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Improving the Efficiency of an Eddy Current Sensor Measuring the Thickness of a Heat-Resistant Metal Film of Turbine Blades During Its Deposition in Vacuum

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The article analyzes the design features and general modeling of an eddy current sensor for measuring thickness of a metal film. The main tasks of the work are formulated to improve the accuracy and efficiency of the eddy current sensor based on the analysis of different solutions in the turbine industry. The purpose of the research is to study the peculiarities of the sensitive element (coil) of the eddy current sensor measuring the thickness of the heat-resistant metal film of the turbine blades in a vacuum chamber, followed by computer simulation of its functioning to identify the optimal parameters of the oscillatory circuit. The set goal is achieved by solving the following problems. Firstly, a constructive implementation of the eddy current sensor of the measuring transducer for working in a vacuum chamber at a temperature of 300°C is proposed. Secondly, the calculation of the sensitive element of the sensor (inductance coil) is performed for operation at elevated temperatures. Thirdly, corrections for the intrinsic and mutual inductance of the turns, as well as the inductance correction from temperature are studied in detail and taken into account when calculating the inductance. Finally, computer simulation of the developed measuring transducer is performed based on the oscillatory circuit and the quality factor conception of the simulation models. The most significant important results of the work are the following: a) the proposed methodology makes it possible to develop an optimal sensitive element for operation in vacuum and at elevated temperatures, and b) the simulation model helps to determine the best electrical parameters of the measuring transducer elements. The significance of the obtained results lies in the possibility of improving the accuracy and, accordingly, the efficiency of measuring the thickness of the heat-resistant metal film of the turbine blades.

Keywords: eddy current sensor; turbine blade; heat resistant coating; metal surface; thickness; measuring transducer; oscillatory circuit

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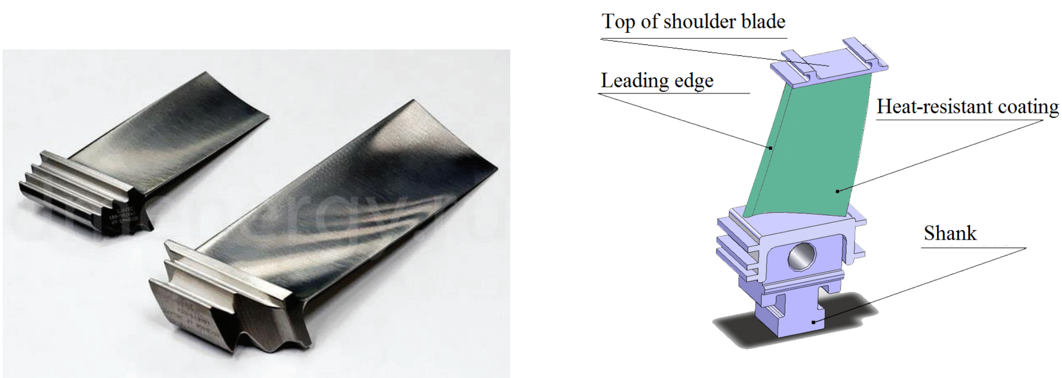
Introduction

Turbines are the main energy converters of powerful energy complexes [1]. In recent years, developed countries have been developing and upgrading a new generation of advanced high power turbines in order to meet the development needs of advanced high power turbines. Advanced integrated components such as an integrated impeller, an integrated diffuser and so on are increasingly used for the modern turbines' development and production in order to improve the efficiency, increase the pushing mass ratio, improve the reliability of operation and extend the service life. Today the design of these one-piece components combining several parts into a single whole has been improved and has a smaller volume and lighter weight compared to previous designs. Due to the complex geometry of all turbine components and blades in particular, some materials are particularly difficult to machine, and the manufacture of high-strength impeller blades and the diffuser, in general, becomes a manufacturing technology problem. All advanced industrial countries are working diligently to research and develop appropriate production technologies to produce all components with high quality, high efficiency and at low cost.

In order to improve the ratio of the pushed mass and reduce the level of fuel consumption it is necessary to design and manufacture turbines with high load and high efficiency. Simultaneously, the use of a turbine with a high pressure ratio makes the centrifugal impeller outlet speed high and the uniformity poor, also the centrifugal impeller outlet width is very small, the diffuser inlet and centrifugal outlet are very close, and the non-stationarity of the interaction between them is greatly enhanced, that leads to an increase in working temperatures. Under conditions of elevated temperatures the durability of turbine blades is largely determined by the possibility of their protectio with heat-resistant coatings. Air cooling supplied to the internal cavity ensures normal operation at metal temperatures up to 1000-1200°C depending on the type of heat-resistant alloy. With a subsequent increase in gas temperature, the use of blades without coatings becomes impossible, since a further increase in the temperature of the heat flux supplied to them can lead to a deterioration in their cooling and, as a result, an increase in the surface's temperature above the critical one. This adversely affects the resource of the working blades. Replacement during the repair of failed blades is a rather expensive and time-consuming procedure. An effective way to protect the internal and flow surfaces of the blades from corrosion damage and high-temperature oxidation is the application of modern heat-shielding coatings designed to reduce heat gain to the blade material. Existing studies show that the use of a heat-resistant ferromagnetic coating (Fig. 1) on the blades is one of the main ways to solve the problem of using turbines with a high compression ratio [2,3].



