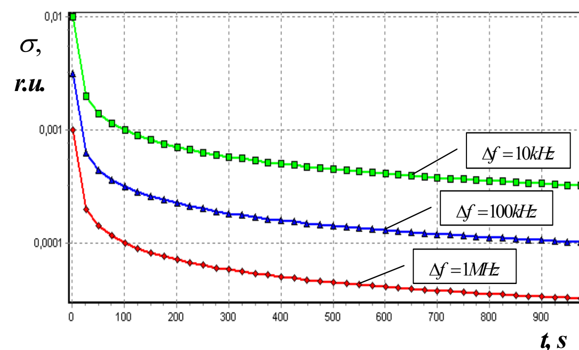

Fig. 1. Dependence of a standard deviation of a noise signal variance on the time of averaging.

To reach the relative mean square value of the variance of a noise signal 0.01 % for the bandwidth $\Delta f = 100$ KHz, we should conduct measurements for 1000 s, and for $\Delta f = 1$ MHz – 100 s. Taking into account that other sources of noise signals are present in the input circuit (resistance of a connecting line, amplifiers, feedback resistors), the dependence of

mean square value of a noise signal variance on the time of averaging becomes more complicated. Time of measurement for reaching the equal error rises as compared to an ideal case. Correspondently, the measurement of integral characteristics of noise signals could require some length of averaging: tenth – hundredth of seconds.

If there is a necessity for measuring the integral characteristics within narrow bandwidth, the time of measurement rises considerably. So to reach the relative mean square of noise signal variance 0.1 % at the bandwidth of a noise signal $\Delta f = 10\,\text{Hz}$, time of measurement has to be approximately 30 hours.

Analysis of uninformative noise signal influence on the result of measurement within the input circuit. Beside the noise signal being measured, uninformative noise signals exist in the input circuit, appearing in the connective line and the input circuit of a measuring part. In a general case, noises determine the lower limit of measurement. The ratio "noise – signal" should be reduced to minimum for any measurement [7]. A signal is determinable in the majority of measurements.

Thermal, shot, generation-recombination noises and flicker noise are regarded within the scope of the given work [8-12]. Thorough investigation of the nature of these noises and influential factors changing the noise-parameters enables not only conscious development of methods of mitigating the levels of those noises but also their employment in the analysis of different systems state.

In our case, the signal being measured is random, i.e. has a noise nature which complicates the extraction of the particular measured signal at the background of a noise interference; signal and interference could be commeasurable in terms of their level.

Thermal noise appears at the expense of random motion of charge carriers in any conductor. Consequently of this motion, the randomly variable electro-motive force arises at the ends of the conductor. The similar phenomenon is observed in the conducting channel of field transistors. Thermal noise is decisive in any device of electrical nature that remains in thermo-equilibrium with the environment. Generation-recombination noise appears when free carriers are generated or recombined in the semiconducting substance. Fluctuating speeds of generation and recombination could be considered as consecutions of independent randomly appeared events, and therefore the process could be regarded as a shot noise.

For the thermal noise, the spectral density $S_{Utn}(\omega)$ of the disconnected circuit noise-voltage [13] and that $S_{Itn}(\omega)$ of short-connected circuit noise-current are correspondently equal to:

$$S_{Utn}(\omega) = \frac{4kTR}{1+\omega^2\tau_e^2}, \quad S_{Itn}(\omega) = \frac{4kT}{R\left(1+\omega^2\tau_e^2\right)}, \qquad (2)$$

where τ_e is the average time of free run of electrons in substance between collisions, ω is the circular frequency.

For all frequencies of practical relevance, the item $\omega^2\tau_e^2$ is negligibly small. In this case the expression (2) is shaped as:

$$S_{Utn}(\omega) = 4kTR, \quad S_{Itn}(\omega) = \frac{4kT}{R}, \qquad (3)$$

To decrease the influence of uninformative thermal noise, the measurement conditions should be assured providing a noise-measurand is as much as possible in comparison with uninformative thermal noise hereby satisfying the needed ratio "measured noise signal – noise interference". Besides, the influence of uninformative thermal noise on the result of measurement could be minimized following the correlation measurement method [14].

