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System for Measuring of Radial Clearances in Gas-Turbine Engine with Self-Compensation of Temperature Effects on the Sensor

Abstract

The paper presents the description of developed hardware, algorithms and software of the system for measuring of radial clearances between stator and blade tips in the compressor of gas-turbine engine. The measuring system implements the method with self-compensation of temperature effects on the eddy-current single-coil sensor with a sensitive element in the form of a conductor segment. Due to the self-compensation the number of used sensors and related mounting holes in the power plant stator was reduced. The core operations of the self-compensation are realized in real time on hardware-and-software level. This makes it possible to use the system for the detection of dangerous states of gas-turbine engines during power plants operation. The previously unexplored phenomenon of "not-complete compensation" of temperature effects is considered. The phenomenon is related to the special features of the conversion of the single-coil eddy-current sensor's informative parameter in the measuring circuit. It manifests in the difference of conversion functions of the system's measuring channels under normal and nominal temperatures. The paper provides the way of the effect elimination by means of program correction. The results of experimental researches of the working model of the measuring system are given. They characterize the metrological appropriateness and efficiency of the system. The experimentally obtained calibration characteristic approximated by polynomial function was used to determine the systematic part of the error as a difference between the given and the calculated radial clearance. The random error was evaluated by the deviation of measured codes from an average value in the sample that was obtained at the specified value of radial clearance for the fixed blade's position relatively to the sensor's sensitive element. The efficiency of the working model was evaluated on the laboratory equipment during the rotation of the electrically driven compressor wheel. The quantitative estimates of speed and accuracy of the working model of the measuring system were obtained during experimental researches. They confirmed the possibility of using the system for the detection of dangerous states of gas-turbine engines applied in the electrical power industry.

Keywords: *gas-turbine engine, radial clearances, measuring system, hardware, algorithm and software, self-compensation of temperature effects, real-time processing, detection of dangerous states, systematic and random errors, efficiency*

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Система измерения радиальных зазоров в газотурбинном двигателе с самокомпенсацией температурных воздействий на датчик

Приводится описание разработанных технических средств, алгоритмов функционирования и программного обеспечения системы измерения радиальных зазоров между статорной оболочкой и торцами лопаток рабочего колеса компрессора газотурбинного двигателя, в которой реализован метод измерения с самокомпенсацией температурных воздействий на одновитковый вихретоковый датчик с чувствительным элементом в виде отрезка проводника. Благодаря применению механизма самокомпенсации удалось минимизировать число используемых датчиков и соответствующих установочных отверстий в статорной оболочке силовой установки. Основные операции, предусмотренные самокомпенсацией, осуществляются в реальном времени на аппаратно-программном уровне. Это открывает возможность применения системы для диагностики опасных состояний газотурбинных двигателей в процессе эксплуатации силовых установок. Рассматривается раннее не изученный эффект "недокомпенсации" температурных воздействий. Эффект связан с особенностями преобразования информативного параметра одновиткового вихретокового датчика в измерительной цепи и проявляется в несовпадении функций преобразования измерительных каналов системы при нормальной и номинальной температурах. В статье предлагается способ устранения влияния указанного эффекта путем программной коррекции. Приводятся результаты экспериментальных исследований действующего макета системы измерения, характеризующие его метрологическую состоятельность и работоспособность. Для определения систематической составляющей погрешности действующего макета системы как разности заданного и вычисленного радиального зазора использовалась экспериментально снятая градуировочная характеристика, аппроксимированная полиномиальной функцией. Случайная погрешность оценивалась по отклонениям кодов от средних значений в выборке для фиксированной позиции лопатки относительно чувствительного элемента датчика при заданной величине радиального зазора. Оценка работоспособности действующего макета производилась на специализированной лабораторной установке в процессе вращения рабочего колеса реального компрессора от электропривода. В ходе экспериментов были получены количественные оценки быстродействия и точности разработанного макетного образца, подтверждающие возможность использования подобного рода систем измерения для диагностики опасных состояний газотурбинных двигателей, применяемых в энергетике.

Ключевые слова: *газотурбинный двигатель, радиальные зазоры, система измерения, технические средства, алгоритмическое и программное обеспечение, самокомпенсация температурных воздействий, обработка в реальном времени, диагностика опасных состояний, систематические и случайные погрешности, работоспособность*

Introduction

According to [1, 2], the main indicators of the reliability and cost-effectiveness of gas turbine engines (GTE) used in transportation vehicles, electrical power systems, and gas transmission are depends on the radial clearances (RC) between the stator and the blade tips of the rotor wheel (RW) of the compressor and turbine. It is obvious that this dependence is the cause of multi-year interest of GTE developers for measuring RC and using the results of such measurements in control and diagnostic systems of GTE [3—6].

There are lots of RC measurement methods based on different physical principles [7, 8]. But their implementation is limited to the harsh conditions in the gas-air-duct, such as those relating to the temperature which reaches 600 °C in the compressor and 1000 °C in GTE turbine.