(a) (b)

Fig. 1. Turbine blades: (a) the appearance of the blades; (b) the structure of the blade

A special role in the deposition of metal on the blades has a constant control over the thickness of the heat-resistant metal film deposited in vacuum. The quality of the blade depends very much on the thickness of the deposited film, as well as on the magnitude of the deviation of this thickness from the specified value. Many scientific teams have studied the problems of measuring the thickness of metal and outlined the requirements for measuring instruments [4–10, 12–22]. Sensors must be high-performance, provide further improvement in measurement accuracy, be able to work in automatic mode with the control of technological equipment, have built-in capabilities for processing measurement information, and ensure joint operation with the computing devices in automated control and monitoring systems [4–8].

The electronic measuring devices are widely used in the industrial practice of turbines' construction, among the latter the main place is occupied by devices with the inductive primary measuring transducers, in particular the metal thickness gauges. To date, a large number of the inductive sensors have been created, which can be used to measure the thickness of coatings both in the laboratories and in the factory. All types of the sensors depend on the methods on which they are based, but the eddy current sensors deserve special attention [9,10]. The eddy current sensor works according to the inductive eddy current principle. It measures the thickness of metal based on the extraction of energy from the oscillatory circuit, which is required to generate eddy current in electrically conductive materials. When an alternating current is applied to the oscillatory circuit from the generator of sinusoidal signals, a magnetic field is formed around the inductor. If an electrically conductive material is placed in this field, then, in accordance with Faraday's law of induction, an eddy current field is induced. Due to a change in the thickness of the layer of conductive material, the total electrical resistance of the inductor changes, that is proportional to the thickness of the metal. The indisputable advantage of such sensors is that the magnetic and electric fields are non-contact and invariant to temperature, pressure, radiation and other factors such as dirt and oil, as well as they are among the best wear-free, non-contact gauges for measuring metal thickness in harsh industrial environments such as those found in the turbine plants. The eddy current sensors are covered in various scientific studies, e.g. in [11–14] the inductance coils of the eddy current sensors are studied in detail, the electromagnetic parameters of which depend on the thickness of the plate. One of the methods in this area is eddy current [9, 10], that is based on the creation of eddy currents by an inductor coil in a magnetic conductive plate, and the coil itself acts as a sensitive element with an alternating magnetic field, so the coil's electromagnetic parameters depend on the thickness of the plate [11–14]. The main advantages of eddy current sensors are low cost and reliability [15, 16]. The disadvantage is the significant influence of the working gap between the sensor and the plate on the measurements [17, 18, 21]. The architecture of the sensors also has a significant impact [19, 20, 22], it is obvious that the sensor architecture based on the detector coil is commonplace in the application of quantitative determination of the thickness of a ferromagnetic material [23–27]. The eddy current sensors based on detector coils can take several forms: usually they can be round [24], sometimes rectangular [28], oval [29], or even other shapes.

The development and research of such sensors in turbine construction can be noted in the following works [30–34]. For example, paper [30] describes an innovative eddy current sensor specially designed to measure the thickness of metal (MCrAlY) coatings deposited by vacuum plasma spraying on nickel-based heat-resistant alloys. The new technique uses fast frequency scanning of the electromagnetic field in the range of 100 kHz-10 MHz that corresponds to a probing depth of 1 mm to 0.1 mm. The analysis of the measured data (i.e. probe impedance versus frequency) to evaluate the relevant diagnostic parameters (coating thickness, coating and base metal conductivity) is based on a theoretical plane interaction model. In [31] Eddy Current (EC) inspection is proposed for quantitative evaluation, which involves estimation of: (1) thickness of the top coating to identify possible thinning and (2) thickness and conductivity of bond coating to detect delamination and degradation. In an effort to implement the fast inversion, the closed-form expressions of the Jacobian matrix are derived based on Truncated Region Eigenfunction Expansion (TREE) modeling. The Levenberg–Marquardt (LM) algorithm is also adopted in the inversion for the parameters.

In works [32, 33] the authors show the main advantages of probes creating an uniformly oriented magnetic field in order to reduce the partition disturbances. Furthermore, they propose a measurement process allowing to separate the wall thickness parameter from the EC signals. Finally, some experimental results validating the proposed technique are presented.

Thus, the development of high-precision sensors that could control the thickness of the deposited metal film in the process of deposition on the blades is an urgent task for many turbine-building enterprises and research teams. At the same time, the operation of such a sensor in vacuum chambers at a high temperature of 300°C is poorly understood. In addition, to study the sensitivity of the sensor at the design stage, it is also rational to use computer simulation methods [35–38], which are quite effective and low-cost compared to experimental approaches.

Intensive design improvements are ongoing for inductive measuring instruments, aimed at improving their metrological characteristics. Characteristic features of increasing the efficiency of inductive transducers are: expanding the measurement range, increasing accuracy, reducing various components of the transducer error and increasing sensitivity. These performance indicators are achieved through the development, at the design stage, of high-quality mathematical models of the elements of the converter and the inductor in particular for work in a vacuum chamber at a temperature of 300 degrees. They can improve the output parameters of the sensor and will be applicable to the problem of synthesis and optimization of the design of an inductive measuring transducer in terms of metrological applications in the turbine industry.

The purpose of this work is to study the sensitive element (coil) of an eddy current sensor, measuring the thickness of a heat-resistant metal film of turbine blades in a vacuum chamber, followed by computer simulation of its operation to identify the optimal parameters of the oscillatory circuit improving the efficiency of measurements at high temperatures (up to 300°C).