Shot noise, always present in the case a noise-phenomenon, could be regarded as succession of independent random events [15]. For instance, with releasing electrons by thermo- or photo-cathodes, electron emission constitutes the consecution of such events. To wit, shot noise is inherent in emission currents. The phenomena of crossing the *p-n* junction by charge carriers (electrons or holes) make the succession of independent events in transistors. Therefore these currents reveal the features of shot noise. It is also valid for the transitions between two energetic levels, for example, with generating and recombining the carriers in a semiconductor or with emission of laser photons. Input circuits of measuring means could be constructed with the use of bipolar and field transistors. For bipolar transistors on low-frequencies, when $\alpha(\omega) = \alpha_0$, the spectral densities of collector, emitter and base noise currents [16] are:

$$S_{Ic}(\omega) = 2q_e I_c, \quad S_{Ie}(\omega) = 2q_e I_e, \quad S_{Ib}(\omega) = 2q_e I_b, \qquad (4)$$

where q_e is the electron charge, I_c is the collector current, I_e is the emitter current, I_b is the base current.

For field transistors the spectral densities of channel current and gate current are:

$$S_{Ic}(\omega) = \frac{2}{3}4kTG_m, \quad S_{Ig}(\omega) = \frac{4\omega^2 C_i^2}{15G_m}4kT + 2q_e I_g, \qquad (5)$$

where G_m is the mutual (transferring) conductivity, I_g is the gate current, C_i is the input capacitance of a field transistor.

The influence of shot noise could be mitigated by marking off active elements with small values of noise currents and voltages, and by applying the correlation measurement method.

Flicker noise that could appear consequently of different reasons is characterized by special spectral

density nonlinearly rising within the area of low frequencies. The main property of flicker-noise is resemblance of spectral density to $1/f$. In the case of a semiconductor element, the spectral density $S_{Inp}(\omega)$ of current random component and the same $S_{Unp}(\omega)$ of random voltage component on the coal resistor make:

$$S_{Inp}(\omega)=\frac{2\pi\alpha I_0^2}{N_0\omega},\quad S_{Unp}(\omega)=\frac{2\pi AI_r^2}{\omega}, \tag{6}$$

where α, A are the constants, I_0, I_r are the currents passing through the semiconductor element and resistor, respectively, N_0 is the equilibrated amount of carriers in a semiconductor.

The typical dependences of spectral density of thermal, shot and flicker noises are represented in the Fig. 2.

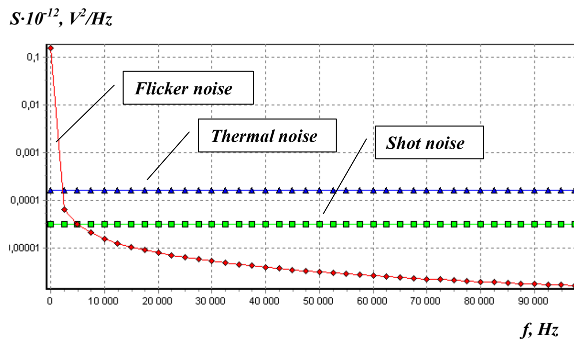

Fig. 2. Typical shape of spectral density of noise signals.

Under some conditions the level of thermal noise could be lower than that of shot noise, and flicker noise may acquire the dominated value to the frequencies 20 – 30 kHz. To reduce the influence of flicker noise on the result of measurement, the operating bandwidth should be above 1 - 20 kHz, depending on the conditions of measurement, sensor resistance value and etc. If necessary to conduct flicker-noise measurements at low frequencies, the need for the considerable increase in measurement duration should be taken into account (see the aforesaid).