At the same time, RC measurement systems using single-coil eddy-current sensors (SCECS) with a sensitive element (SE) in the form of a conductor segment have been successfully tested in bench tests of GTE. The sensitive element of the sensor is connected through noninductive conductors to the volume coil of a matching transformer (MT); the equivalent inductance of the primary winding of this transformer is an informative parameter which depends on the RC. The SE as well as the other structural components of the SCECS (current conductors and the volume coil) is made of the same heat-resistant alloys as blades. The SE is inserted through a mounting hole directly into the wheel space, where it interacts with the blade tips. RC changes are converted to changes in the equivalent inductance of the primary winding of the MT. The MT of the SCECS is located outside the stator shell of the GTE under favorable temperature conditions [9—11].

The temperature effects on the SCECS components in RC measurement systems are reduced by means of additional witness SCECS, which SE is inserted through an additional mounting hole into the wheel space so that the temperature conditions are identical to the conditions of the SE of the working SCECS and there is no electromagnetic interaction with the blade tips. The witness SCECS is connected to the general measuring circuit (MC) with the working SCECS, where it performs compensation functions. This method was widely used in experimental studies of gas turbine engines under bench conditions [9—11]. However, the use of additional SCECS (and additional mounting holes) in the normal operation of GTE is extremely limited. There are also difficulties with selection of a pair of SCECS with identical parameters associated with the existing manufacturing technology of the sensors.

The RC measurement method described in [12] does not require using an additional witness SCECS because of the fixation of extreme values of the equivalent inductance of the MT primary winding of the SCECS, which depends on the RC and temperature, when a controlled blade passes by the SE (position RWI) and only on temperature when a blade-to-blade gap passes by the SE (position RWII), with the calculation of the difference of the measured values, which is determined only by the RC. Using models of the electromagnetic interaction (EMI) of the SE with the compressor blade tip, families of conversion functions (CF) of SCECS and MC were obtained [13] as well as the influence functions (IF) of a number of the disturbing factors (DF) on the difference of the extreme code values [14—16]. Moreover, the structures and the operation algorithms of the system for RC measuring with self-compensation of temperature effects on SCECS are considered in [17].

But the above-mentioned papers [12—17] do not contain any information about experimental studies that confirm operability and effectiveness of the RC measurement method with self-compensation of temperature effects on the sensor and illuminate the ways in which they can be realized. The paper is written to eliminate existing gaps. For this, we give a description of the developed hardware, algorithms and software of the system for RC measuring with self-compensation of temperature effects on SCECS. The previously unexplored phenomenon of "not-complete compensation" of temperature effects and the way of its elimination are considered. The results of the experimental studies of the working model of the measuring system are given. They characterize the metrological appropriateness and efficiency of the system. The specific example of the application of the developed system for the detection of dangerous states of GTE compressor applied in the electrical power industry is given. The quantitative estimates of the speed and the accuracy of the working model of measuring system were obtained during the studies and are given too.

System's hardware, algorithms and software

The system consists of both standard and non-standard technical facilities (Fig. 1).

The non-standard facilities include SCECS with two thermocouples (TC_1 & TC_2) intended for additional temperature correction[1], transducer (Trans.) which is the MC, containing differential scheme on the input with SCECS and its imitator, a "current-to-voltage" converter, a scaling amplifier and ten-unit ADC on the exit [13]. The transducer is plugged in the communication line between SCEDS and the device for preprocessing of digital data (DPD).

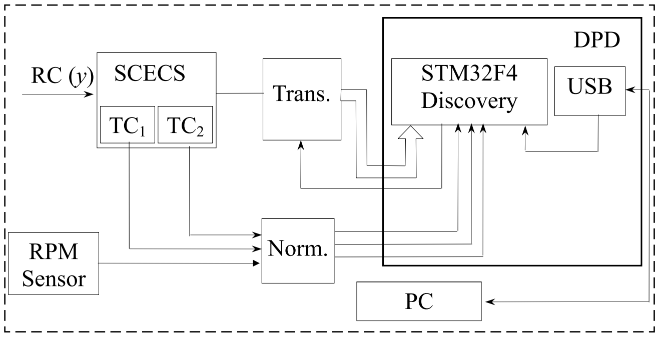

Fig. 1. Technical facilities of RC measurement system

The standard facilities are composed of RPM sensor, normalizer (Norm.) of the signals of TC and RPM sensor; the standard block STM32F4Discovery on the base of microcontroller STM32F407VGT6B [18].

DPD is linked with PC through USB-channel. The voltages corresponding to signals of TC_1 and TC_2 come from output of the normalizer to the analog input of ADC plugged in microcontroller and the normalized sequence of pulse signals from RPM sensor comes to the discrete input of microcontroller for measuring of RW rotation period.

According to [19, 20] the preliminary digital data processing (DPD, Fig. 1) includes the set of operations which on account to their content, importance, goals and tasks separately or in combination (in algorithms) can be presented as three methods for determination of:

- averaged extreme code values of blade-to-blade gaps $\bar{C}_{II}^{ext}$;
- extreme values of the difference of averaged codes of blade-to-blade gaps and codes corresponding to each blade during one period of RW rotation ΔC^{ext};
- averaged extreme value of the difference of codes for several (N) periods of RW rotation corresponding to each blade $\left(\frac{1}{N}\sum_{i=1}^{N}\Delta C_i^{ext}\right)$.

