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Metrological Array of Cyber-Physical Systems. Part 14: Basics of Metrology and Techniques for Accuracy Improvement

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Abstract: It is examined the specific of metrology of Cyber-Physical Systems as well as the sequence of methods for accuracy enhancing. For precise operation of full-fledged CPS the metrological control of group of measurement parameters is needed. Different approaches of received results processing are studied aiming the improvement of accuracy of CPS operation. *Copyright © 2016 IFSA Publishing, S. L.*

Keywords: Cyber-Physical System, Methods of Accuracy Improvement, Errors approach, Uncertainty approach, Hybrid approach.

1. Introduction

Day after day the globalization of industry, agriculture, transport, health-care and so on becomes more total. Certainly it contributes to continual development of Internet technologies, one manifestation of which is the occurrence of Cyber-Physical Systems (further CPSs). Realization of existing CPS development programs is impossible without taking into account the metrological aspects of designing and operating CPSs. Therefore current NIST program [1] mainly focuses on involving metrological science to resolve some CPS-problems at the design stage. Next row of problem seems to emerge the evident tasks in CPSs operating modes, firstly trying to provide traceable and quantitative data for validating the process models, calibrating in-process sensors, and determining the optimal process conditions, and furthermore endeavoring to obtain the objective quantitative information of technological processes by measuring their parameters and at last to assess the quality of final CPSs products.

Just because measurement should be considered as a holistic process that starts from perception and transformation of object measurement data to its processing, storage, transmission and application for developing retroactivity in controlled technological objects. Therefore, one of the most important CPSs' parameters is their general and metrological reliability due to continuously varying structure, modes, conditions, and environment of particular components and units. Additionally, the manufacturing CPSs would not cause environmental damage, greater from the acceptable standards. The problem of preventing the environmental and technogenic accidents and disasters should be noted also.

Current article tries to consider the classic metrology approach to CPSs operation, and to ensure their development in applied problems by studying:

- Verification and validation of the metrological units for parameters determining the controlled equipment, process, materials through the development, implementation and realization of specific metrology and standardization methods and techniques, instruments and facilities, and etc. For instance, calibration could be performed remotely under condition of code access to CPS subsystems with implemented appropriate software;

- Aspects of metrological reliability, including its prediction, particularly of CPS integrated metrological subsystems remote nodes. This includes not only microwave research essential for the link at optical wavelengths, but low and ultralow frequency methods in which it can be detected successfully the hidden and latent defects of complicated CPSs.

2. Shortcomings

Unique and newly created CPSs often require checking and verification of metrology facilities to ensure their quality operation.

To reach the necessary metrological reliability of information and measuring subsystems of CPSs, in practice, try constantly to supervise the measurements. Reliable measurement information of required accuracy can be obtained only through technically informed choice of measuring instruments (further MIs) and includes the following data: availability of measured or monitored parameters of object; tolerance for deviations of these parameters and allowable measurement uncertainties; allowable probability of false and unidentified rejections for each of monitored parameters and the values of confidence for them; distribution laws of measuring parameters and their measurement errors that can arise while using the MIs; measuring conditions: mechanical loads (vibration, shock, acceleration, etc.), climatic impacts (temperature, humidity, pressure, etc.), and so on. The existing measures applicable for CPSs calibration lose their values (accuracy characteristics) by several orders while transferring them to the end user, and that is actually considered as a normal metrological practice. However, such practice cannot be deemed adequate for development of CPSs.

3. Aim of Paper

Goal of this paper is presentation and consideration of main trends in the branch of metrology of Cyber-Physical Systems which are becoming a key element of everyday life. Trying to highlight emergence and development of these systems, we present published in the current set of 15 works, as well as reviewed previously by means of 2 similar rows of articles, 2013, *Sensors & Transducers*, Issues 3-11 (common notion “Development of Noise Measurements”) and 2012 – “Research in Nanother-mometry” studies at an angle of CPS metrological specific. A new outcoming aim has emerged – metrological assurance that embraces the adjustment of necessary measurement precision by means of continuously self-checked, self-verificated and self-adjusted MIs, self-validated metrological procedures, and finally obtaining the high-level metrological traceability and adequate metrological assurance of CPS’s final product.

4. Theoretical and Practical Consideration

There are considered traditionally that CPS is a system of collaborating computational elements controlling physical entities. Today, a precursor generation of CPSs can be found in areas as diverse as aerospace, automotive, chemical processes, civil infrastructure, energy, healthcare, manufacturing, transportation, entertainment, and consumer appliances [2]. The reliability of such systems is ensured by maintaining the operability of its components due to redundancy, regulatory replacement of components etc. Unlike more traditional embedded systems, a full-fledged CPS is typically designed as a network of interacting elements with physical input and output instead of as standalone devices. On the basis of available experience of metrology of the mentioned units operation, it seems appropriate to extend the understanding of aforesaid systems in the direction of natural affiliation, to the next concept: **a full-fledged CPS with the metrological assurance of group of operating parameters as well as the basic characteristics of the intermediate product has to be designed as a network of interacting elements with physical input and output of every element that is controlled at each stage of operation providing a qualitative final product.** Furthermore, the CPS can change over time, and a priori is known that the components and connections between CPS’s units are not 100 per cent reliable.

Firstly, such interacting elements may be sensors and actuators. Best modifications of them inherent in their own function-transformative computing properties. The brief example seems to be a smart sensor. It is the analog or digital primary thermosensitive transducer combined with a processing unit and a communicating interface [3] and able to perform a row of smart metrological functions due to installed metrological software. This is intelligent sensor with a number of specialized algorithms provided in the design or installation stage, i.e. a sensor with such embedded algorithms that are necessary to provide implementation of the following specialized metrological functions. Namely, such functions include, f.i. the ability to realize automatic switching of sub-range of measurement, depending on input signal value; automatic self-validation, self-check, self-diagnostics and etc.; the introduction of adjustments when the action of impact factor takes place; linearization of metrological characteristic; compensation of cold-junction temperature for thermocouples and so on.

The major problem of CPSs operation is determined mostly by credibility of obtained information which depends as on sensors metrological reliability as well as on actuators precision and accuracy. The latter has to be gauged and control by a set of different sensors whose participation in the management is determined in the design phase or changes automatically by adjusting. Unfortunately these units become obsolete, and more importantly metrological characteristics drift up to mechanical failure. Possible consequence of running processes affect in lowering the quality of service/product.

According to current practice of standardization the traceability of measurements is provided by periodic calibrations (graduations, verifications, etc.). Then duration of the intercalibration interval defines the period of operation of the mentioned unit with a certain, previously accepted probability of mainly metrological or total failure.

The state of MI is usually verified by comparing with measure or standard, or by supplying electrical signal of reference value to its input, or by verifying the installed metrological software versus the checked one. Since two from three failures of MIs are caused by metrological failures and they usually precede major failures, increases the need for cost calibration procedures of every sensor within calibration period (~2-3 years) or its substitution. The latter may be unrealized for instance for temperature and pressure sensors of nuclear power plants. The special issue seems to be a necessity to suspend the production cycle aiming to provide the calibration of sensor(s). Unreliable information received from the MIs with the considerable drift of characteristics degrades the quality of the final product.

CPS technologies companies have to utilize the sophisticated metrology equipment for production lines. This involves the estimation of the comparability of CPS component MI by verification. Development of portable, highly-precise devices is able to provide in-place precision measurements. Chip-scale devices could be directly integrated into equipment to provide continuous quality control and assurance, freeing manufacturers and customers from complex measurement traceability chains and lengthy calibration procedures.

For metrological calibration of MIs usually one applies the direct measurement by the verified MI of outgoing signal of multivalued measure with determination of the error as a difference of its readout and mentioned signal. Correction methods of systematic error constituent are realized by operator impact or automatically in offline mode when, for example, self-calibration is carried out [4]. For CPSs operation is important not only equipping them with the MIs, but also providing CPSs by reliable information. For these information and measuring subsystems the periodic verifying the certain parameters is assumed.

4.1. Major Metrological Characteristics of CPSs and Their Units

Each of the following factors entails that the results of measurements differ from the true values of the measurands. The quality of measurements deteriorates, and thus the quality of CFS gets worse. These factors are the next [5]: problem of object model and the measurand (it is due to simplification of measurement procedures as well as experimental and theoretical generalizations that results in idealization of object properties); mutual influence of object and MIs (for example caused by placing the sensor at the facility); imperfection of MIs (among all other possible factors deteriorating quality of measurement result, the instrumental factor is always available); calibration of MIs (is considered below); conditions of measurement (almost impossible to determine accurately the impact functions or their values as they may by unstable over time); dynamics of variables (significant influence on the dynamic characteristics of measurands is observed in nanotechnology); mathematical simplification of sensors transfer function; volume of measurement data and conjugated computing problems (too small array of experimental data can lead to misconceptions about the course of the considered process and, conversely, too big amount of data may result not only in low-quality changes weakening and in loss of reliability of controlled parameter, so it can be resolved involving cloud technologies).

4.2. Interpretation of Measurement Results within Different Approaches

Errors approach produces established way to the classification of errors based on their specific properties. This separation of errors defines methods of reducing their impacts and results assessment. Errors can depend or not depend on the value of measurand. In this regard the additive, multiplicative and nonlinear errors are distinguished. Additive one is independent on the value of the measurand, and the amendment is algebraically added to the measured value. Multiplicative error increases or decreases linearly with measurand increasing; it is proportional to the product of certain factor (positive or negative) and the measured value. Nonlinear errors nonlinearly depend on the measured value. The ultimate goal of the measurement errors analysis is just assessment of boundary errors in which they are located with a certain probability. Then measurement result with intervals determined by these error boundaries with given probability, covers the true value of measurand.