Low level of a noise signal. Mainly a noise signal is of a very low level. So for example the average value of a square of noise voltage calculated after the Nyquist formula [17] and the mean square value of noise voltage for the bandwidth $\Delta f = 100$ kHz for a sensor of resistance 100 Ohm at the room temperature are:

$$\overline{e_x^2(t)} = 0.16\cdot 10^{-12}V^2,\quad U_x=\sqrt{\overline{e_x^2(t)}}=0.4\cdot 10^{-6}V. \tag{7}$$

Therefore while creating the means of measuring the integral characteristics of noise signals we should use the wide-band amplifiers with the coefficient of the level 1000 – 10000, depending on the value of a noise signal.

Optimal choice of noise parameters of amplification elements enables reaching the necessary ratio “signal being measured – noise interference”, decreasing the error of measurement and improving the metrological characteristics of the measuring means. For the relation of spectral densities of the measurand S_x to the noise interference S_{nz} prevailing 10, the relative standard deviation of a methodical error for different averaging times is practically stable. The further improvement of the ratio “noise signal being measured – noise interference” does not provide the considerable decrease in the methodical error of temperature measurement, and 10 could be treated as the nominal ratio. Manufacturers of operation amplifiers (OA) norm the values of noise voltage and current as the square root of spectral density of noise voltage and current:

$$U_{oa}=\sqrt{S_{Uoa}},\quad I_{oa}=\sqrt{S_{Ioa}}, \tag{8}$$

where U_{oa} is the spectral density of noise voltage mean-square-value of OA, S_{Uoa} is the spectral density of OA noise voltage, I_{oa} is the spectral density of mean-square-value noise current of OA, S_{Ioa} is the spectral density of OA noise current. Correspondently, taking into account (3) and (8), the ratio of spectral densities of the noise signal under measurement to noise interference could be estimated after:

$$\frac{S_x}{S_{oa}}=\frac{4kT_xR_x}{U_{oa}^2}=10 \tag{9}$$

To satisfy the given ratio using the sensor of the nominal resistance 100 Ohm at the room temperature, an amplifier with the following parameters should be used:

$$U_{oa}=\sqrt{\frac{4kT_xR_x}{10}}=0.41\frac{nV}{\sqrt{Hz}} \tag{10}$$

On the other hand, we could increase the value of sensor resistance (the subject of research), and hence the level of a measured noise signal, hereby assuring the needed ratio of measured noise signal and noise interference spectral densities. With using OA in the input circuit (e.g. LT1028 with $U_{oa}=0.85\,nV/\sqrt{Hz}$), the value of sensor resistance, taking into account (9), should be equal to:

$$R_x=\frac{10U_{oa}^2}{4kT_x}=430\text{ Ohm} \tag{11}$$

It is a real approach to the problem solution. However, we also should consider the proper input noise current of OA whose effect on the result of measurement rises with an increase in resistance of a sensor and eventually could become predominating. To wit, using OA the special attention should be paid to such OA parameters as proper noise voltage and input noise currents.

The usage of a correlation amplifier enables minimizing the influence of OA noise voltage. Minimization of the influence of a noise current could be reached by reducing the nominal sensor resistance and selecting OA with small values of noise current. Consequently the question of optimizing the input circuit and hence the means of measuring the noise in general has become vital.

Ways of increasing the noise immunity of the means of measuring the integral characteristics of noise signals. As was mentioned above, the low level of the measured noise signal leads to the necessity for applying the wide-band amplifiers with the coefficient of amplification more than 10000. At such an amplification coefficient the high-sensitive input of the device gauging part with a wide bandwidth of the signal being measured has been gained. It has entailed the high requirements to the noise immunity (interference-resistance).

The source of outer interference could be the subject of measurement itself; or/and power network feeding the measurement device; or/and computer connected with the measuring device by installation wires and so on. Inner interference could arise due to a high coefficient of amplification – the influence of high-volt output circuits on the input high-sensitive circuits consequently of parasite resistive, inductive and capacitance connections.