[1]According to the method in [7], the thermocouples TC_1 & TC_2 provide a higher accuracy of the temperature measuring in GTE flow section. This temperature is used during data processing in the measurement system and allows to reduce the temperature effect on the controlled and adjacent blades and as the result — to increase the reliability of information about RC.

The first method for determination of the code $\bar{C}_{\text{II}}^{ext}$ and the algorithm, corresponding to it, are implemented at one of the initial periods of RW rotation. They include a number of operations related to the construction of the statistical distribution (histogram) of ADC codes and fixation of the most probable code value $\bar{C}_{\text{II}}^{ext}$ found on the basis of the histogram. This value of code is used on the next period of RW rotation[2].

The second method involves a combination of several algorithms during one period of RW rotation and their implementation in real time in microcontroller. The algorithms are:

- calculation of codes difference $\Delta C(t) = \bar{C}_{\text{II}}^{ext} - C(t)$, where $\bar{C}_{\text{II}}^{ext}$ is determined on the previous period of RW rotation and $C(t)$ are current code values from ADC output;
- searching for extreme code values ΔC^{ext} corresponding to each blade by a brute-force approach;
- redefinition of averaged extreme code values $\bar{C}_{\text{II}}^{ext}$ on the current period of RW rotation for use them on the next period.

The third method and the algorithm, corresponding to it, are intended to reduce a random component of the measuring error through the averaging of the extreme values of the difference of codes ΔC^{ext} corresponding to each blade during a fixed number of completed periods of RW rotation.

Listed in the methods for preliminary data processing algorithms are implemented within the existing resources (hardware and software) of one microcontroller: timer, ADC, floating point unit and interrupt controller. The timer is used in "capture" mode for measuring of the period of RW rotation by signals of RPM sensor. The signals case interruption after each period of RW rotation. These interruptions are used for synchronization of the algorithms corresponding to each method.

The operations of codes processing corresponding to each blade during one period of RW rotation are presented in the methods and the implementing algorithms. Such operations are carried out by interrupts with other priority. The initial signals for the interrupts are produced adaptively after the fact when each blade passes by the SE SCEDC and the extreme difference code ΔC^{ext} is firmly fixed. The operation of accumulation of the averaging sums of the extreme difference of codes $\left(\sum_{i=1}^{N} \Delta C_i^{ext}\right)$ for several (N) periods of RW rotation corresponding to each blade is carried out in this interruption handler. So, the operations intended by methods and relevant algorithms are executed comprehensively and in real time. Thanks to periodicity of the RW rotation process all blades pass by the SE SCEDC in turn on each period of the wheel rotation. This provides easy access to the averaged extreme code values of the complete ensemble of the RW blades during several periods of the wheel rotation in real time. The resulting array of averaged codes relevant to the blades is transferred to the upper level in PC.

The specified in the working model of the measurement system PC (Fig. 1) is used for RC calculating in the same way as it was done in the measurement systems for experimental studies of GTE under bench conditions [9, 10].

Study results

The main attention is given to the experimental studies of the working model of the RC measurement system. The studies include the definition of the meteorological parameters of the measurement system and the evaluation of its efficiency. At the same time the section starts with examination of vital and unexplored phenomenon of "not-complete compensation" of temperature effects on the SCECS. The phenomenon manifests in the difference of CF (or calibration characteristics) of the system's measuring channels in the form of the dependencies ΔC^{ext} on RC under normal and nominal temperatures. The quantitative estimates of the speed of the working model of the measurement system and the possibility of the random error reducing on several periods of the RW rotation are considered in the final part of the section.

Temperature effects on the CF of RC measurement system and the way to reduce it. Even with the working model of the RC measurement system the calibration device for experimental research of temperature effects is needed. It should provide guaranteed accuracy for RC settings (⩽0,01 mm) within a specified range 0,5—2,5 mm under normal (20 °C) and nominal (620 °C) temperatures in compressor's gas-air duct.

In the absence of applicable calibration device for experimental research of temperature effects the well-known model of the EMI of the SE with turbine blade's tips can be used [11]. The model should be adapted to the blade used in GTE compressors. The similar model was used in [12—16], where the

[2]The most probable code value $\bar{C}_{\text{II}}^{ext}$ is taken for its averaged value.

required for simulating data are given (including the reference frame *OXYZ* which origin (point *O*) is located in the center of SE, the *X* axis is directed along the RW axis, the *Y* axis is directed radially (the RC value is characterized by the y coordinate) and the *Z* axis is in the direction of RW rotation).

The simulation results make it possible to determine the CF of SCECS — the dependences of extreme values of the inductance of the MT primary winding on RC (y) under the normal temperature ($L^{ext}_{\mathrm{MT}}(y)$); the value of $L^{ext}_{\mathrm{MT}}\big|_{y\to\infty}$ ($L^{ext}_{\mathrm{MT}\infty} = L_0$), and the changes of $\Delta L_y = L_0 - L^{ext}_{\mathrm{MT}}(y)$ [13].