1 Inductive Calculation of an Eddy Current Sensor Coil

The inductive sensor is a variable inductance and its output parameter is the impedance Z_L. The impedance of the converter can be represented as reactive X_L and active R_L components or as inductance L and quality factor Q. The last two values are convenient because they allow to characterize the measuring converter in a certain operating frequency range. In the case when the quality factor of the converter is high, only its inductance L can be considered as its output parameter. Thus, the static characteristic of the inductive converter can be represented as $Z_n = f(l)$ or $L_n = f(l)$, Z_n is the resistance of the transducer, L_n is the inductance of the transducer, l is the thickness of the deposited metal.

The input impedance of an inductive transducer determines the response of the input signal when the transducer is connected to the input source. The output impedance of a transmitter determines the response of its output signal when a fixed load is applied to its output. For an inductive transducer, the output impedance is determined by its impedance or reactance in the case of a high quality factor.

The functioning of the inductor is determined by the effect of the mutual transition of the energy of the electric field of the voltage source applied to its terminals into the energy of the magnetic field covering the circuit of the coil, and back under the action of the electric current flowing through the circuit of the coil. The quality factor of the inductor is directly related to the loss resistance, a parameter associated not only with losses in the wires, but also taking into account losses in the dielectric and core and shield. The core loss is the sum of the eddy current loss and the hysteresis loss associated with the remagnetization of the material over a period. Losses in the dielectric are due to both the parasitic interturn capacitance between adjacent turns of the coil and the magnetic properties of the dielectric of the coil frame (these losses are similar to losses in the core). Shield losses are due to induced currents in the conductive layer. The coil itself can have a different ratio of length to width, be single-layer or multi-layer. Moreover, multilayer coils of ordinary winding in their quality qualities are much worse than single-layer ones, since they have a relatively large self-capacitance value [39]. In the design of coils, special measures are used to minimize unaccounted losses – ceramic or ribbed frames, frameless coils (with an "air" frame), refusal to use a core.

It is obvious that for designing a sensor for measuring the thickness of a metal film, one should opt for a single-layer coil (solenoid) without the use of a core that in turn will ensure high stability of the operation in the measuring transducer. The main parameter of an inductor is its inductance, which is numerically equal to the ratio of the magnetic field flux created by the current, penetrating the coil, to the strength of the flowing current [40].

The thickness of the solenoid winding layer can be taken equal to zero $t=0$, and the calculated inductance formula will have the form

$$L = \frac{\mu_0}{4\pi}\omega^2 d\Phi,$$

where μ_0 is the magnetic constant, $\mu_0 = 4\pi 10^{-7}$ H/m; ω is the number of turns of the solenoid; d is the diameter of the solenoid, m; l is the length of the solenoid, m; Φ is a coefficient that depends on the ratio $a = l/d$.

For a long solenoid, i.e. $\alpha > 0,75$, the correction factor will be

$$\Phi = \frac{\pi^2}{a}\left(1 - \frac{4}{3\pi\alpha} + \frac{1}{8a^2}\right).$$

For a short solenoid, i.e. $\alpha < 0,75$, the correction factor is

$$\Phi = 2\pi\left[\left(1 + \frac{a^2}{8}\right)\ln\frac{4}{a} - \frac{1}{2} + \frac{a^2}{32}\right].$$

In addition to design parameters the parameters of the winding wire (diameter, insulation thickness, winding pitch) also affect the inductance [40]. Therefore, the total inductance of the coil can be represented by the following expression

$$L = L_P + \Delta L = L_P + \Delta_1 L + \Delta_2 L,$$

where L_P is the calculated inductance; ΔL – the correction for "isolation", $\Delta_1 L$ – the correction taking into account the influence of the inductance of the turns; $\Delta_2 L$ – the correction taking into account the influence of the mutual inductance of the turns.

In the general case, the correction for the self-inductance of the turns is calculated by the following expression

$$\Delta_1 L = \mu_0\omega\frac{D_{CP}}{2}I,$$

where D_{CP} is the average coil diameter, m; I is a coefficient depending on the location of the turns of the coil.

The coefficient I is determined depending on the location of the wire. For the case when the wire is wound in one layer along the length of the coil with a step p the calculated inductance L_P, in that the winding thickness t is taken equal to zero (calculated as a solenoid), then the coefficient I will be equal to

$$I = \ln\left(\frac{2p}{s_p}\right) - 1.25 = \ln\left(\frac{p}{s_p}\right) - 0.56,$$

where p is the winding pitch along the length of the coil, s_p is the diameter of the bare wire (without insulation).

In the general case the correction for the mutual inductance of the turns $\Delta_2 L$ of the coil is determined by the expression

$$\Delta_2 L = \mu_0\omega\frac{D_{CP}}{2}J,$$

where J is a coefficient depending on the shape of the coil and on the number of turns of the coil.

For a coil made in one layer along the length of the coil (solenoid), when determining the calculated inductance L_P the winding thickness t is taken equal to zero (calculated as a solenoid), the coefficient J will be

$$J = \frac{1}{1,3\omega + 2} - 0.334.$$

The inductance also depends on the ambient temperature. Since the sensitive element (coil) of the sensor is located in a vacuum chamber at a temperature of about 300°C, the correction for inductance depending on temperature can be determined by the following formula