Minimization of the noise interference influence on the measurement result could be made by means of screening and grounding in the schemes of analog signal conversion, optimal parting and galvanic segregation of common conductors of digital and analog schemes etc. For any construction the analysis of the most vulnerable areas in relation to interference should be conducted. Besides, the certain constructive decisions supporting the steady work of schemes should be made.

Screening and grounding in the schemes of analog signal conversion far not completely obviate the noise interference effect. Then the filtration methods for marking the measured signal off the input one which could be a superposition of the measured signal itself and interference should be applied.

In most spheres of science and techniques, the measurements of determined signals are conducted, whilst in the case of noise values the random signals are of interest. The interference could be both determined and random. Besides, taking into consideration the fact that measurements are performed within the wide bandwidth, the determined interference could reveal itself at the various frequencies. Therefore we should use the filters of complicated configuration that combine a band filter for forming the work-bandwidth of a measuring device, and rejecter filters for some frequencies which could be numerous.

Taking into account the specific conditions of measurement as well as difficult construction and working principles of such filters, the synthesis of digital intelligent filters with the usage of rapid Fourier transformation [18] which meets the enumerated requirements is optimal.

Each of the considered problems leads to the appearance of the whole chain of error components of measuring the integral characteristics of noise signals. These components depend on the method of measurement, metrological characteristics of measuring means and their proper noise characteristics (noise- voltage and current). The analysis of possible error sources, minimization of their influence on the result of measurement, consideration of the specificity of the measurand, satisfaction of appropriate ratio "noise-signal being measured – uninformative noise-signal" and etc. enable gaining the reliable results of measuring the integral characteristics of noise signals.

4. Electrical Noise at Electrical, Mechanical and Thermal Loadings

The sources of electrical noise appearance are different, so are the bandwidth and spectral density. Essential and considered below are current frequency-dependent noise at the low frequencies and thermal noise at the high frequencies.

The research [9] of frequency dependences of noise power spectral densities (PSD) of metal contacts and thin semiconducting films allows us to specify the nature and origin of the mentioned noise by dint of attracting electron microscopy and other structure-sensitive methods. Particularly, the PSD frequency-dependence at the low frequencies reminds the similar dependence of the fatigue limit studied by the method of internal friction. Here the *1/f* dependence of PSD is characteristic for the low frequencies 15…200 Hz. With a rise in frequency it becomes frequency-independent which is related to the marked heat-waste during cyclic deformation.

Continuous energetic feeding of the substance by passing the electric currents of considerable density enables [9] simultaneous observing and segregating of *equilibrated and disequilibrated noise components of* $1/f^{\gamma}$ *type*, which are researched through the spectrum form index γ, through the apparition of 2- and 3- multiple frequency-satellites and through the ratio of components. Thus, with an increase in current, the spectrum form index γ rises from 1 to 2 and higher which is revealed at 320 ... 410 K in the films of aluminium and its alloys with silicon (current density makes 0.3 ... 2.5 10^4 A/mm^2). The same refers to the study on CNT [1]. To reveal $1/f^2$ noise at the direct current, the measurement has

been conducted within the bandwidth 0.01 ... 1.0 Hz, since it was masked at higher frequencies by the equilibrated *1/f* noise with the spectrum form index $\gamma \approx 1$.

Equilibrated 1/f noise of metal films including nondeformed and annealed ones appears due to motion fluctuation of charge carriers while their dissipating on the lattice. The processes of substance electrotransfer to different stocks in the volume (volume diffusion) or on the grain borders (surface diffusion) entail the irreversible structural changes in the films emitting disequilibrated $1/f^2$ noise. The given component called as the electromigration $1/f^2$ noise has nonstationary nature and is practically absent at the alternating current and room temperature. With an increase in temperature, the electromigration processes leading to enlargement of the spectrum form index γ to 2 tend to intensify. In general, the dependence of average noise-power density $S(f) \sim 1/f^2$ on the direct current density is described by the expression: $S(f) = j^3 B T^{-1} f^{-2} \exp(-E_a / kT)$, where B is the constant; E_a is the energy of electromigration process activation corresponding to that of matrix atom self-diffusion activation. For instance, in the case of polycrystalline aluminium film it is equal to 0.6 eV at 327 ... 396 K. In the metal conductors of submicron dimensions with a monocrystalline or bamboo structure, in which the average longitudinal grain size considerably prevails the film width and therefore mass transfer by the grain boundaries is absent, the values of activation energy, determined from the temperature dependences of average $1/f^2$ - noise-power density, are much larger as compared to polycrystalline films. They make 0.8 eV and are assigned to the energy of activating the diffusion along dislocations.