It should be noted that changes of the equivalent inductance of the primary winding of the MT due to the temperature changes up to 600 °C were determined experimentally for the three SCECS samples of one type and size. The SE of SCECS were placed in hot air steam and the volume coils of MT were cooled by the water. The inductance changes (ΔL_Θ) averaged to $0{,}03L_0$ (3 %) under temperature changes up to 600 °C. This led to obtaining CF at a temperature 620 °C [13].

The detailed description of the MC[3] is given in [13]. The same literature source presents the CF of MC in the form of dependences of codes C^{ext}_{II} and C^{ext}_{I} in positions RWI and RWII on the inductance changes ΔL_y and ΔL_Θ:

$$C^{ext}_{II} = K_S K_C E\left(\frac{L_a}{L_0} + \frac{\Delta L_\Theta}{L_0}\right)\frac{1}{\left(1+\frac{\Delta L_\Theta}{L_0}\right)\left(1-\frac{L_a}{L_0}\right)}; \quad (1)$$

$$C^{ext}_{I} = K_S K_C E\left(\frac{L_a}{L_0} + \frac{\Delta L_\Theta}{L_0} - \frac{\Delta L_y}{L_0}\right)\times$$
$$\times\frac{1}{\left(1-\frac{\Delta L_y}{L_0}+\frac{\Delta L_\Theta}{L_0}\right)\left(1-\frac{L_a}{L_0}\right)}, \quad (2)$$

where E is a supply voltage of the scheme, K_S is a scaling coefficient and K_C is a coefficient with dimension 1/Volt.

The difference of codes C^{ext}_{II} and C^{ext}_{I} in (1), (2) corresponds to the extreme value of codes difference ΔC^{ext} calculated in the measurement system. Taking this into account:

$$\Delta C^{ext} = C^{ext}_{\mathrm{II}} - C^{ext}_{\mathrm{I}}, \quad (3)$$

and then after substitution of (1) and (2), the difference of the codes becomes

$$\Delta C^{ext} = K_S K_C E\frac{\Delta L_y}{L_0}\times$$
$$\times\frac{1}{\left(1-\frac{\Delta L_y}{L_0}+\frac{\Delta L_\Theta}{L_0}\right)\left(1+\frac{\Delta L_\Theta}{L_0}\right)}, \quad (4)$$

or

$$\Delta C^{ext} = K_S K_C E\frac{\Delta L_y}{L_0}\frac{1}{K_\Theta\left(K_\Theta-\frac{\Delta L_y}{L_0}\right)}, \quad (5)$$

where $K_\Theta = 1 + \frac{\Delta L_\Theta}{L_0}$.

Under the assumption that $\frac{\Delta L_\Theta}{L_0} \ll 1$ and $\frac{\Delta L_y}{L_0} \ll 1$ the coefficient $K_\Theta \to 1$ and the codes difference ΔC^{ext} is determined only by the RC (y) $\left(\Delta C^{ext} = K_S K_C E\frac{\Delta L_y}{L_0}\right)$ and the temperature changes do not affect on it. In other words, the full self-compensation of temperature effects on the SCECS is achieved.

But in real conditions the coefficient K_Θ depends on the temperature and the phenomenon of "not-complete compensation" of temperature effects has taken place. According to the simulation results of the EMI of the SE of the SCECS with the blade used in the GTE compressor, and also taking into account the experimental data, the quantitative estimates of $\frac{\Delta L_y}{L_0}$ as a dependence on y-coordinate (RC) and $\frac{\Delta L_\Theta}{L_0}$ for temperature drop per 600 °C (from normal to nominal) were obtained.

Fig. 2, *a* shows the system CF obtained under normal (20 °C) and nominal (620 °C) temperatures. The CF demonstrate the "not-complete compensation" effect about 20 code units or more than 6 % from code deviation in RC range from 0,5 to 2,5 mm.

To reduce the "not-complete compensation" effect the method that involves the multiplication of calculated in the system difference code value by unitless number, defined by:

$$\left(K^2_\Theta - K_\Theta\frac{\Delta L_y}{L_0}\right)\frac{1}{1-\frac{\Delta L_y}{L_0}} \quad (6)$$

is offered.

[3] The SCECS is connected to one branch of the differential circuit with pulse supply (pulse time is 0,1 μs, frequency is 1 MHz). The SCECS simulator (SSCECS) is connected to another branch of the circuit (it inductance is equal to L_0—L_a, where L_a is usually chosen to $\Delta L_{y,\max}$). The currents in circuit branches are converted to the voltages on current-to-voltage converters (CVC) outputs. The voltages difference is amplified in scaling amplifier and further is converted to digital code on the output of 10-digit ADC.