$$\Delta L_t = L_P \cdot z_t(T_2 - T_1),$$

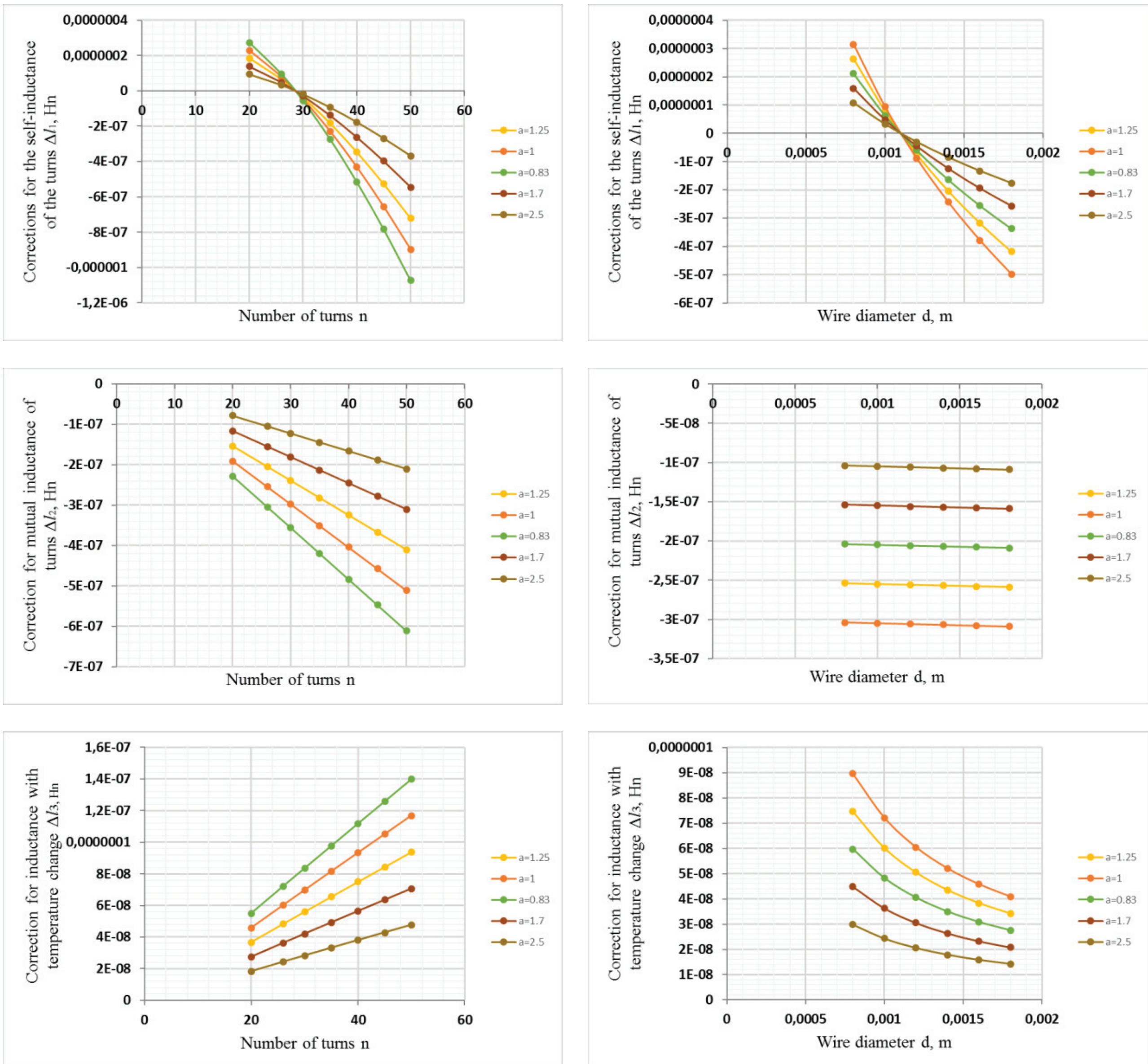
where z_t is the temperature coefficient of inductance; T_2 – maximum temperature, °C; T_1 – minimum temperature, °C.

The temperature coefficient of inductance (TCI) characterizes the change in the actual value of inductance depending on changes in ambient temperature. The effect of temperature leads to a change in the resistivity of the winding. The consequence of this is a change in the penetration depth of the high-frequency components of the alternating current, which is equivalent to a change in the diameter of the winding turn and, consequently, the inductance of the entire coil.

This high-frequency component of the TCI is determined through the quality factor of the coil for the value of the coefficient for a round wire

$$z_t = \frac{k \cdot 10^{-3}}{Q}.$$

Figure 2 shows the inductance corrections for different solenoid shapes depending on the number of turns and wire diameter – they are both linear and non-linear. An increase in the parasitic inductance modulus is observed with an increase in the number of turns of the same wire (Fig. 2, a), so the correction for mutual inductance is negative, and the inductance correction for temperature is positive, wherein both inductance corrections have almost linear dependences. As a separate case it is possible to designate a correction for its own inductance, where it is absent with a quantity of 30 turns and acquires maximum values at 50 turns.



(a) (b)

Fig. 2. The value of the inductance correction for different solenoid shapes: a = 0,83 (l = 0,05 m, d = 0,06 m); a = 1 (l = 0,05 m, d = 0,05 m); a = 1,25 (l = 0,05 m, d = 0,04 m); a = 1,7 (l = 0,05 m, d = 0,03 m); a = 2,5 (l = 0,05 m, d = 0,02 m); (a) dependence on the number of turns of the same wire, (b) dependence on the wire diameter for a fixed number of turns

With an increase in the diameter of the wire (Fig. 2, b) an increase in the parasitic inductance modulus is observed similarly to the previous case, but the nature of the graphs has a different form. The correction for self-inductance has a zero value point in the region of the wire diameter of 0,0011 m, and the maximum value is 0,0018 m. The correction for mutual inductance has a negative, almost horizontal (linear) character, which indicates a weak influence of the wire diameter on this correction. In turn, the inductance correction for temperature has a significant non-linear character and decreases with wire thickening.