There are known cases of appearance of disequilibrated noise in the films whose structure differs from thermodynamically equilibrated one: freshly made films, deformed or irradiated films. The similar is observed in the aluminium films on a polyimide substrate where for frequency 20 Hz while applying an external bending force (within the area of elastic deformation), the average power density of $1/f^\gamma$ noise was rising approximately 30 as much at the increasing of efforts from 0 to 120 MPa [19]. Within the carbon fibers of the diameter 6 microns and of the length 10 cm with the electric resistance 41.3 kOhm at the efforts of extension up to 250 MPa, a 20-fold increase in average $1/f^\gamma$ noise power density is fixed (electric resistance rises negligibly). Moreover, irreversible changes in the noise level are related to the plastic deformation of fibers.

In length of time the structures of films being exposed to temperature or electric current are being ordered: the inner energy and the amount of defects are decreasing exponentially. Consequently, nonstationary noise is smoothly converted in the stationary one during relaxation time decreasing with a rise in temperature. Moreover, the spectrum form index γ of the given disequilibrated noise was changing within the limits 2 ... 3. For only just precipitated films of chromium a decrease in the spectrum form index γ is also observed [9] but from 2.5 ... 3 to 0.7 ... 1.2 consequently of vacuum annealing duration 30 ... 45 minutes. It has proved the necessity for attracting the disequilibrated mechanisms of clarification the reasons for the noise level decrease in the process of chromium films aging. An increase in a specific material volume consequently of combining the disequilibrated vacancies into complexes or into closed micro- or submicro- pores under pressure of internal mechanical stresses may be one of those reasons [20].

The case of equilibrated noise (current does not pass through the researched substance). Thermal noise prevails at the frequencies above 100 Hz and its nature is uncorrelated. The analysis of PSD frequency dependences has revealed the considerable influence of dissipation of the accumulated energy [21]. The frequency-dependent *1/f* noise of low-frequency range (lower than 80 Hz) corresponds to the reversed transformation of energy into phonons at the tensile defects. Their PSD is $S(f) = P_{el}/\Delta f = c/af$.

The case of disequilibrated noise (the ratio of amplitudes of feeding voltage and noise voltage makes ~ 10^{-7} and of their powers 10^{-14}) has been studied in [9] on the molybdenum films of the thickness 247 and 560 nm. The average density of harmonic tones amplitude fluctuation power of a response signal concerning the test effect of sine voltage of the bandwidth 10...1000 Hz, and also on the effect of direct current 0.45 mA have been considered. The latter has provided the total PSD of equilibrated and disequilibrated noise. The mechanism of multi-phonon capture [24] has been activated on the tensile defects as the phonon traps. The dependence of the index γ within the limits 2...3 on the frequency is explained by the influence of electro and mass transfer.

5. The Research of Dynamics of the Change in Noise Voltage at the Thermal Shock

At the considerable speed of temperature alteration all transfer processes are much complicated. For example, in substance kept at the certain temperature and rapidly moved into the medium with higher temperature, surface-volume mechanical tensions capable of accumulating the inner energy appear consequently of forming the dislocation ensembles. All real crystals have their defects distributed due to distortions in the atom allocation providing atom sizes exceed considerably the crystalline lattice constant. In dynamical

temperature mode the presence of such structural defects could lead to the change in noise characteristics.