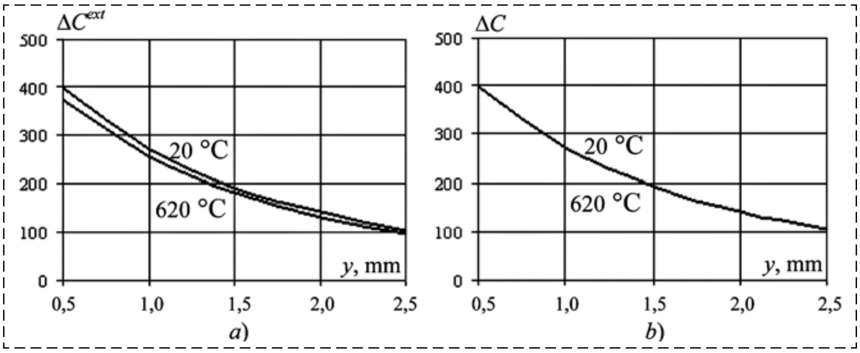

Fig. 2. Dependences of $\Delta C(y)$ under normal (20 °C) and nominal (620 °C) temperatures with "not-complete compensation" effect (*a*) and without it (*b*)

In the first approximation the expression (6) is equal to K_Θ^2 when the impact of changes $\frac{\Delta L_y}{L_0}$ is not taken into account. Meanwhile, the coefficient K_Θ is equal to 1,03 for nominal temperatures (620 °C) in the flow section of GTE.

The calculations show that the proposed method allows to reduce the "not-complete compensation" effect by more than two orders and the "not-complete compensation" effect is mostly invisible on Fig. 2, *b*. Indeed, if y is equal to 0,5 mm the "not-complete compensation" effect is only 0,2 code units (less than 0,1 % from the deviation of codes difference and it decreases with RC (y) increasing). The calculations also show that the changes of "not-complete compensation" effect are insignificant and do not exceed $5 \cdot 10^{-12}$ codes unit, taking into account the changes of $\frac{\Delta L_y}{L_0}$ in the same RC range.

Metrological indicators. Two indicators are discussed — the systematic and random parts of the error of the working model of the RC measurement system.

The calibration characteristic (CC) is needed for quantitative evaluation of the systematic part of the measurement error. It is like a CF $\Delta C^{ext}(y)$, but obtained by an experimental way with the help of three-dimensional calibration device equipped with mechanical timepiece indicators with a resolution of 0,01 mm. The indicators are used for the control of the displacements of the blade which is fixed to a movable platform.

The methodology for CC obtaining at first provides the pre-installation of given RC (y coordinates) and then a manual search of the extreme code value C_{I}^{ext} (along z coordinate). The procedure is repeated with a given step Δy_s in the full range of the RC (0,5—2 mm). When $y \gg 2{,}5$ ($y \to \infty$) the code C_{II}^{ext} is fixed and the desired code differences $\Delta C^{ext}(y)$ are calculated. However, to analyze the systematic part of the measurement error the inverse of the CC function $\Delta C^{ext}(y)$ seems to be more convenient:

$$y = F(\Delta C^{ext}) = \sum_{i=0}^{I} A_i \Delta C^{ext}, \qquad (7)$$

where A_i are the coefficients of the polynomial and I is its order.

Meanwhile, the approximated CC are used as a "supporting" functions for the determining of the systematic part of the measurement error as a difference of the given RC and the RC calculated after approximation (y_a) according to (7):

$$\Delta y = y - y_a. \qquad (8)$$

It should be noted that the experiment in the normal temperature conditions is enough for obtaining of the CC (the functions of type (7)) of the working model of the RC measurement system. The distinctive features of the experiment are that the function $C_{\mathrm{I}}^{ext}(y)$ is determined with a small step 0,2 mm during the calculation of the difference $\Delta C^{ext} = C_{\mathrm{II}}^{ext} - C_{\mathrm{I}}^{ext}$ at each y position and the repeating of the listed operations at least 10 times with further averaging of the obtained results ΔC^{ext}. The averaged CC of the system is given in table 1.

This averaged values ($\Delta\overline{C}^{ext}(y)$) are used for the approximation function (7) obtaining. The result of the approximation is the polynomial function $y_a(\Delta\overline{C}^{ext})$. For the polynomial order I = 6 the polynomial coefficients are: A_0 = 4.2255955938; A_1 = -6.1557237945$\cdot 10^{-2}$; A_2 = 6.1365638609$\cdot 10^{-4}$; A_3 = −3.7526730997$\cdot 10^{-6}$; A_4 = 1.3236791821$\cdot 10^{-8}$; A_5 = −2.4719351918$\cdot 10^{-11}$; A_6 = 1.8893005772$\cdot 10^{-14}$.