So, a quality coil has the following characteristics. The winding material must be made of metal with a minimum specific resistance and with the maximum possible (within reason) wire diameter (copper or silver-plated copper). The coil must be made in large sizes. However, in addition to the dimensions of the coil, you should pay close attention to the form factor – the ratio of the length to the diameter of the product. At the same time in the course of the presented studies coils with minimal inductive losses were distinguished, in which the length exceeded the width. To minimize the proximity effect and reduce the self-capacitance of the coil, it is necessary to take the optimal ratio of the winding pitch (distance between the centers of adjacent turns) to the wire diameter, equal to ≈ 2. At the same time, depending on the corrections for mutual and intrinsic inductance, the optimal coil has 26 turns with 0,001 m a wire diameter, and a dimensional length-to-diameter ratio of the coil is 2.5, since in this configuration there is compensation for the positive correction for intrinsic inductance and the negative corrections for mutual inductance. As a result, the main error for the coil is the temperature correction of the inductance, but due to the high quality factor, it is insignificant and has a multiplier of 10^{-8}.

Therefore, the calculation of the inductance of the coil of an eddy current sensor must be made with a margin that takes into account all corrections for inductance. The resulting inductance of the coil is taken as the working one for further investigations.

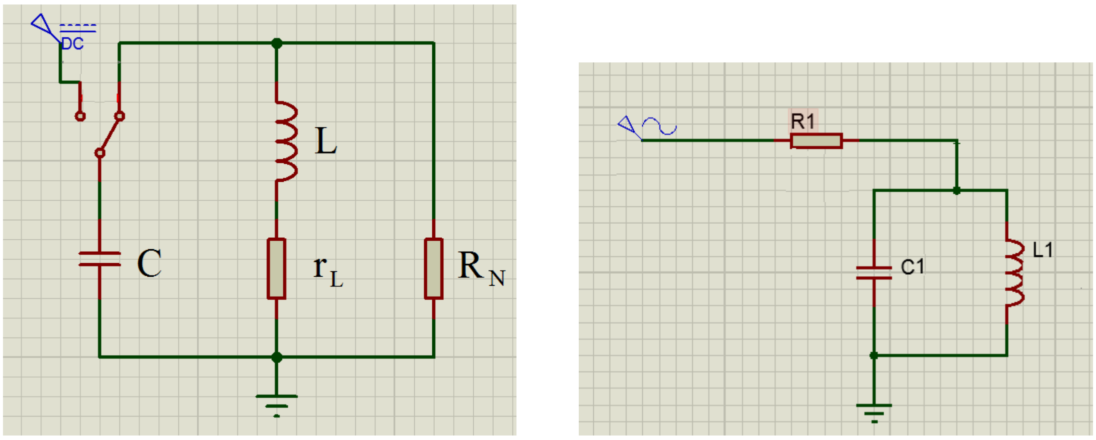
2 Determination of the Maximum Quality Factor of the Oscillatory Circuit

The quality factor of the circuit is the parameter of the oscillatory system that determines the width of the resonance and characterizes how many times the energy reserves in the system are greater than the energy losses during the phase change by 1 radian. The quality factor is inversely proportional to the damping rate of the natural oscillations in the system. That is, the higher the quality factor of the oscillatory system, the less energy loss for each period and the slower the oscillations decay.

The oscillatory circuit of the eddy current sensor is shown in the Fig. 3, where the following designations are adopted: L and C – the intrinsic inductance and capacitance of the components that make up the oscillatory circuit, r_L – the coil resistance, equivalent to the loss of electrical energy in the wire of the inductor, R_N – the sum of the resistances due to losses in the wire insulation, frame, screen, core of the inductor and also losses caused by the presence of leakage currents in the capacitor. When the external circuits are connected to the presented circuit, an additional resistance R_n is added in parallel with R_N that is introduced by these external circuits. Figure 3 (a) does not show one more capacitance equal to the sum of the parasitic capacitances of the inductor, external circuits and the parasitic capacitance of the installation. At high frequencies, these added capacitances can have significant values commensurate with the capacitance of the loop capacitor itself. These capacitances do not have a significant effect on the quality factor, but when calculating the resonant frequency, they must be taken into account and summed up with the value of the main capacitance C.

In the general case the number of oscillations from the moment of excitation of free oscillations until the moment when their amplitude decreases by a factor of 23,14 times will exactly be numerically equal to the quality factor of the circuit Q. The number of periods of free oscillations in the circuit can be counted by a pulse counter and thus find out the quality factor of the oscillatory circuit.

For low (sound) frequencies, the quality factor is equal to the ratio of the reactance of an inductive or capacitive nature (characteristic resistance) to the total series resistance of losses in the resonant circuit. In view of the fact that the capacitors at these frequencies practically do not introduce losses, the quality factor of the circuit is equal to the quality factor of the inductor, the value of which directly depends on the active resistance of the coil. At high frequencies the value of the active resistance of the coil can be fractions of an ohm, in addition, the effect of the quality factor of the capacitor on the overall quality factor of the circuit is possible, therefore it will not be possible to manage with the same primitive methods as in the case of low frequency. In this case the authors propose to use computer simulation to determine the quality factor and select the parameters, which increase the efficiency of the sensor that can significantly reduce the number of experimental studies and the time required to conduct them with the real sensor.