In *uncertainty approach* of measurement result [6] on the one hand does not use the concept of true quantity value because it is unknown, and, on the other hand, implements a unified approach to quantitative assessment of results quality regardless of origin and method of various factors impact on the measurement result. Another quantitative characterization of measurements quality, namely uncertainty of measurement result, is introduced. Although, most of the errors approach principles are successfully utilized in hidden form. Thus both methods rely on the use of source distribution density that causes the outcome. Standard uncertainty is the uncertainty of result expressed by standard deviation. It may also be given in the form of dispersion as the square of the standard uncertainty. The standard uncertainty of type A is calculated by statistical processing of the results of series of successive observations. The standard uncertainty of type B is calculated other than in statistical way, for example basing on a priori specified source of uncertainty density distribution. The combined standard uncertainty is uncertainty that is determined in case if during measurement the effect of several uncertainty sources is simultaneously revealed or if obtained result is a certain function of other measurement results. The combined uncertainty is defined as the square root of sum of the squares of the particular standard uncertainties for the appropriate weight factors and eventual statistical relationship (correlation) between uncertainty components.

Hybrid approach of measurement result evaluation [7] that combines the error approach and uncertainty approach turned out to be the next step in the development of an integrated assessing the measurements accuracy. According to it, error is considered as the measurand with uncertainty determined by the assessment (evaluation or calculation). It reveals the possibility of simultaneous application of error and uncertainty approaches, which corresponds to hybrid approach of measurement result evaluation and assessment. To wit, an error is being calculated and evaluated as a physical value whose particular coefficients are defined with some uncertainty (Fig. 1).

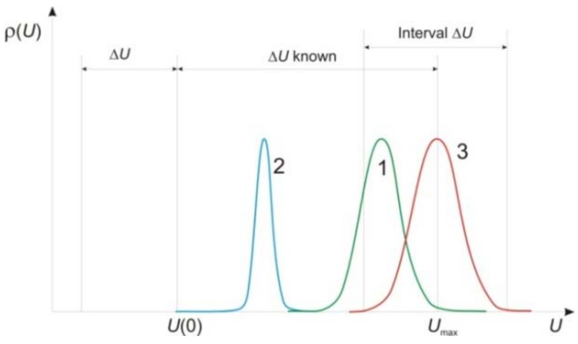

Fig. 1. Threshold weight of summary error and its uncertainty of result (3): systematic component due to impacts of MI and fluctuation of its properties (2); similar factor due to influence of thermometry-processed object (1).

Hybrid-thermodynamic approach of measurement result evaluation [8] is an extension of the hybrid approach towards consideration of the origins of fluctuation deviations in metrological characteristics on statistical-thermodynamic basis. Hybrid-thermodynamic approach of measurement result evaluation implies researching the total error of a temperature transducer with involving Non-equilibrium thermodynamics. In this case the threshold value of cognizable component of instrumental error systematic constituent is determined as the additive totality of multiplicative pairs of influence functions and their coefficients. Hereby, the pairs are formed so that one of the multipliers is determined by fluctuations of thermometric substance properties, and another – by that of applied outer field parameters. It corresponds to the content of Fluctuation dissipation theorem of Irreversible thermodynamics.

Hybrid-thermodynamic approach of measurement result evaluation has been developed consequently aiming to decrease the issues of MI intrusion and to improve the measurement accuracy of micro-, nano-object temperature. It roots in the threshold value determination of an instrumental error systematic component as an additional totality of influence-functions' multiplicative pairs (see below). However assessments of the origin of errors and uncertainties, based on thermodynamics, form the basis of hybrid-thermodynamic approach of measurement result evaluation. Its main reason roots in the next: the measurement result evaluation is quite good elaborated for macroobjects, having not been even established in the case of nanosamples. Nowadays the hybrid-thermodynamic approach of measurement result evaluation concerns with the study of origin sources of particular errors and influence functions and effectively applies in complicated cases of metrological reliability evaluation of measuring instruments. In particular, the research of energy-transmission processes, based on statistical thermodynamics, enables us to determine a methodical error component as well as cognizable part of systematic component of an instrumental error component, and thus to decrease substantially the guaranteed by the producer of thermometric means a total error of measuring the temperature in exploitation conditions.

Here the accepted IMC approach has been modified by the way of cognizing the certain components of an instrumental error through the extraction, study and evaluation of the factors influencing a MI, on the basis of statistical thermodynamic nature of their formation. The results of thermometric substance fluctuation concerning the summary influence function $\delta T_{Met\_\max} = K_{\Sigma}$ of thermoelectric transducers at presence of external thermodynamic fields are determined as $K_{\Sigma}=(K_X+K_M)K_T$, where K_X; K_M; K_T are the chemical, mechanical and thermal influence functions respectively caused by specific transport processes created by the external effect in thermometric substance. At the availability of fluctuations, additional impact functions (temperature, density, strain and etc. gradients) multiplicity the influence actions related by the fluctuation effect of external environment up to: $K_{\Sigma}[F(T, p, V,\ldots, t)] = (K_X K_P + K_M K_{П}) K_T K_E$, where K_P; $K_{П}$; K_E are the recrystallization, porous and entropy influence functions respectively.

Joining in the pairs, where one of the multipliers is defined by the fluctuations of thermodynamic substance properties, and another – by those of the parameters of the applied outer fields caused by the thermometry-processed object, meets the content of the fluctuation-dissipation theorem of thermodynamics. This approach is quite precious and allows determining the recognizable component of systematic error component of MI reducing significantly the guaranteed instrumental error.

The combined impact function of temperature measurement is defined within received by summation coverage interval:

from $\pm(\frac{K_P+K_\Pi}{K_X+K_M}+\frac{K_E}{K_T})$ in the presence of two independent systematic constituents;

by $\pm(\frac{\sqrt{K_P^2+K_\Pi^2}}{K_X+K_M}+\frac{K_E}{K_T})$ for the correlated constituents;

to $\pm(\frac{\sqrt{K_P^2+K_\Pi^2}}{K_X+K_M}-\frac{K_E}{K_T})$ for uncorrelated values ($C_{cor}=-1$).

As result, thermotransducers with the foreseen and managed value of an instrumental error are developed on this basis. Thus firstly, the decrement of unrecognizable error component of nanoobject temperature measurement (absolute values, covering intervals and so on) has been reached, and secondly, the fluctuation restrictions of statistical physics for the improvement of metrological characteristics have been employed.

4.3. Reliability of Measurements

One of main metrological characteristics of MIs at periodic verification is reliability of measurement parameters that indicates the probability of unexceeding by measurement error value the permissible values with a certain probability $P(\Delta_\Sigma \le \Delta_{al.}) \ge P_{conf.}$, where P is an actual value of probability; Δ_Σ is the results total error obtained by means of selected measurement units; $\Delta_{al.}$ is the maximum allowable error of measurement result; $P_{conf.}$ is the given value of confidence. Impossibility of establishing the measurand true value and accurate determination of measurement error as well as difficulty of taking into account all the possible destabilizing factors have contributed to the creation by IMECO the normative documents. To evaluate the measurement quality, the last applies the term "uncertainty" of received results, and also the recommendations to ensure the quality of both MI and of actual CPS performance or its final product.

5. Techniques for Accuracy Improvement

Universal techniques of errors identifying do not exist, because there is a wide variety of measurement methods, MIs, and conditions. Therefore, it should be carefully study the impact factors during the preparation of measuring experiment.

5.1. Methods to Improve the Accuracy, Errors and Examples of their Reduction

There are developed a lot of different methods for improving accuracy that are divided into three groups: methods of prevention of errors arising; methods of reducing the current errors; techniques of methodic errors reduction.

The first group includes structural and technological, protective and preventive methods. They prevent the occurrence of the error or do not allow it exceeded the permissible value. These methods base on the use of elements and components of highest quality with the most stable parameters. F.i. to reduce the temperature error, apply temperature-independent resistors. Protective and preventive methods reduce the impact of external factors and consist in diminishing their impact on measuring instrument. Examples of such methods are: temperature control; magnetic or electrostatic shielding; stabilizing the power supply.

5.1.1. Methodical Error

Methodical error of electric noise research caused by the improper technique or measurement means is one of determined components of methodical error that is due to the impossibility of increasing the integration time or bandwidth Δf for selective filter. It results in the dependence, f.i. in the close to cubic dependence of power spectral density (PSD) $S_\omega(f)$ on frequency. The main reason is the Hrenander uncertainty principle: $t\Delta f = Const$. According to it, narrowing the filter bandwidth requires longer measuring duration, thus there remains the same referred component of an error. The shortening the bandwidth at fixed duration or reducing the duration at fixed bandwidth of filter results in the significant uncertainty of noise measured PSD.

- ***Methodical error of electric noise research caused by the performance linearization*** while processing is a component of measurement error due to imperfect method or object discrepancy of model adopted for the measurement. More precisely it is caused to insufficiently correct interpretation of experimental results while further processing or to their imperfection.