The reduced systematic part of the error is:

$$\delta_y = \frac{\Delta y}{\Delta y_{\max}} \cdot 100\%, \qquad (9)$$

Table 1

Averaged CC ($\Delta\overline{C}^{ext}(y)$)

y, mm	0,5	0,7	0,9	1,1	1,3	1,5	1,7	1,9	2,1	2,3	2,5
$\Delta\overline{C}^{ext}(y)$	340,27	260,75	203,91	162,78	130,35	105,30	85,87	71,00	59,16	49,42	41,37

Table 2

$(\Delta\bar{C}^{ext}(y))$ **values in the centers of the intervals between CC "nodes"**

y, mm	0,6	0,8	1,0	1,2	1,4	1,6	1,8	2,0	2,2	2,4
$\Delta\bar{C}^{ext}(y)$	297,61	231,34	182,88	144,82	116,97	94,47	77,99	64,81	53,84	45,16

where Δy is calculated according to the expression (8) and Δy_{max} = 2 mm is the largest possible RC changing. Δy is calculated according to the given values of RC (y) in the nodes of the table 1 and the values y_a, found through the expression (8)[4]. The calculations show that the systematic part of the error δ_y is small in the full range of RC (y) changing and its maximum value doesn't exceed 0,06 %.

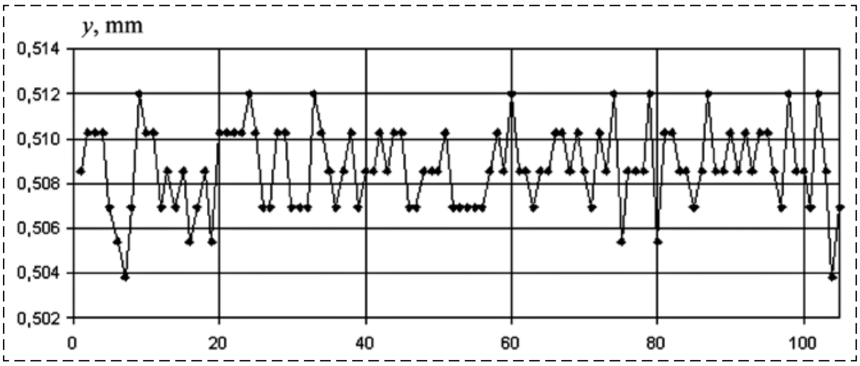

Fig. 3. Sample of the calculated RC (y) to a given value of y = 0,5 mm

It is known that the approximation errors between the "nodes" can be much more than in the "nodes" when the order polynomials are used. To evaluate these errors the values of the difference $\Delta\bar{C}^{ext}$ were obtained experimentally (they are given in the table 2 at the RC (y) selected in the centers of the intervals between y coordinates given in table 1). After the calculation of the y_a value for the same y coordinates the errors δ_y were obtained. They are much more than the errors in the "nodes", but their maximum value does not exceed 0,26 %.

The experiment on the estimation of the random part of the error is carried out in fixed position of the blade relatively to SE of SCECS when the RC (y) is 0,5 mm. The analysis of the sample fragment with the size 105 codes C_{I}^{ext} shows that the most of the codes are within 5 digits of dispersion (standard deviation is 1,11 digits). The random error of codes C_{II}^{ext} is virtually eliminated in the RC measuring system due to the statistical techniques by means of the histogram. That is why the standard deviation of codes ΔC^{ext} will be the same as of codes C_{I}^{ext}. At the same time the reduced random part of the error is determined by the ratio of standard deviation to changes of the differenced code in the RC range from 0,5 to 2,5 mm. According to the table 1 these changes are about 300 code's digits and when the standard deviation is 1,11 code's digits the reduced random part of the error is estimated in about 0,3 %.

Referring to the codes sample C_{I}^{ext} it should be noted that for known $\bar{C}_{\text{II}}^{ext}$ the ΔC^{ext} can be calculated and then ΔC^{ext} can be converted to RC (y) according to (7). The results are given on fig. 3.

When ΔC^{ext} is converted to RC the random error is substantially reduced because of the curvature of the ΔC^{ext} (y) function in the neighborhood of y = 0,5 mm. The RC (y) standard deviation is 0,00184 mm and its relative value led to the range of 2 mm is about 0,1 %.

The evaluation of the efficiency of the working model of the measuring system. The evaluation is carried out by the experimental comparison of the given RC between SE of SCECS and the blade tips of the real RW of the compressor with an electric drive (during its rotation) and the RC obtained after data processing in the measuring system (the RW speed is constant during the experiment). The changes over time of the $C(t)$ codes on the exit of the transducer, the difference of the codes $\Delta C(t) = \bar{C}_{\text{II}}^{ext} - C(t)$, its extreme value ΔC^{ext} and the histogram that illustrates the obtaining of $\bar{C}_{\text{II}}^{ext}$ code for one period of the RW rotation are fixed during the experiment too.

Fig. 4 shows a schematic of the RW with a blade row and SCECS which SE is located at a distance of RC from the controlled blade tip.

The displacement of SCECS along Y axis of the reference frame $OXYZ$ which simulate possible RC changes during the compressor operation is carried out by a special equipment. The compressor wheel is driven by direct current electric motor with controlling of its rotational speed up to 500 rpm (rotational speed is limited owning to safety reasons). The RC changes are monitored by the mechanical

[4]As such the systematic part of the error is in fact an approximation error.