At the rapid heat of the sensors of noise thermometers the transient noise process caused by thermodynamic disequilibrium has been detected. Such a behavior of a noise signal could be revealed at the expense of internal changes intensified consequently of applying an uneven temperature gradient on the substance with inner defects.

The research on the behaviour of a noise signal in the dynamic temperature mode (Fig. 3) has been made following the methods of rapid transferring of a sensor from the medium with one temperature into that with higher temperature [22].

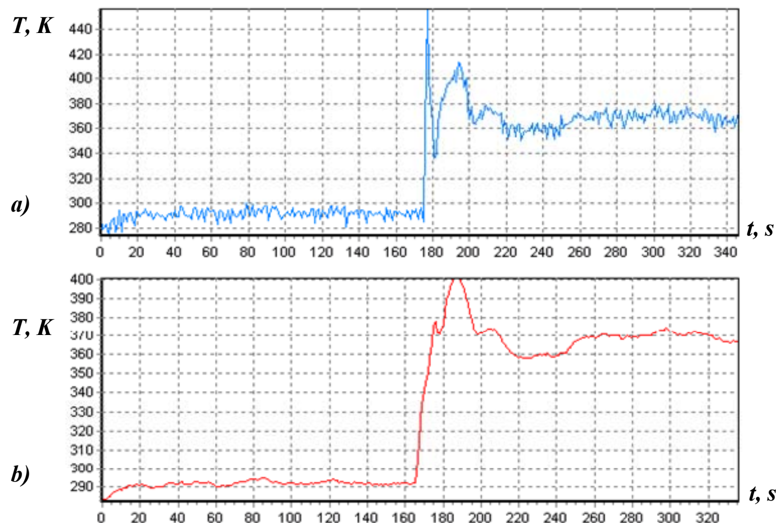

Fig. 3. Process of altering the indices of a noise thermometer at temperature jump from 288 K to 368 K (bandwidth of a noise signal: 10 – 110 kHz; averaging time: a) 1 s.; b) 10 s.)

In the moment of time approximately *170 s.* from the beginning of measurement, the temperature of the researched medium is changing abruptly from *288 K* to *368 K*. The temperature that was fixed during the transient process (Fig. 3) and determined by the noise power exceeds the temperature value of the researched medium almost 1.5 as much.

While studying [23] resistance thermometers and thermoelectric thermometers, the similar deviations from the equilibrated indices have also been observed (Fig. 4).

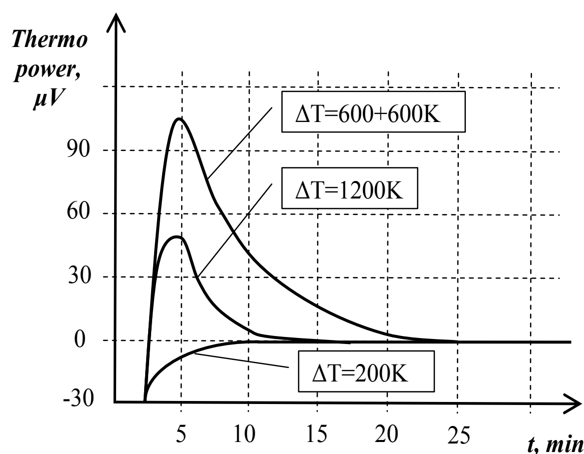

Fig. 4. Transient thermo-process according to the indices of differentially connected two thermocouples at the different temperature overfall ΔT.

Temperature exceeding has been stimulated by an increase in temperature overfall ΔT. Besides, this process was getting more intensive while a two-stage jump ($\Delta T = 600 + 600$ K). Those changes could be related to the appearance and relaxation of mechanical stresses causing the changes in thermoelectric power and taking place [24] nearby structure defects.

Moreover, the probability of passing the researched substance from one thermodynamic state into another at negligible temperature changes is determined by the value of a temperature jump, entropy and time. At the considerable temperature changes, entropy remains to be the most decisive factor determining all the transient processes inside the concrete substance.