Stochastic systems are characterized by PSD $S_\omega(f)$, proportional to $1/f_\gamma$. This is the flicker-noise. Experimental data have revealed that PSD could be defined as: $S_\omega(f)=\frac{\alpha}{f^\gamma}$, where α is the constant; γ=0…3. For instance, our research has concluded γ=2.8 at the frequency band 3-12 Hz and γ=0.5 at 12-17 Hz for *Pt*; and γ=2.28 γ=0.9 for oxide resistor respectively. Considering the problem of thermal and low-frequency noises, we discuss the peculiarities of electron-phonon interaction by applying different approximations, regarding the possible types of adequate descriptions.

The measuring and processing of experimental results suggest the invariance of PSD noise $S'_\omega(f)$, cut by a filter within the certain bandwidth Δf. Thus, it does not take into account that PSD $S_\omega(f)$ is represented by the expression: $S_\omega(f)=\lim\limits_{\Delta f\to 0}\frac{P_{el}(f,\Delta f)}{\Delta f}$, where $P_{el}(f,\Delta f)$ is the PSD at the frequency band from $f-\Delta f/2$ to $f+\Delta f/2$ reduced to approximation equation: $S'_\omega(f)\approx\frac{P_{el}(f,\Delta f)}{\Delta f}$. As a result, the additional error appears caused by the linearization of previous expression by the last one. It strengthens significantly the character of PSD dependence at frequency approaching to 0.

Conducted analysis for PSD spectral distribution by Debye model approximation has shown that error $\delta S_\omega(f)=C/f^2$ is methodical one. That is, the measured dependence of PSD noise $1/f$ is quadratically related to the frequency. Einstein model approximation within which the temperature dependence of PSD is absent (the case of thermal electric noise) allows to get rid of the methodical error $\delta S_\omega(f)=0$.

- ***Methodical error of temperature measuring in micro- and nano- world*** is an error caused by raising the significance of energy-transmission processes in the system "thermometer – controlled object" with decreasing sizes of object as well as thermometer.

Less the object we deal with, the more considerable methodical error of temperature measuring in micro- and nano- world is. Due to the intervention of sensor in energy exchange with controlled object it affects the gauge exactness, causing the emerging systematic component of methodical error. During prolong mutual contact of sensor and controlled object, while measuring, there was facilitated the determination of relative methodical error δT_{met} of temperature measurement, caused by heat transfer: $\delta T_{met}=\frac{(abh)_{sens}}{(ABH)_{ob}}$, where a, b, h are the linear dimensions of sensor, and A, B, H are the same of object. Hence, the relatively smaller sensor of measuring instrument, the smaller relative methodical error of temperature measuring. As result of prolonged thermal contact of warm sensor and cold controlled object, the latter is heated and the sensor is cooled, fixing the situation of heat exchange: $c_{ob}m_{ob}(T_x-T_0)=c_{sen}m_{sen}(T_{sen}-T_x)$. Here T_0 is the temperature of controlled object before measurement; T_x is the temperature of controlled object, which has established thermal contact with the sensor; T_{sens} is the initial temperature of sensor; c_{ob}; m_{ob}; c_{sen}; m_{sen} are the specific heat and mass of the object and the sensor respectively. In this case, the sensor measures the averaged temperature of "controlled object – sensor" over the initial temperature of the first one.

Error depends on the ratio of volume or linear dimensions of sensor and controlled object. Let us consider that at comparable thermal characteristics of the object and the sensor ratio of the volumes will be 1:1 (Fig. 2(a)), 10:1 (Fig. 2(b)) and 1:10 (Fig. 2(c)).

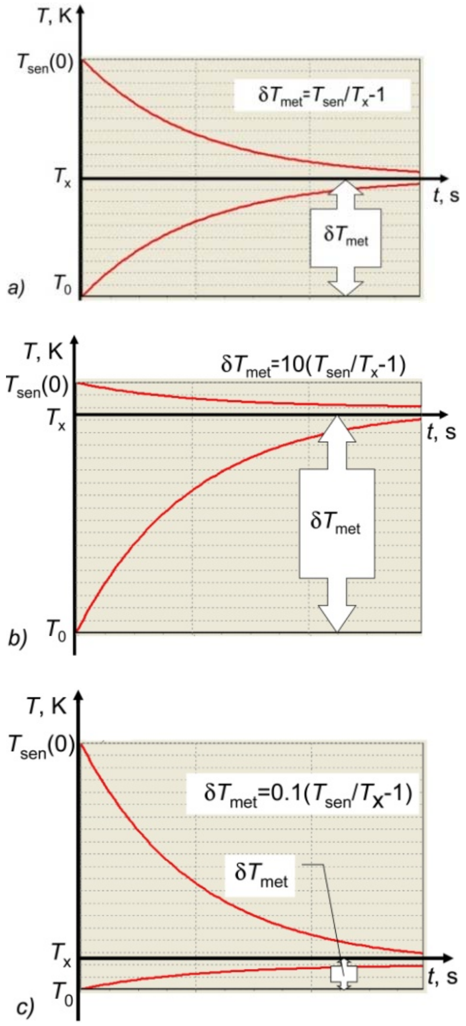

Fig. 2. Temperature vs. time changes of sensor cooling and object heating during their prolonged thermal contact: a) $c_{ob}w_{ob}V_{ob}=c_{sen}w_{sen}V_{sen}$; b) $10c_{ob}w_{ob}V_{ob}=c_{sen}w_{sen}V_{sen}$; c) $c_{ob}w_{ob}V_{ob}=10c_{sen}w_{sen}V_{sen}$.

Thus, the sensor changes smoothly over time its own temperature from T_{sens} to T_x measuring the temperature of the object with a certain error.

Expressing mass via specific density of matter w and its volume V and taking the object and the sensor uniform discoid shape (diameter D; d and height H; h, respectively), we obtain the equation of energy balance during prolonged contact of sensor and controlled object: $c_{ob}w_{ob}D^2H\Delta T_{met}=c_{sen}w_{sen}d^2h(T_{sen}-T_x)$. Dividing in $c_{ob}w_{ob}D^2H$ the left and right sides, we receive a relative methodical error of measurement:

$$\delta T_{met}=\frac{c_{sen}w_{sen}V_{sen}}{c_{ob}w_{ob}V_{ob}}\left(\frac{T_{sen}}{T_x}-1\right)=\frac{c_{sen}w_{sen}d^2h}{c_{ob}w_{ob}D^2H}\left(\frac{T_{sen}}{T_x}-1\right) \quad (1)$$

Measurements of bulks assume by default that a sensor linear size does not exceed 0.1 linear size of controlled object, and the ratio of their volumes – 0.001. That defines a relative methodical error of measurement no higher than 0.1 %. This value loses in combined measurement error, including the instrumental constituent. So therefore is possible not to consider methodical error of temperature measurement. For nanosized sensors and controlled objects with comparable thermophysical properties (Fig. 2(b)) relative methodical error is specified as $\delta T_{met} = \frac{T_{sen}}{T_x} - 1$ F.i., while controlling microobject temperature 270 K by commensurate-sized sensor of temperature 300 K, δT_{met}=0.11=11 % was received. This concerns the methodical errors in nanoobjects temperature gauging with help of nanosized sensors.

5.1.2. Random Error

The notion “random” indicates that the measurements are inherently unpredictable and their results vary nearby the true value and are inherent in average deviations equal to zero for repeated measurements, performed several times with the same MI.

- ***Random error of temperature measurement with help of gas sensor*** is random error which value is determined by volume of the gas thermosensitive substance. This error decreases to 0 if volume of thermosensitive substance of sensor increases, and vice versa it increases if volume decreases. As the latter is mainly known (at Avogadro number 6.02×10^{23} *mol.*$^{-1}$) it enables to express the equation with indication of numbers of gas moles n in sensor sensitive element: $D[Q] = C_w m \frac{T_1^2}{nN_A}$, where m is the mass of thermosensitive substance. In the case of conversion to standard units of volume the next formula can be used $n = \frac{V}{22.4}$, where V is the concrete value of gas volume that is determined in m^3. Then we change the form of last equation to: $D[Q] = C_w m \frac{T_1^2}{N_A} \cdot \frac{22.4}{V}$.

Calculation of error that is specified by decreasing sensitive element chamber dimension can be done by the impact of temperature fluctuations or of heat quantity fluctuations. Root-mean-square deviation of heat quantity as function of chamber volume of sensitive element is: $\sigma[Q] = \pm T_1 \sqrt{\frac{22.4 C_w m}{V N_A}}$. Relative root-mean-square deviation is equal to: $\delta\sigma[Q] = \pm\frac{\sigma[Q]}{Q} = \pm\frac{T_1}{T_2 - T_1}\sqrt{\frac{22.4}{C_w m V N_A}}$. Having substituted value of constants in it we simplify the equation to: $\delta\sigma[Q] = \pm\frac{6.1\cdot10^{-12} T_1}{T_2 - T_1}\sqrt{\frac{1}{C_w m V}}$. Received results of dependence of relative root-mean-square deviations of heat quantity on the volume of sensor element under different mass indexes of its copper walls are demonstrated in Fig. 3. Here is demonstrated that under significant decrease of fire sensor sensitive element dimensions (to 4 ml), the relative root-mean-square deviation increases to ±0.007 %. Such value of random error is admissible for fire technology, where due to sensor sizes thermal inertia index is ≤ 1 s.