(a) (b)

Fig. 3. The oscillatory circuit of the eddy current sensor: (a) ideal; (b) simulation model (real)

The Proteus Design system [41–43] was decided to use in the paper, because it is the leading software for electronic circuit simulation. A number of simulation models of oscillatory circuits of sensors with different parameters of capacitance and inductance were developed at a fixed frequency of the master oscillator at 1 MHz. A coreless solenoid calculated according to the proposed method was used as an inductance, and a capacitor with a low leakage current was used as a capacitance. The implementation scheme of the oscillatory circuit is shown in Figure 3 (b).

Since the oscillator frequency is fixed (1 MHz), other circuit parameters were calculated based on the resonant frequency formula:

$$f = \frac{1}{2\pi\sqrt{LC}},$$

where f – resonant frequency of the circuit, Hz; L – coil inductance, H; C – the capacitance of the capacitor, F.

The quality factor is determined from the amplitude-frequency characteristics of the simulated models presented in Fig. 4. The bandwidth of each circuit Δf is conditionally determined according to the amplitude-frequency characteristic. At the same time it was assumed that the voltage within this band has the right to decrease to the level of 0,707 from the maximum. Based on this, the formula for determining the quality factor takes the following form:

$$Q = f_{res}/\Delta f.$$

The frequency values of the passbands and the quality factor of each oscillatory circuit are summarized in Table 1.

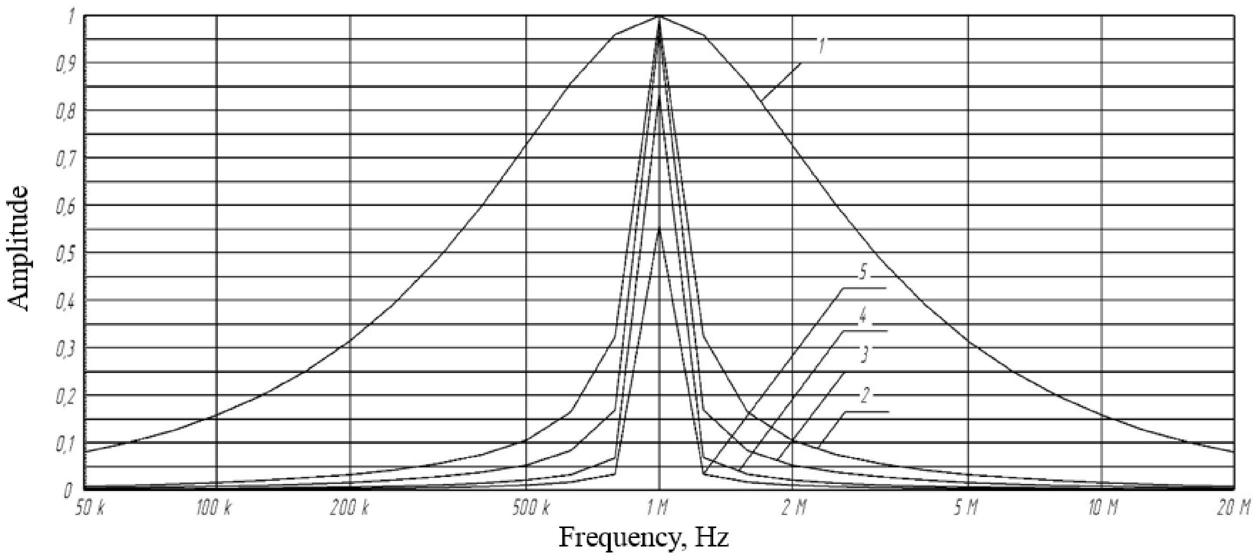


Fig. 4. Amplitude-frequency characteristics of oscillatory circuits at frequency 1 MHz: 1 – L=253,128 μH, C=100 pF, R=1kOm; 2 – L=253,312 μH, C= 1000 pF, R=1kOm; 3 – L=12,656 μH, C=2000 pF, R=1kOm; 4 – L=5,062 μH, C=5000 pF, R=1kOm; 5 – L=2,531 μH, C=10000 pF, R=1kOm

Табл. 1 The frequency values of the passbands and the quality factor of each oscillatory circuit

№	Coil inductance, μH	Capacity, pF	Resistance, kOm	Amplit ude	Quality factor	Minimum band frequency, Hz	Maximum band frequency, Hz
1	253,128	100	1	1	0,626	483 000	2080000
2	25,312	1000	1	0,98	5	910 000	1110000
3	12,656	2000	1	0,96	5,917	926 000	1095000
4	5,062	5000	1	0,83	6,329	930 000	1088000
5	2,531	10000	1	0,55	7,194	936 000	1075000

The quality factor increases linearly with increasing frequency and reaches a maximum at the self-resonant frequency, when the capacitance is minimal and equal to the self-parasitic capacitance of the coil and the parasitic capacitances of the source, load and installation, the eddy EMF field in the surrounding conductors. To achieve the maximum quality factor at a certain frequency, there is an optimal value for the inductance of the coil. The quality factor decreases with a decrease in frequency, but not linearly, but somewhat more slowly due to a decrease in the influence of the skin effect, and with an increase in frequency it also gradually decreases due to the apparent dependence of the total parasitic capacitances on frequency (varicap effect).

The scheme of the proposed oscillatory circuit is a voltage divider in which the resistance of the parallel oscillatory circuit (the reactances of the coil and the capacitor) depends on the frequency of the generator, we replace the oscillatory circuit with the equivalent resistance of the circuit R_{con} that includes the total active resistance of the coil circuit and the capacitor. In this case a voltage divider is obtained from the resistance R_1 and R_{con}. Less resistance drops less voltage, more resistance drops more voltage. At the resonant frequency the resistance R_{con} will be maximum, as a result of which a greater voltage will "fall" on this resistance.