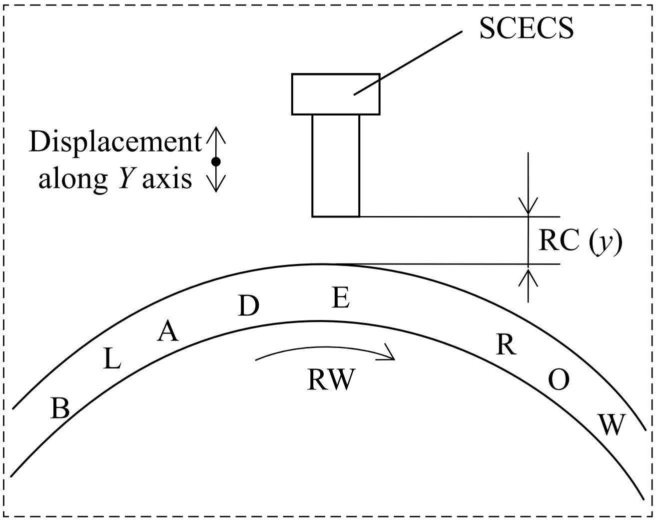

Fig. 4. Schematic of the RW with a blade row and SCECS

timepiece indicator with resolution 0,01 mm (the indicator is not shown in Fig. 4).

It is obvious that the listed equipment makes it possible to obtain the CC not only in static mode of RW, but also in the dynamics (i.e. during its rotation). Of course, the use of dynamic mode of obtaining the CC cannot rely on the official certification and guarantee the metrological validity of the experimental results. But its possible use for the evaluation of the measuring system hardware and software is unquestionable.

In order to obtain the CC target values of RC (*y* coordinate) are set in the limited range from 0,75 mm to 2,25 mm with step 0,5 mm. The extreme values of codes difference ΔC^{ext} are defined for the blade no. 1 for each *y* value during RW rotation. The obtained CC as the function $y = f(\Delta C^{ext})$ are approximated by the polynomial with the order downgraded to 3. Its coefficients are entered into the system for use in special procedure for calculation of the desired RC (*y*).

Then the intermediate *y* values between "nodes" of the CC table are set and the calculation of the RC takes place in the measuring system.

The difference between the given and the calculated values of RC (*y*), expressed as a percentage of the RC measuring range was approximately about 1 % RC 1,5 and 2,0 mm and about 5 % for RC 1,0 mm. The obtained results confirm the operating capability of the hardware and software tools of the working model of the measuring system.

Fig. 5, *a* shows the changes over time of the codes on the transducer exit ($C(t)$) when the blades no. 1, 2, ..., 6 (minimum) and corresponded blade-to-blade gaps (maximum) (1) pass the SCECS. The changes were obtained on the working model of the measuring system during the RW rotation and they illustrate the operation of the system (temperature changes ($\Delta\theta \approx 600$ °C) are simulated by additional coil with inductance $L_a \approx 0{,}03L_0$ connected in series to the primary winding of MT). There the changes over time of the codes difference $\Delta C(t) = \bar{C}_{II}^{ext} - C(t)$ and its extreme values which are defined in the system (they are shown by a dots) (2) are presented.

The averaged extreme values of the codes were found on the previous period of the RW rotation as a result of the statistical processing with the help of the histogram (Fig. 5, *b*). The vertical line sets the array $g|C|$, where symbol "*C*" corresponds to the value of the registered code and the value of the array element $g|C|$ is a frequency of its appearance in the sample. The global extremum of the histogram corresponds to the desired averaged value of the code $\bar{C}_{II}^{ext}$ [20]. The averaged value of the code $\bar{C}_{II}^{ext}$ is shown by a horizontal dashed line.

About the performance of the system and the possibility of reducing of the random part of the error. The frequency of the codes on the exit of the transducer is defined by the frequency of a pulsed power supply of SCECS which equals to 1 MHz (at a constant and very short duration of the pulses $\Delta t = 10^{-7}$ s) and limited to a marginal capabilities of the selected microcontroller.

It should be noted that when determining the desired extreme values of the differenced codes corresponding to each of *n* blade their updating is happening with time intervals equal to the period of RW rotation. Assuming a compressor is an object of the diagnostics of dangerous states and GTE

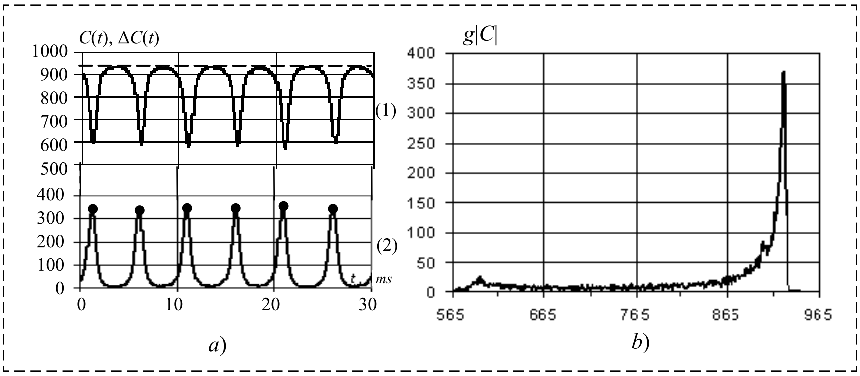

Fig. 5. Dependence of the code on the transducer exit *C*(*t*) (1), codes difference Δ*C*(*t*) and its extreme values (dots) (*a*), the histogram for averaged values of the code $\bar{C}_{II}^{ext}$ (*b*)