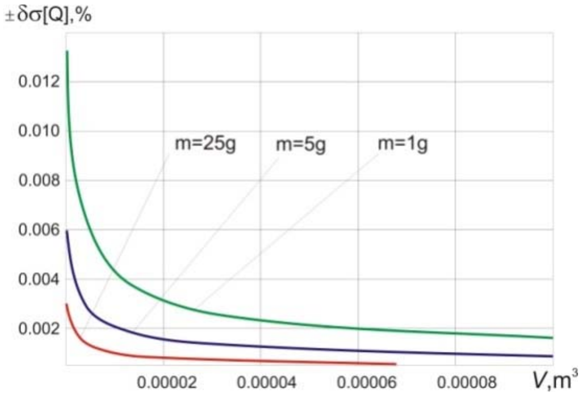

Fig. 3. Dependence of relative root-mean-square deviations of heat quantity *δσ[Q]* on volume *V* of sensitive element.

- ***Random error in noise measurement*** is an error that emerges in obtained results and its value varies while performing the repeated measurements of the same quantity.

The source of random error appearance could root in the influence of proper noise of measuring systems, interferences and etc. The estimation of random error could be made due to the variance D or standard deviation $\sigma = \sqrt{D}$ of the received results. One of the methods of reducing a random error is the averaging of measurement results, particularly with the N-fold increase in the quantity of gauges, the standard deviation σ_{av} at $\sigma_x = \text{const}$ decreases: $\sigma_{av} = \frac{\sigma_x}{\sqrt{N}}$. A random error could be reduced by enlarging the number of gauges just to the some extent. The matter is that random error is also considerably influenced by the state of object of measurement, namely thermodynamic state when the values of object parameters are the functions of time.

All these processes are specially complicated at the reducing of object size to a nano-area. In the case of the single measurements of unique properties, especially in nanotechnology, the theory of uncertainty could become expedient. Here the evaluation of a result is supposed to be made with some uncertainty determined by the effect of the same impact factors. Within the framework of an uncertainty approach the expounded above results could be reduced to the extended standard uncertainty of the type A by introducing the factor $1/\sqrt{3}$.

- ***Random error in temperature measurement.*** Let us consider the possible realization of concrete gauge of certain duration concerning the object that is characterized by the given relaxation time. The most trivial case seems to be the study of relaxing thermometric properties, e.g. the research on fluctuation-dissipation changes in thermoelectric thermometers depending on annealing time at high temperature. Those changes are exponential, and we can reduce the coverage interval of transformation function drift by lowering the values of random error and increasing the reliability of measurement.

So, we may consider the response of substance as linear. Then the power spectral density (further PSD) $S_\omega(f)$ of the fixed fluctuations is proportional to the spectral absorption coefficient (Debye model): $S_\omega(f) = k_p \Pi_\omega(f) = \frac{k_p}{2\pi f}$, where k_p is the coefficient of measuring system power transfer. To wit, in consequence of stipulated application of Debye model, the frequency dependence of PSD appropriate for *1/f* noises is gained. Stationary random processes with *1/f*–spectrum are characterized by the critical dynamics and scale-invariant fluctuation distribution. In those systems the energy of fluctuations could be accumulated at the low frequency bandwidth, increasing the probability of emergency emissions.

In the case of Einstein model, at the concentration of phonon energy on physically elementary volumes – tensile quasi-defects – an absorption coefficient is found: $\Pi = \frac{n'\hbar\Delta\omega}{2\pi k_B T} = \frac{n'\hbar\Delta f}{k_B T}$, and spectral absorption coefficient is proportional to PSD: $\Pi_\omega(f) = \frac{\Pi}{\Delta f} = \frac{n'\hbar}{k_B T}$

Here $\Pi_\omega(f)$ is frequency-independent which corresponds to the case of thermal noise. Experimentally fixed square character of *1/f*–noise PSD could be caused by an instrumental measurement error; then the higher level of degree dependence up to cubic one would probably be related to the restriction of frequency-time analysis range and integration of gained signal at the measurement of substance remaining in a non-stationary disequilibrium thermodynamic state.

- ***Random error, dependent on quantity of noise measurements;*** it is a value that decreases with increasing the number of measurements in different ways depending on the type of noise. That is notified (Fig. 4) for “white” noise (WN), flicker-noise (FN) and “white” noise with a flicker-component (WN+FN). We can see there that the averaging of the results of 100 gauges produces the 10-fold reduction of the error in the case of “white” noise, ≈1.2-fold reduction in the case of flicker-noise and ≈1.4-fold reduction for “white” noise with flicker-component. Thus, the random error could be reduced to the negligible value only if the spectrum of the measured value is the same within the frequency bandwidth from 0 to super high frequencies.

The results of real measurements are represented below. Hereby, the interval of time between results of measurement is chosen from condition: $\Delta t = \frac{1}{f} = \frac{1}{2f_h}$, here f_h is the upper frequency in spectrum of measured value. Most gauges are made in the static mode of the measured value, hence $f_h \to 0$ and the flicker-component becomes of importance in the spectrum. Hereby, the error of measurement could not be reduced to infinitesimal value by the method of averaging the results of measurement.

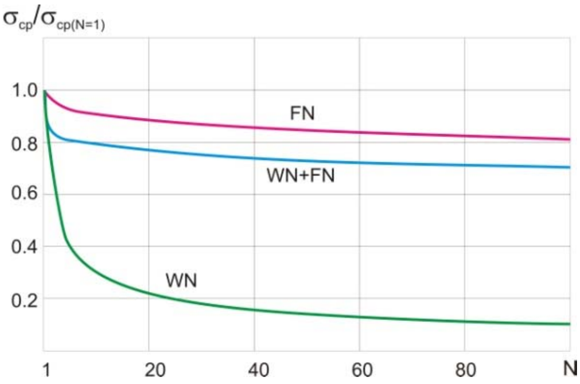

Fig. 4. Random error dependence on the number of gauges at f_h=10^{-6} Hz and Δt=1 s for different types of noise.

5.1.3. Duration of Noise Signal Gauging

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

Such integral characteristics of random process as the mean of a square (variance in statistical investigations), root-mean-square (standard deviation) and spectral density of noise signal tend to be measured firstly. Since the noise signal is a random process, its true value could be gained during the infinite time of averaging. Any restriction on the averaging time leads to the appearance of a methodic error. In the ideal case, if there are no other noise signals excepting the measured one in the measuring circuit, the standard deviation of noise signal variance σ could be calculated as: $\sigma \approx \frac{1}{\sqrt{t\Delta f}}$, here t is the time of measurement, Δf is the bandwidth of noise signal. Results of modeling the dependence of standard deviation of noise signal variance on the time of averaging at the different values of bandwidth Δf are notified in Fig. 5.

To reach the relative root-mean-square value of the variance of noise signal 0.01 % for the bandwidth Δf = 100 kHz, we should conduct measurements for 1000 s., and for Δf = 1 MHz – 100 s.

Taking into account that other sources of noise signals (resistance of a connecting line, amplifiers, and feedback resistors) are present in the input circuit, the dependence of root-mean-square of noise signal variance on time of averaging becomes more complicated. Time of measurement for reaching the equal error rises as compared to an ideal case. Correspondently, measurement of integral characteristics of noise signals could take a lot of time for averaging – up to tenth – hundredth of seconds.

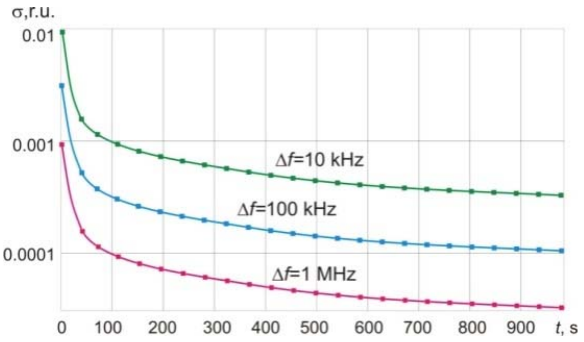

Fig. 5. Dependence of a standard deviation of a noise signal variance on the time of averaging.

If there is a necessity for measuring the integral characteristics within narrow bandwidth, the time of measurement rises considerably. So, to reach the relative root-mean-square of noise signal variance 0.1 % at the bandwidth Δf = 10 Hz, measurement should last approximately 30 hours.

5.2. Accuracy of Raman Thermometry

Raman thermometry is elaborated insufficiently due to the novelty and uniqueness of method. This problem is considered below basing on error, uncertainty and other approaches of metrology.

Within error approach, Raman thermometry considers few components of the combined error of temperature measurement. The first one is instrumental and could be determined by the accuracy of measuring device. The second one is methodical and is caused by heating the object during the process of measurement. There exists the third component that is also of instrumental type and is related to the changes in feeding parameters during the measurement. There is also the forth component caused by the instability of a surface and adjacent layers as result of light beam effect (close to drift error).

Instrumental error with systematic and random components is caused by the fluctuation of number and frequency of scattered, especially anti-Stocks quants. To reduce this error, is necessary to perform the signal time-averaging. At light exciting within Raman method with lasers of different wavelengths these effects are expressing themselves in various ways. Therefore the instrumental errors are distinguished at different wavelengths. While using two lasers different wavelengths we gain two diverse instrumental errors with different results dispersion.