3 Implementation of an Eddy Current Sensor and its Verification

The eddy current sensor consists of a sensitive inductor included in a parallel LC oscillatory circuit with a high quality factor. This sensor measures the thickness of the metal film using the witness method, which allows you to select the operating temperature of the measuring element in the vacuum chamber. Its scale is graduated in units of the thickness of the deposited film (microns) and depends very much on the relative position of the deposited part, the sensor, and the crucible. The device of the eddy current sensor for measuring the metal film on the blades is shown in Fig. 5.

Figure 5 shows the construction of the proposed sensor that consists of the following parts: 1 - a base, 2 - a coil, 3 - a plate, fixed on the base of a measuring glass 4, tightly pressed to the coil frame by a frame 5, fixed by springs 6, mounted on a plate of a heating element 7, mounted on the sensor frame. The sensor is placed in a vacuum chamber, where metal is sprayed onto the blades, and operates in a wide temperature range up to 300°C. The measuring block of the sensor is located outside and consists of: a reference signal generator, a coilless oscillatory circuit, a subtractor and a measuring device.

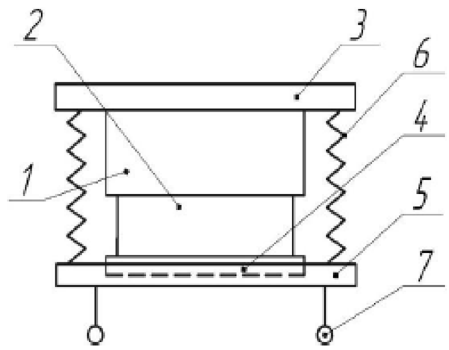


Fig. 5. Scheme of the device sensor for measuring the thickness of thin metal films: 1 - base, 2 - coil, 3 - plate, 4 - measuring cup base, 5 - frame, 6 - springs, 7 - heating element plate

A standard signal generator can be implemented using a Wien bridged sine waveform generator on the OP275GP chip and generates a signal at a frequency of 1 MHz. The generator is an electronic amplifier covered by a frequency-dependent positive feedback via a Wien bridge. The generator can generate a voltage in a wide tunable frequency range and a sinusoidal voltage with small differences from an ideal sinusoidal signal by changing the parameters of the Wien bridge. For the electronic implementation of the oscillatory circuit the following components were selected: the sensing element is a heartless choke with a single-layer winding (26 turns), the operating inductance L1=25.31 μH (coil dimensions: diameter 0,088 m, length 0,14 m), capacitance - capacitor with low leakage current C1=1000 pF, resistance R1=1 kOhm. The subtractor is based on the MAX4194ESA operational amplifier and processes rectified signals after high-pulse 1N4148 diodes.

The modern approach to the design of the sensors includes the mandatory modeling and analysis of the electronic circuit in computer-aided design software systems [8, 43, 44]. For verification it was decided to simulate the eddy current sensor circuit using the Proteus Design system that is based on the models of electronic components adopted in PSpice and is the leading software for modeling and studying electronic circuits of sensors, transducers and other electronic devices. The scheme of the eddy current measuring block developed in Proteus Design is shown in Fig. 6.

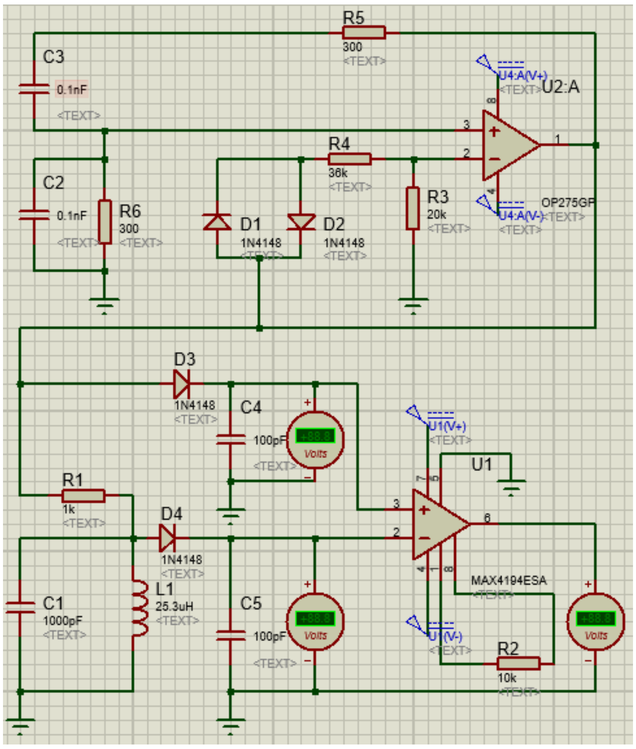


Fig. 6. Scheme of the implementation of the sensor and measuring device

The thickness gauge of the deposited film in the vacuum chamber works as follows. A clean measuring glass is installed on the sensor, tightly pressing it to the frame with a frame. A batch of turbine blades is loaded into the chamber, the chamber is closed. Then the necessary degree of vacuum is created in the chamber by turning on the heating element for 7-10 minutes to warm up the measuring glass, and the deposition installation is turned on. A metal film is sprayed onto the measuring glass, the thickness of which increases with time. To control its thickness, you must turn on the measuring device. The generator of standard (sinusoidal) signals sends a signal of a certain frequency to the coil of the measuring element; then this signal, after rectification, enters the subtraction unit, where it is subtracted from the constant component that comes from the rectified signal of the generator. The difference between these signals can then be fed to a measuring device, the scale of which is calibrated in units of the thickness of the metal film.