We tend to consider further the researched sensitive substance as a subsystem (thermodynamic system with minimal outer influences), forming the part of a larger transducer system and being the smallest part of much larger system of the monitored environment. The probability of the transition of the given subsystem from the state X_0 to the state $X_0 + \Delta X$ is determined by the prehistory of substance:

$$dP \sim \exp\left[-\Delta W\left(X\right)/kT\right], \tag{12}$$

where ΔW is the work equal to the change in inner energy ΔU that the outer medium should apply to the given subsystem to put it out of state with the parameter X_0 to the state with the parameter $X_0 + \Delta X$. In general, $\Delta W(X)$ is considered as a measure of fluctuation probability of the parameter X.

From (12) the probability of independent transition of the given subsystem from the state X_0 into the state $X_0 + \Delta X$ (or probability of fluctuations) is the larger, the smaller ΔW is. Therefore (12) could be written as:

$$dP \sim \exp\left[-\Delta U(X)/kT\right], \quad (13)$$

Thermodynamic equations imply the connection of internal energy and the heat degree of freedom TS [25]:

$$\Delta U = T\Delta S + S\Delta T, \quad (14)$$

substituting which into the equation (13), we will have the equation:

$$dP \sim \exp(-\Delta S/k)\exp\left(-\frac{S\Delta T}{kT}\right), \quad (15)$$

According to the law of minimal speed of entropy production that is treated as the more general case of the widely known statement of saving invariable entropy ($dS \to 0$): $\frac{dS}{dt} = \min$. It means that the entropy of substance subsystem primarily taken out from the state of thermodynamic equilibrium consequently of medium temperature change from T_0 to T, is increasing with time:

$$S(t) = S_0 + \Delta S = S_0 + gt, \quad (16)$$

where S_0 is the entropy in the moment of time $t = 0$, g is the constant determined by the speed of entropy change for the given subsystem. Then the probability of its transition from one stage into another will be:

$$\begin{aligned} dP &= C\exp(-gt/k)\exp\left(-\frac{S_0(T-T_0)}{kT}\right) = \\ &= C_1\exp(-a_1 t)\exp(a_2/T) \end{aligned}, \quad (17)$$

where $a_1 = g/k;\ a_2 = S_0 T_0/k;\ C_1 = C\exp(-S_0/k)$; C – is the constant. Consequently, the probability of spontaneous transition is proportional to the power of thermal noise. Moreover, the parameters of a temperature jump are included in the coefficient a_2 whilst the technological parameters, determining the primary entropy value and its change at the dissipation of a thermal shock, are defined by the coefficients C_1 and a_1.

Under the condition $T >> T_0$ i.e. that in the initial state the given substance is remaining at the low and even room temperatures, we can gain: $dP = C_2\exp(-a_1 t)$. It means that the changes in considered noise voltage depend also on temperature and on a substance prehistory (e.g. on the mechanical processing or/and on vibrations).

6. Conclusions

The problems of measuring the integral characteristics of noise signals have been considered in the article. The influence of uninformative noise signals (thermal, shot and flicker noise) in the input circuit on the measurement result has been researched. It is ascertained that to reduce the influence on the result of measurement of:

- Flicker noise, we should work within the bandwidth above 1 - 20 kHz where its level is negligible;
- Thermal noise, we should provide the conditions when a noise measurand is as much as possible in comparison with uninformative thermo-noise, and use the correlation method of measurement;
- Shot noise, we should select the active elements with small values of noise currents and voltages, and use the correlation method of measurement.

The optimization of sensor resistance is proposed in order to satisfy the needed ratio of spectral densities of the measured noise signal and noise interference with taking into account the proper input noise current and voltage of an input circuit.

The ways of increasing the interference protection of measuring means have been analyzed, and metrologically correct methodology of investigating the integral characteristics of noise signals has been evolved.

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