Errors of photocurrent measurement depend on metrological characteristics both of laser and spectrometer. Moreover, their stability is quite important: there exist instabilities caused by the errors of setting and determining the certain value of irradiation. Fortunately at serial measurements of anti-Stocks and Stocks signals the given error components compensate each other. Under the condition that photo detector sensitivity at Stocks and anti-Stocks frequencies slightly differs we could adopt that $\delta_{is} \approx \delta_{ias}$. By neglecting the slight deviation of SL 03/1 laser frequency with the wavelength 632.9910 ± 0.0002 nM, we could advance that the instrumental error is defined as:

$$\delta T = \frac{2}{Z} = \frac{2}{\ln {}^{i_{as}}\!/_{i_s} - 3\ln\frac{\nu_i - \nu_0}{\nu_i + \nu_0}}, \qquad (2)$$

where i_{st} and i_{as} are the intensities of Stocks and anti-Stocks components of scattered radiation respectively, ν_0 and ν_i are the wavenumbers of reflected phonons at the given number of dispersed phonons and used laser bunch respectively.

Methodic error related to heating the researched object by laser irradiation depends on its surface energetic luminosity. Even the effect of under-powered laser leads to surface heating and arising methodic error (~27 K), which could reach much larger values for small objects. We should indicate that methodic error as well as instrumental one encloses the cognizable and incognizable components (Fig. 6).

The drift is caused by the changes both in the chemical composition and surface shape of measured object as consequence of intensive irradiation. It is related to complicated transform processes in surface-adjacent object layers and is attributed to the systematic component of instrumental error. Apart from it, the latter is treated as partly cognizable due to its different influence factors. Their estimation is carried out involving the thermodynamics of irreversible processes: the more intensive irradiation and the larger methodical error are, the stronger entropy changes and the larger drift occur. To reduce this error, the known in metrology method of nearing to measuring point from both sides could be successfully applied.

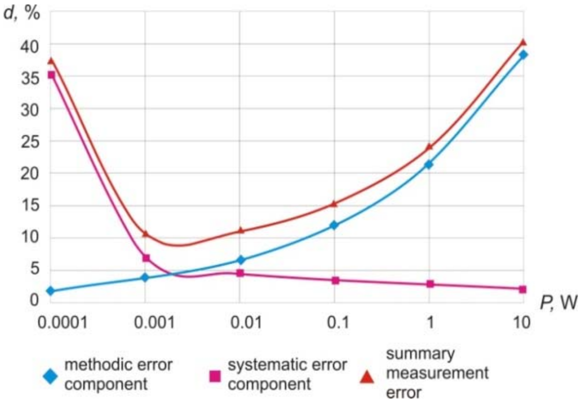

Fig. 6. Optimization of methodic and instrumental components in decreasing the combined error of temperature measurement at laser power 2 mW.

Adopting that under the condition of linear alteration in time the calculated frequency of reflected anti-Stocks component becomes such a point. So in order to get rid of drift, becomes necessary to measure the Stocks frequencies before and after measuring the anti-Stocks frequency, and then to average the Stocks frequencies results.

Within uncertainty approach in Raman thermometry, the measurement of chips temperature in the process of their manufacturing has performed only once, since the next measurements are usually realized in other conditions. For one-time measuring an error approach is not quite adequate.

The estimating concept for measurement results could be based on the uncertainty approach. Here the methodic error is being calculated and evaluated as a physical value, which certain components and coefficients could be estimated with a certain errors. To wit, this component of the combined error is considered with particular uncertainty. We take into consideration peculiarities of both MIs and standard patterns. For instance, with help of Raman method the measurement of CNTs temperature within the range 30…250 ºC is made. These tubes are treated as standard nanopatterns for testing and calibrating the nanotechnological means. Hereby, to study the action of seven and more possible influence factors (angle of light bunch incidence, distance to a photo-receiver, exposure time, duration of spectrum passing, power and mode of laser operation, drift characteristics and so on), 28000 gauges have been performed, enabling us to ascertain the following indices of the measurement accuracy.

Approach of errors is applied to results processing, consequently of which one of the gained results (with introduced correction to systematic error component) looks as T_{real}=287.27 K±1.72 K (±0.6 %). At the same time, due to uncertainty approach, the gained result makes T_{real} =287.27 K with expanded error 0.58 % and combined standard uncertainty 0.3 % at the credence level P=0.95, expanded coefficient 1.96 and efficient value of freedom degrees 130.6.

5.3. Temperature Dependent Accuracy Threshold

Accuracy threshold is due to the fluctuation deviations in the processes which determine the metrological characteristics of the extra-sensitive MIs. Due to such great sensitivity, the accuracy threshold becomes temperature dependent since fluctuations intensity depends on temperature.

5.3.1. Accuracy Threshold of Sensitive Balance

Main constructive unit of torsion balance is a thin thread on which a light mirror hangs. It should be noticed the same part is the basis for a ballistic galvanometer construction. Molecules thermal motion of the environment leads to irregular in time molecules bombarding of the mirror that limits instrument sensitivity and not let to better the measurement accuracy. Thread torsion module is $a = \frac{\pi^2 d^2 G}{8l}$, where G is the shear modulus; d and l are the thread diameter and length. Then moment of force that effects on the thread is linked with rotation angle φ by the next ratio: $M=a\varphi$, and the potential energy of curled thread is $U = {a\varphi^2}/{2}$. In accordance with Boltzmann formula, the dispersion of value of angle close to which the mirror vibrates is equal to: $D[\overline{\varphi^2}] = D\left[\frac{\int_{-\infty}^{\infty}\varphi^2 e^{-a\varphi^2/2T}d\varphi}{\int_{-\infty}^{\infty}e^{-a\varphi^2/2T}d\varphi}\right] = \frac{T}{a}$. Obviously the root-mean-square deviation of this angle is equal to: $\sigma[\varphi] = \left(\frac{T}{a}\right)^{1/2}$. At room temperature when $a \sim 10^{-13}$ J, the mirror rotation angle root-mean-square deviation is determined as ~10^{-4} radian. This is a real limit of single measurement sensitivity for practically all MIs in nanometrology.

By the same way the fluctuations impact on metrological parameters of a spring balance with coefficient of elasticity k and equilibrium stretching X_0 is considered. Mass center oscillations occur in it as result of the temperature fluctuations presence. That's why counting of equilibrium position of the pointer X_0 cannot be made more accurate than with the root-mean-square deviation of absolute value of the instrumental error random component: $\sigma[X_0] = \sqrt{\overline{(\Delta X_0)^2}} = \pm\sqrt{\frac{T}{c}}$, where c is the constant that links mechanical qualities and sizes. On this basis let determine the root-mean-square deviations of absolute and relative value of instrumental error random component of mass determination:

$$\sigma[m] = \pm\frac{c}{g}\Delta X_0 = \pm\frac{k}{g}\sqrt{\frac{T}{c}},$$
$$\delta\sigma[m] = \pm\frac{\sigma[m]}{m} = \pm\frac{1}{mg}\sqrt{\frac{T}{c}} \qquad (3)$$

Hence the instrumental error random component is smaller as the spring is weaker. However in this case the equilibrium stretching increases: $X_0 = mg/k$. It specifies practical inconvenience of balance construction. Hereby temperature dependent fluctuations limit the metrological characteristics of balance.

5.3.2. Accuracy Threshold of Sensitive Ballistic Galvanometer

In electrical measurements, fluctuations specify the absolute error independent of MI perfection state. So far as the ballistic galvanometer is used as supersensitive mean for small values of impulse current measurement, it is considered in details. The galvanometer current *I* is measured by the mirror deviation angle φ. In equilibrium state when spring forces moment $c\varphi$ is equal to electromagnetic forces effect moment γI, the mirror rotation angle is $\varphi_0 = \frac{\gamma I}{c}$ (here c, γ are the constants).

Root-mean-square deviation estimation of the mirror rotation angle is in line by its content with the similar estimation of the instrumental error random component of spring balance (see p.5.3.1). In such a way it was derived the root-mean-square deviations of absolute and relative values of the instrumental error random component of the current determination:

$$\sigma[I] = \pm\frac{c}{\gamma}\sqrt{\frac{T}{c}}\,,\ \delta\sigma[I] = \pm\frac{\sigma[I]}{I} = \pm\frac{\sqrt{cT}}{\gamma I} \tag{4}$$

Hence for the galvanometer accuracy improvement it needs to take smaller value of constant *c* and higher value of constant γ (otherwise to increase the number of winds in the galvanometer current coil). This leads to the equilibrium angles φ_0 deviation that contradicts with springiness demands of the hanging thread deformation $\varphi_0 << \pi/2$. Therefore temperature fluctuations limit the galvanometer accuracy: $A=1/|\delta|$. Then the accuracy limit which can be gained in measurements is determined by assigned in advance sensitivity.

5.3.3. Dynamic Error

It is considered (on example of thermotransducer) as an error caused by heat inertia of transducer and inertia of measuring device, and is equal to the difference between transducer error in variable temperature mode and its static error.

Dynamic error emerges due to transducer not has enough time to follow the rapid temperature changes of controlled object. Exactly this delay characterizes thermal inertia index. If to consider that temperature in the cross area of transducer is uniform and heat removal and radiation exchange are absent, it becomes possible to submit the nature of change in temperature on the basis of elementary theory of thermal inertia for uniform transducer by expression:

$$\Delta T_{dyn}(\tau) = T_T(\tau) - T_0(\tau) = -\frac{1}{m}\cdot\frac{dT_T(\tau)}{d\tau}, \tag{5}$$

where $T_T(\tau)$ is the temperature of sensitive element of transducer, $T_0(\tau)$ is the object temperature, τ is the time, *m* is the parameter which characterizes the rate of heat exchange due to convection [9].