is applied in the electricity industry, providing the rotation of the generator rotor with constant speed 3000 rpm, the period of the RW rotation will be 20 ms. That time is enough, for example, for detection of the engine surge that can be fixed on the changes of ΔC^{ext}, to be exact — on the RC changes related to the beginning of oscillations in the gas-air duct (if the number of blades is n = 100 and the frequency on the exit of the transducer is 1 MHz then the extremes of the codes difference appear through 0,2 ms and the number of codes is 200 per blade). Unlike the existing systems for RC measuring with SCECS where data processing is done in PC, the proposed working model provides the data processing in real time in the microcontroller during one period of RW rotation [20].

In the same literature source [20] the opportunities for reducing of the random part of the errors are considered. At the same time, it is pointed out that the discretization process and unremovable noise in MC (transducer) are the main reasons for the random errors. It is obvious that the sampling step depends on the frequency of a pulsed power supply of SCECS and the RW rotation speed. With the increase in the frequency the sampling step decreases (at a constant rotation speed) and increases with the increase in the rotation speed (at constant frequency of a pulsed power supply). The changes of the sampling step at the given frequency of a pulsed power supply can be a source of the error of a random nature. To quantify these errors the well-known model of the EMI of the SE with the turbine blade tip, adapted to the compressor blade, was used [20]. Computational experiments showed that at the frequency of a pulsed power supply equals to 1 MHz and RW rotation speed equals to 3000 rpm the reduced error is only 0,012 %. This means that in the example the sampling error can be ignored (especially in view of increase of the frequency of a pulsed power supply and using the microcontroller with higher performance).

However, there is still the random part of the error related to the unremovable noise in MC. As it was shown earlier (during studies of the metrological indicators) the standard deviation at RC (y) 0,5 mm is 1,11 units of code and the relevant part of the error normalized to the maximum possible deviation of the codes difference ΔC^{ext} is about 0,3 % and that is far above the sampling error at the rotation speed 3000 rpm.

Then the averaging of the extreme values of differenced codes corresponding to each blade at several periods of RW rotation will reduce the random part of the error by $\sqrt{N}$ times [20], where N is the number of the periods of RW rotation. It means that at rotation speed 3000 rpm and N = 10 the error 0,3 % will be less than 0,1 %. The duration of the conversion will be 0,2 s.

Conclusion

The hardware, algorithms and software of the system for the RC measuring are developed. The working model of the measuring system for experimental studies of the metrological indicators and the efficiency of the system is made. The distinctive feature of the system and its working model is the self-compensation of temperature effects on the SCECS. The operations envisaged for the self-compensation are executed in real time in microcontroller.

The phenomenon of "not-complete compensation" of temperature effects on SCECS is considered. The phenomenon is related to the special features of the conversion of the SCECS informative parameter in MC with ADC on its output and the method of its elimination is given. Using the self-compensation coupled with the proposed method ensures the minimization of SCECS and related mounting holes in the compressor stator and makes it possible to use the system for detection of dangerous states of GTE during its operation.

The results of the experimental researches of the metrological indicators of the measuring system were carried out. In order to define the systematic part of the measuring error the CC was used. It was approximated by the polynomial function and the error was found as a difference between the given and the calculated RC (y). It was shown that the reduced systematic part of the error in the range of the RC from 0,5 to 2,5 mm does not exceed 0,06 % in the "nodes" of the calibration table but it equals 0,26 % between the "nodes". It is also shown that the reduced value of the random part of the error that was determined at the minimum RC (0,5 mm) as the ratio of standard deviation to changes of the differenced code in the same RC range is about 0,3 %. The error decreases to 0,1 % when the standard deviation is converted to RC (y) changes using the CC approximated by the polynomial function (due to the increased slope of CC when RC is 0,5 mm).

The efficiency of the working model was evaluated on the laboratory equipment during the rotation of the electrically driven compressor wheel. The CC without claiming to metrological validity was obtained according to the simplified method.

The CC was entered into PC and used to compute the RC physical values. It is shown that the difference between given and calculated values of RC (y), expressed as a percentage of the RC measuring range, does not exceed some percentage units and this confirm the system's efficiency.

The quantitative estimates of speed and accuracy of the working model of the measuring system are given. They confirmed the possibility of using the system for detection of dangerous states of GTE applied in the electrical power industry. It is shown that at the constant speed of the compressor RW rotation equals to 3000 rpm, the updating of the information about the RC to each blade tip is happening in one period of RW rotation (i. e. 20 ms) by applying the microcontroller. This time is enough for using the system for detection of the engine surge in gas-air duct. It is also shown that the random part of the error can be reduced three times over 10 periods of RW rotation to which corresponds to 0,2 ms.

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