5.3.4. Instrumental Error

- ***Instrumental error of noise thermometer*** is a component of measurement error due to its intrinsic properties. It may contain few components, including error of measurement and the error caused by the interaction of transducer with the object of measurement. For example, 100 Ω (at 27.15 K) sensitive elements of noise thermometers were made from pure *Ni, Pt, Cu*; alloys (*Ni-Cr* and composites of various oxides). Research has been performed in reference points of ITS (4.2 K; 77 K…273.15 K) according to IMECO method, and at higher temperatures. Revealed deviations from linearity of calibration characteristics as the relative error δT increase from *Cu* (0.05 %) to *Ni* (0.26 %) sensitive elements. Mentioned deviations are not fixed for elements made from transition metal alloys and composites.

Analysis of measurement error of noise thermometer has shown the additional component existence that goes beyond a basic acceptable error. This error is caused by structural processes in thermometric element due to its manufacturing (bending, tension). The constancy of research temperature – 77 K – does not mean the thermodynamic equilibrium state of sensitive element and environment. The relaxation of nonequilibrium thermodynamic state depends on several factors (temperature, time, type and concentration of defects). Otherwise, condition of thermodynamic equilibrium, at which Nyquist formula is derived, has been broken in the case of a real noise thermometer wound at 300 K and used at low temperatures.

Temperature dependence of electrical noise power is derived directly from the basic equation of thermodynamics. In the stationary nonequilibrium state, the thermometer calibration characteristic nonlinearity appears due to violation of energetic processes of environment – thermometric substance exchange. It is expressed by the instrumental (absolute ΔT and relative δT) error as:

$$\Delta T = T_c - T_r = (b_c - b_r)P_{el}\,,\ \delta T = \frac{b_c - b_r}{b_r} = \frac{\Delta b}{b_r}, \tag{6}$$

where T_c and T_r are the estimated and real temperature, respectively; b_c and b_r are the constants of estimated and actual calibration characteristics. The prolonged use of a thermometer leads to maximizing the constant $b \sim (dS/dt)^{-1}$ at minimizing the entropy dissipative flow: $\frac{dS_\vartheta}{dt} = \frac{\Delta S}{\tau_p} = \min$. Nonstationary nonequilibrium thermodynamic state corresponds to the power change of nonequilibrium electrical noise in the elastic-plastic deformed thermometric substance.

Therefore its relaxation effects lead to error emergence. Substance of density ρ rapidly releases the previously accumulated elastic energy with appearing microcracks of length *2 l*. Thus, relaxation constant τ_l is estimated as $\tau_1 \sim l\sqrt{2\rho E/\sigma^2}$, where $\sigma^2/2E$ is the density of elastic energy. The latter can be transformed into surface microcracks energy with its relaxation constant τ_2: $\tau_2 \sim l\sqrt{\rho l / \gamma}$, where γ is the specific energy of surface tension; or removed from the relaxation place with constant τ_3, linked to thermal diffusivity a: $\tau_3 \sim l^2 / a$. At temperatures lower than 20-30 K, thermal diffusivity in 100 and more times is higher than at 300 K. So τ_3 is much smaller in comparison with the relaxation constant of motion τ_4 ($\tau_4 \sim \lambda / \omega$) or reproduction τ_5 of dislocations ($\tau_5 \sim (\frac{\rho l^3}{nL_d E_d})^{1/2}$). Here λ is the effective length of dislocation run; ω is the dislocation velocity; L_d is the typical size; E_d is the dislocation energy, referred to one interatomic distance.

Effect of the mentioned above constants $\tau_1 \ldots \tau_5$ is combined, and depends on the temperature and background of substance, forming the total relaxation constant $\tau_{n.st} = \frac{1}{\sum_{i=1}^{n} \frac{1}{\tau_i}}$. Consideration of competitive effects of constant τ_2 due to microcrack formation, and constant τ_3 due to heat removal from the place of energy relaxation produces the modified constant $\tau_{st} = \frac{\tau_2 \tau_3}{\tau_2 + \tau_3}$. The joint effect of these two mechanisms creates the reasons for changes in the electrical noise power and thus changes in the readings of noise thermometer. Hence, the error of thermometer, whose sensitive element is in stationary nonequilibrium state, is determined by the competitive action of two major in those conditions dissipation processes that form deviation from the calibration characteristics: $\delta T = \tau_2 / \tau_1 = A(ad)^{1/2} c / \chi$, where C is the sound velocity; a is the grain size; d is the atomic size, χ is the thermal diffusivity. Hence, the lower speed of sound and higher thermal diffusivity, the more efficient work mechanism for a heat removal and the less noticeable influence of dislocations on the electrical noise power and consequently on a noise thermometer error.

Described before concerns pure metals and is not related to alloys and composites due to significance of the process of dislocation multiplication (constant τ_5) that occurs in their blades and is accompanied with the microcrack formation. Finally, high temperatures up to a melting point are matched with diffusion removal at the relaxation constant τ_4. That is, in the high-temperature case, one should consider the competitive action of two relaxation mechanisms: diffusion mechanism and formation of microcracks in the deformed local substance microvolumes. Introduced before criterion is varied at the high temperatures to: $\tau_4 / \tau_1 \sim (ad)^{1/2} c / D$. Here coefficient of diffusion D which increases exponentially with temperature means deviations absence of calibration characteristics at high temperatures.

- ***Instrumental error of thermoelectric thermotransducer.*** Its study has been completed by elaboration of algorithmic principles of thermotransducer error minimization realized on basis of thermodynamic forces and fluxes consideration in sensitive substance (Fig. 7). Consequent evaluation of certain influence functions due to complicated transfer processes described by corresponding freedom degrees in basic equation of thermodynamics is realized. Preliminary algorithm settings comprise the values of:

1) Transformation function and its dispersion;
2) Temperature range, environment, exploitation time and mode;
3) Peculiarities of sensor substances and thermotransducers manufacturing.

Moving along the chart, from magnetic freedom degree, alternately estimate the effects of influence functions of all possible degrees on the transformation function.

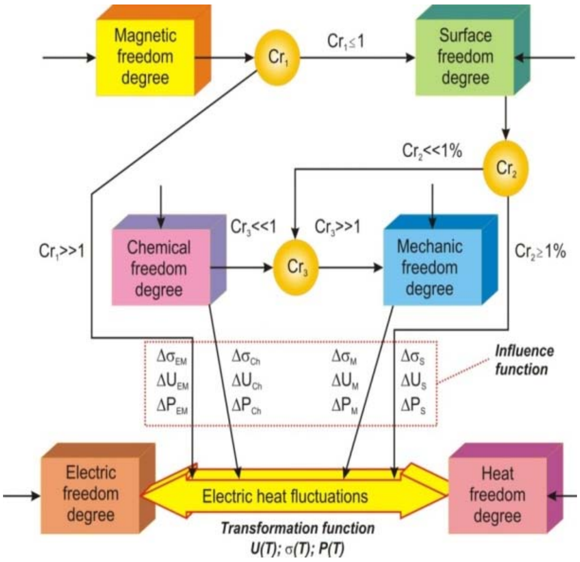

Fig. 7. Transformation and influence functions in thermotransducers: thermoelectric ΔU; resistive Δσ; noise ΔP.

6. Methods of Correction and Statistical Minimization of Errors

The mentioned methods are directed at reducing of already existing errors. Adjustment (or functional minimization) is considered to be the method that reduces errors, mainly systematic ones, by means of analytical or experimental study. Under statistical minimization we understand reducing the expected but not identified measurement errors; it is carried out both during and after the measurement (error reduction by spatial or temporal averaging). Examples include: reducing the random errors of the multiple measurement results by time or spatial averaging; reduction of quantization error [2].

For MIs calibration the direct measurement by verified MI of outgoing signal or by multivalued measure with determination of the error as a difference usually apply. Correction methods of systematic error constituent are realized by operator or automatically in off-line mode when, f.i., self-calibration is carried out.

Errors adjustment with the operator participation can be fulfilled in 2 ways. The first one is the calibration of MI (Fig. 8).

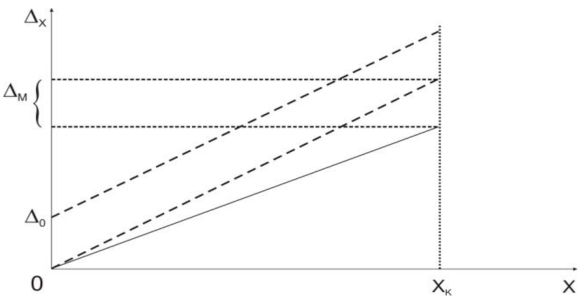

Fig. 8. Measuring instrument error adjustment by calibration [5].

To correct the dominant error additive and multiplicative constituents the instrument calibration is usually performed in two points of scale: at shorted input and at supplying the measure's output signal to input of verified MI. At shorted input, the operator sets the zero readouts of the mentioned device, then at connected measure with help of calibration unit sets the readout that corresponds to submitted value of measure.

Calibration without action on the measuring instrument is performed by introducing amendments, or during the measurement results processing. For example to correct error additive constituent, two measurements are performed; two indications are recorded: $y_1 = kx + \Delta_0$ and $y_2 = \Delta_0$, and the measurement result is computed as $y = y_1 - y_2 = kx$. Automatic correction aims the amendments introduction into device structure or into measurement algorithm.

There exist some specific measurements which include the next methods of error adjustments.

Auxiliary measuring method is the version of invariance principle, according to which are needed as many additional channels measuring as the impact values exist. *Iterative method* consists in the multiple specifying of adjustment results performed by successive approximations. Therefore it requires the precise feedback transducer. *Method of standards* establishes the real conversion performance by connecting a set of standards (or one multi-level standard) to input of MI.

When to turn off the physical quantity from device input or realize its set of measures is impossible, the test methods are applicable. The latest generate the test values involving both measured and model quantities.

6.1. Reducing the Methodical Errors

Due to complexity of setting the correct experiment, inevitably arise methodic errors caused by inadequate of considered method to real conditions of measurement. They can include an incorrect transmission function and mismatching the characteristics of different measuring instruments. To correct methodical errors, detailed study of conditions and nature of these instruments should be performed. To reduce some methodical errors, the special measurement methods have been developed: method of substitution, method of error compensation by sign, method of contradistinction, method of symmetrical observation, etc.

Method of substitution consists in submitting the initially measured value to input of measuring instrument. Subsequently this value is replaced by the appropriate measure of known value at which the readout of instrument remains unchangeable.

Method of error compensation by sign consists in double measuring of the same value at variable measuring conditions in a way that unchangeable systematic error would be included in the measurement result with the opposite sign.

Method of contradistinction consists in the double gauging the measured value; firstly it is compared with the value that is reproduced by measure; and before the second comparison these two values are mutually changed in measuring circuit. So, result of measurement becomes independent of the transfer factor of measuring circuit.

Method of symmetrical observation is as follows. First value X is measured, then after a time Δt full or partial substitution with measure of known value X_M is performed; over the time interval Δt measurements is repeated again. This excludes the permanent and linearly-dependent systematic error constituents.

6.2. Eliminating the Systematic Errors

During analysis of adjusting methods, the absolute value of the combined error of MI is conveniently to divide in three components:

– Additive component Δa, independent of X; it is also named "zero error" (it occurs if MI registers the certain readout when the latter should be zero) and causes concurrent shift of the MI characteristics; this kind of error can be easily detected at $X = 0$;

– Multiplicative component $\Delta_M = \delta_S X$, proportional to X. It is known as "sensitivity error" that causes the MI specifications rotation concerning the zero of coordinates; this kind of error be easily detected while applying the measure or scale transducer;

– Error $\Delta_{non\text{-}lin}$ of non-linearity of MI characteristics that non-lineary depends on X and may be efficiently detected while applying the multi-level measure or scale transducer in measuring circuit.

6.2.1. Common Methods

Amendments. Action of systematic and other regular (e.g., linear-increasing over time error or drift) influences on the received result is reduced by using appropriate types of result adjustment or by introducing the amendments. For this, a variety of methods is developed; most of them are based on performance of additional measurements with applying the so-called standard values, i.e. quantities with certified magnitude. Adjusted result (x_{am}) is obtained by adding to the measured value (x) amendment p which is equal to the corresponding systematic error component with opposite sign: $x_{am} = x + p$.

Introduction of amendments is compulsory for each stage of results processing. However, it is virtually impossible to fully explore the effects of systematic or regular impacts, at least due to the absence of ideal MIs, presence of random influences or time restrictions. Therefore complete correction of systematic effects is impossible. Error can be reduced by adjusting the results only if the relationship between the impact factor and output value is known.

Cold-junction compensator is a brief example of such device. It carries out the compensation of cold-junction temperature of thermocouple, or adjusts its shifted readouts. Electronic means can also compensate the similar errors for thermocouples of various types, and so reach the improvement of accuracy. Also, bridge scheme is designed so that, when changing ambient temperature and therefore cold-junction temperature, it could provide adding the voltage proportional to mentioned temperature to thermo-EMF.

Processing the Measurement Results. When $Y = kX + \Delta Y_a$, the additive error ΔY_a can be excluded by performing one additional observation at $X = 0$, and the following subtraction. If the additive error exists at $X = X_1$, the output value of device is equal to $Y_D(X_1) = kX_1 + \Delta Y_a$. Then at $X = 0$: $Y_0 = \Delta Y_a$. After subtraction we get adjusted value of measurand:

$$\begin{aligned} Y_{adj}\left(X_1\right) &= Y_{II}\left(X_1\right) - Y\left(0\right) = \\ &= kX_1 + \Delta Y_a - Y\left(0\right) = kX_1 \end{aligned} \tag{7}$$

Multiplicative error δ_m is excluded via single-channel fixed measure by calibrating the MI at the given value X_0 and subsequent dividing and multiplying: $Y_1 = kX$; $Y_2 = kX_0$, whereof $X = X_0 \dfrac{Y_1}{Y_2}$. If additive and multiplicative constituents of error in MI readings exist, they are also excluded via similar measure of fixed value by means of two additional measurements at X equal to 0; X_0. So, correct result Y_{cor} is defined by subsequent computing:

$$Y_{adj} = X_0\left(Y_2 - Y_0\right) / \left(Y_1 - Y_0\right) \tag{8}$$

In the case of nonlinear transfer function $Y = k_n(1 + \delta_s + \varepsilon X)X + \Delta Y_a$ of MI, the problem arises of selecting the optimal calibration value X_{Cal}. Firstly, you must reach the readout of MI at zero ($Y = 0$) for $X = 0$. During instrument calibration its transfer function is approximated by a linear dependence:

$$Y_k = k_n(1 + \delta_k)X_k = k_n(1 + \delta_s + \varepsilon X_k)X_k, \tag{9}$$

where δ_a is the adjusted relative error at $X = X_k$. Let us divide at $k_n X_k$ both sides of the equality and bring relative error of MI to input $\delta_k = \delta_s + \varepsilon X_k$. Its absolute error would be ΔX (Fig. 9):

$$\begin{aligned} \Delta X &= \frac{\Delta Y}{k_n} = \frac{k_n X(1 + \delta_s + \varepsilon X) - k_n X(1 + \delta_k)}{k_n} = \\ &= \varepsilon X(X - X_k). \end{aligned} \tag{10}$$

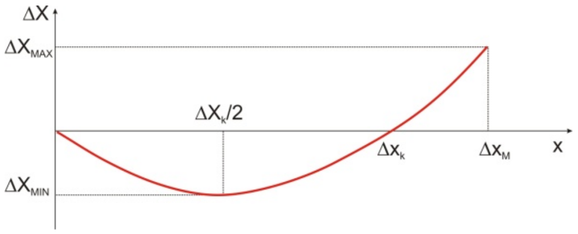

Fig. 9. Absolute error of MI reduced to input [5].

Minimum and maximum errors are respectively defined at the top of the parabola ($X = X_k / 2$) and at the end of measuring range $X = X_m$:

$$\begin{aligned} \Delta X_{\min} &= \frac{\varepsilon X_k}{2}\left(\frac{X_k}{2} - X_k\right) \\ \Delta X_{\max} &= \varepsilon X_m(X_m - X_k) \end{aligned} \tag{11}$$

The condition of minimizing error over the entire range of MI is $\left|\Delta X_{\min}\right| = \left|\Delta X_{\max}\right|$, and at $X_k = \alpha X_m$ we obtain quadratic equation $\alpha^2 + 4\alpha - 4 = 0$, the physical meaning of which has just positive root: $\alpha = 2(\sqrt{2} - 1) = 0{,}82$. So, for a quadratic approximation of transfer function of MI its calibration should be performed at the point $X_\kappa = 0{,}82 X_m$.

Calibration of Measuring Instruments is performed by changing its sensitivity, or by altering the tilt of its characteristic. It is especially effective at predominance of error multiplicative component and can be implemented by operator for circuits with measures, with working standard MI, or with model reverse converter and calculating unit.

If there is multiplicative error component δ_M, the equation for MI readout is presented as $\alpha = k_1 X = k_0(1 + \delta_m)X = k_0 X + k_0 \delta_m X$, here k_0 is nominal transfer factor. While calibrating (at applied to input of such device the measured value X_0), the operator changes factor k of device until at $X = X_0$ readout becomes equal to α_0. The last is usually marked on the scale with red tag, or corresponds to end value of scale. As a result of the calibration, coefficient becomes equal to $k_0 = \alpha_0 / X_0$.

Calibrating the MI with help of the working standard is mostly performed at X-value close to X_0. During calibration, the coefficient is changed as long till readout of calibrated MI do not match the readout of standard which (with model reverse converter and computing chip) is especially suitable for calibration of measuring transducers. While their calibrating, we change coefficient *k* till the error *Δp* in output of reader would be established at the zero. In this case, $X = X_k = {}^{Y}\!/_{k_0} = {}^{kX}\!/_{k_0}$.

6.2.2. Special Methods

Special methods for improving the accuracy are: by-sign-errors compensation; method of contradistinction; method of symmetrical observations; method of substitution [5].

- ***Method of Errors Compensation by Sign.*** Two measurements of the same value are fulfilled with such changeable measurement conditions, but in the second time, the unchangeable systematic error of measurement has to be included in result with opposite sign. So, in the measurement of voltage the result is received by two cycles (for identical and opposite polarities of additionally installed switches). Then if for measuring time the parasitic EMFs are immutable, the result becomes independent to their values.
- ***Method of Contradistinction.*** Measured value *X* is compared twice with adjustable measure X_K, and these two values (*X* and X_K) are swapped before the second measurement. For instance, classic metrological task is the definition of mass in inaccurate balance. Here the result of the measurement $M_x = \sqrt{M_{N1} M_{N2}}$ is derived, considering the system of two equations (Fig. 10):

$$\begin{aligned} M_x L_1 &= M_{N1} L_2 \\ M_x L_2 &= M_{N2} L_1 \end{aligned} \qquad (12)$$

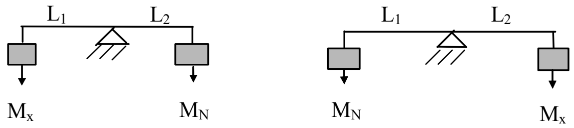

Fig. 10. Improving the accuracy of masses definition with help of inaccurate balance.

- ***Recent example of method application in stepless Z-shift regulation of nanomashines.*** During the creation of hydraulic positioning unit along the axis Z of nanomachine with providing stepless shift and position control possibility along this axis, it is suggested to use hydraulic potential. To this purpose the *U*-shaped hydraulic construction is proposed with ends of large (*D* = 20 mm) and small (*d* = 0.3 mm) diameter. Diameters ratio is equal to: $\frac{D}{d} = 66.66$. Spontaneous or enforced liquid level shift, for instance, in the small diameter tube, is detected by means of micrometer head (Fig. 11).

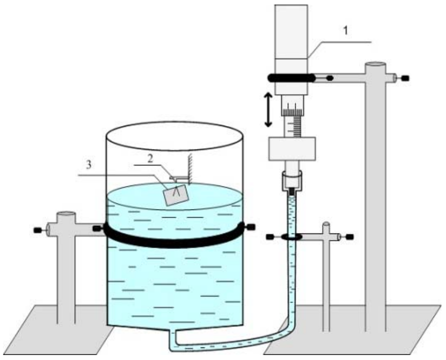

Fig. 11. The unit of nanosized objects hydraulic positioning: 1- shift micrometer head; 2 – cantilever; 3 – float with mounted research nanoobject.

In the motionless fixed tube its pivot sinks by the shift micrometer head pressing hydraulic liquid to the wide cylinder. Consequently the liquid level is increased in this end – on Δh_1. It results to weak but appreciable liquid level increase in the wide end. In accordance with joined vessels law the level increases on ΔH_1 in the wide end. Floating plate mounted in this wide end lifts the same as the studied nanoobject mounted on it. In this case the condition of liquid quantity invariability under pouring from one end to another one can be described by: $\frac{\pi}{4} D^2 \Delta H = \frac{\pi}{4} d^2 \Delta h$, we use $A = \frac{D^2}{d^2} = 4444.4$ as constant for this unit construction. So, we have got the formula specifying the level drops changes in wide (ΔH_1) and narrow (Δh_1) device ends, as $\Delta H_1 = \Delta h_1 / A$. With respect to the error approach [6] the relative errors of liquid level change in both device ends are linked between each other by: $\delta(\Delta H_1) = \delta(\Delta h_1) + \delta A$, where $\delta(\Delta h_1)$ is the relative error specified by the inaccuracy of the drop level measurement by the micrometer head; δA is the relative error specified by the inaccuracy of value *A*.

The first error component is determined by the following way. So far as liquid level measurement drop in the narrow end is 5 µm, then the device measurement step is determined in the wide end is 5.0 µm /4444.4 = 1.1 nm. Micrometer head absolute error in accordance with passport is ± 2.5 µm. Its value included to the result of the level shift in wide end is ± 0.55 nm. The step measurement refinement result is equal to 1.10±0.55 nm. In the case of liquid level shift gauges in the narrow end with error ± 1.0 µm, it seems possible to reach the relative measurement error of hydraulic shift ± 20 %.

Hereinafter the unknown second component of the MI error – the relative error of constant *A* value determination – is considered below.

Metrological experience of error systematic component minimization. Method of contradistinction can be used for accuracy improving by multiplicative error component minimizing. Its peculiarity consists in that the measured quantity H_X is compared twice with regulated measure - $H_{N1}; H_{N2}$ (before the 2nd measurement it is rearranged with the measure). Consequently this quantity value with the eliminated measurement error multiplicative component can be gained: $H_X = \sqrt{H_{N1} H_{N2}}$.

To realize the multiplicative error component minimization we perform the hydraulic device calibration (Fig. 12).

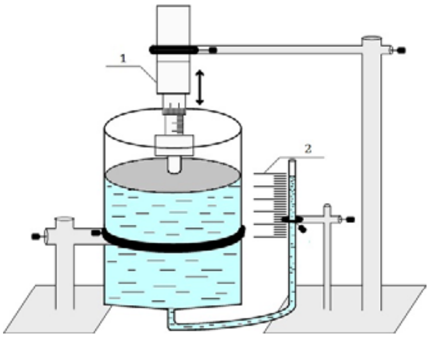

Fig. 12. Calibration unit for hydraulic positioning: 1 – micrometer head; 2 – linear scale of the liquid level shift.

This operation is fundamentally opposite to direct measuring operation. Thereby, device enables to set the liquid level, and nanoobject can be mounted on the floating platform with absolute error which is slightly more than atoms size.

- **Method of Symmetrical Observations** is applied for correcting the additive and progressive (linear-variable over time) components of errors. Three measurements are usually carried out at regular time intervals Δt:

$$\begin{aligned} Y_1 &= X + \Delta Y_a, \\ Y_2 &= X_k + \Delta Y_a + \Delta_1 \Delta t, \\ Y_3 &= X + \Delta Y_a + \Delta_1 2\Delta t. \end{aligned} \tag{13}$$

Errors of measurement results are determined by:

$$\begin{aligned} \Delta_1 &= \left(Y_3 - Y_1\right)/2\Delta t; \\ \Delta Y_a &= Y_2 - X_k - \left(Y_3 - Y_1\right)/2, \end{aligned} \tag{14}$$

where ΔY_a is the additive error component of MI; Δ_1 is its rate of error change; X_k is the value of measure. The adjusted value of obtained result is determined from the 1st expression of mentioned system:

$$X = Y_1 - \Delta Y_a = Y_1 - Y_2 + X_k + \left(Y_3 - Y_1\right)/2 \tag{15}$$

- ***Method of Substitution*** is applied when the experimenter does not have a complete set of MIs to eliminate the errors that arise in them. Let the transformation equation of MI is $Y = f(X)$ and let's consider two basic varieties: its replacement with variable measure and with adjustable scale converter. The first one is used in the exact measurements. Method is implemented in two stages. At the first stage, signal X is fed to input, and output signal Y_1 is fed to a memory element. At the second stage, from regulated measure's output the signal of a variable value X_N is submitted; it changes as long as signal Y_2 does not become equal to Y_1. When using method of substitution, the additive and multiplicative errors of MI do not bring contribution in result [1, 6]. Request is imposed to factor k that consists only in temporary stability, since permanence of k must be provided within a small interval of time which is equal to expectancy of 2-stage measurement. Method with adjustable scale converter is realized on the basis of set of elementary means. It can be recommended if the unambiguous non-adjustable measure X_0, adjustable scale converter for value X are available, and comparison unit fits only for value $k_H X$.

Method of substitution is widespread in the bridge circuit measurements, where firstly the resistance R_x is measured by bridge circuit; then it is substituted by multi-level measure R_N. Under the theory of bridge circuits, the error of resistance measuring by method of substitution δ_x equals to δ_N (error of measure) at its full replacement by measure: $R_X = R_N$.

This method is considered quite valuable in metrology, especially during at the measures calibration. As example, the method of Ohm size transmission from State standard to 1 Ohm, 10 Ohm and 100 Ohm secondary measures is realized in 8 stages with help of ratios measure containing ten 10-Ohm resistors; the latter can be connected in parallel (1 Ohm), in series (100 Ohm) and in series-parallel (10 Ohms).

Moreover, importance of above method we can underline with next linked option, namely with implementation of ***exact measure of electrical resistance on the basis of conductance quantum*** in CPS self-checking operation. Such a standard is able to replace older one in the modern State standardization practice.

Consumers of metrological services of the State Institutes of Metrology and Standardization, who are in great interest in transfer of proposed Resistance unit to CPS working standard, aim the subsequent accuracy improvement of CPS's products. We have considered earlier that the appropriate prototype of resistance measure (12906 Ohms) could be applied for calibrating the MIs of high accuracy.

Elsewise, we have obtained the reference point of Ohmmeter scale important for its calibrating in the high accuracy class. In this way, it can be realized the self-check, self-calibration of MIs and therefore self-validation of gauging data. Advantage of the similar methods of metrological self-check is evident; it was demonstrated in [10] on examples of checking the temperature, pressure and other kinds of smart sensors. By continuous controlling the reliability of metrological data and basing on the self-checking results for previous time duration, the forecasting of device's metrological state is developed as well as CPS's state.

7. Conclusions

1. Basing on the current metrological experience of complex technical objects we suggest the improvement of efficiency of Cyber-Physical Systems at equipping them with enhanced metrological subsystems. The latest have to provide exact measuring the performance including the control of actuators which actually ensure together with sensors the necessary mode of CPS operation.
2. Qualitative metrological instruments, their efficient metrological supervision and ensurance enable us to enhance slightly the accuracy of metrological subsystems. However to improve the CPS accuracy and to raise finally the quality of manufactured products by some orders, providing in-place the man-out-loop metrological procedures such as self-checking, self-validation, self-adjustment and so on becomes crucial.
3. Distinctive feature of such procedures could be introducing the set of special methods of minimizing the different kinds of random and systematic errors, for instance, through the introduction the methods of contradistinction, of substitution or others.

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