The sensitivity of the sensor to an increase in the inductance of the coil was checked based on the proposed simulation model (Fig. 6), the data are summarized in Table 2.

The sensor coil is tuned to resonance with the standard signal generator at a clean measuring glass. During deposition, the inductance of the sensor coil increases and it goes out of resonance; therefore, the signal coming from the sensor to the subtraction unit decreases with increasing thickness of the film deposited on the measuring glass. Consequently, the difference of the signals coming from the subtractor to the measuring device grows with the growth of the film thickness. On the scale of the measuring device, one can read the thickness of the sprayed film at any time during spraying. The scale of the device is graduated in units of the thickness of the sprayed film in microns and is very dependent on the relative position of the sprayed glass, sensor and heating element. The sensor is sensitive to the choice of the working point of measurement in the vacuum chamber and it determines the calibration of the scale. The measurement limits of such a sensor range from 1 to 500 microns. Before the next session of deposition on the measuring element, it is necessary to change the measuring glass on which the film was deposited. On the film from this glass, using control samples, the scale of the device is calibrated.

Conclusion

This paper considers the study and the design of an eddy current sensor for monitoring the thickness of a metal film deposited in vacuum on the turbine blades during the deposition process. A constructive implementation of an eddy current sensor for work in the vacuum chamber at a temperature of 300°C, in real time, is proposed. The sensor inductor was calculated taking into account corrections for its own inductance, mutual inductance and inductance versus temperature, and the results are displayed on families of graphical dependencies. Computer modeling of the simulation models of the oscillatory circuits of the sensors was performed and the amplitude-frequency characteristics were obtained, according to which the quality factors at a frequency of 1 MHz were determined. In addition, the simulation of the sensor work in the Proteus Design software environment was carried out, which gave qualitative and quantitative results within the permissible error and theoretical ideas about the operation of the eddy current sensor. Moreover, the software implementation in Proteus Design significantly reduces the design time, allows to optimize the parameters of the sensor electronic circuit according to the main criteria.

Табл. 2 Operating parameters of the sensor work depending on the inductance of the coil

Coil inductance, uHr	Rectified voltage from the generator, V	Rectified voltage from the oscillatory circuit, V	Voltage on the instrumentation amplifier, V	Percent inductance increase	Voltage deviation from the reference value, V
25,3	2,4	2,287	1,35	0	0
25,8	2,4	2,275	1,38	1,976	0,03
26,5	2,4	2,274	1,39	4,743	0,04
27	2,4	2,269	1,44	6,719	0,09
27,5	2,4	2,263	1,51	8,696	0,16
28	2,4	2,249	1,66	10,671	0,31
28,5	2,4	2,243	1,73	12,648	0,38
29	2,4	2,232	1,85	14,625	0,5
29,5	2,4	2,219	1,99	16,6	0,64
30	2,4	2,206	2,13	18,577	0,78

The use of the methods considered in the work makes it possible to increase the accuracy and efficiency of the eddy current sensor for monitoring the thickness of the deposited metal film on the turbine blades that increases reliability and facilitates the assembly of products, resulting in an increase in the volume of output and an increase in labor productivity. The efficiency of the sensor is estimated by the high quality factor of the oscillatory circuit due to the sensitive coil, which ensures, with a minimum change in inductance, the oscillatory circuit exits from resonance and the measured voltage deviates from the reference value. So with an increase in inductance of 18%, the measuring voltage increased by 58%. In this case, high measurement accuracy in the micrometer range is achieved due to the uniform spraying of metal on the glass of a much larger area compared to the cross-sectional area of the coil, which leads to minimal changes in the inductance in the coil. This design of the sensor provides high inertia to instantaneous changes in electrical parameters in the coil, which allows the sensor to respond only to a constant perturbing signal proportional to the dust of the metal. The advantage of this sensor is a relatively high versatility in the field of application, small dimensions, weight, long time of continuous operation, the ability to operate in a continuous tracking mode in a wide temperature range (20-300°C). In addition, this sensor can be used in other areas of the national economy where there is a need to control thin metal films, for example, in enterprises engaged in metallization of parts and materials.

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Підвищення ефективності датчика вихрових струмів, що вимірює товщину термостійкої металевої плівки лопатей турбіни під час її осадження у вакуумі

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У статті аналізуються конструктивні особливості та загальне моделювання вихрострумового датчика для вимірювання товщини металевої плівки. Сформульовані основні завдання роботи щодо підвищення точності та ефективності вихрострумового датчика на основі аналізу різних рішень у турбобудуванні. Мета дослідження – вивчення особливостей роботи чутливого елемента (котушки) вихрострумового датчика вимірювання товщини плівки жароміцного металу лопаток турбіни у вакуумній камері з подальшим комп'ютерним моделюванням його функціонування для виявлення оптимальних параметрів коливального контуру. Поставлена мета досягається вирішенням наступних завдань. По-перше, запропоновано конструктивну реалізацію вихрострумового датчика вимірювального перетворювача для роботи у вакуумній камері при температурі 300°C. По-друге, виконаний розрахунок чутливого елемента датчика (котушки індуктивності) для роботи за підвищених температур. По-третє, при розрахунку індуктивності докладно вивчені та враховані поправки на власну та взаємну індуктивності витків, а також виправлення індуктивності від температури. На останок, проведено комп'ютерне моделювання розробленого вимірювального перетворювача, виконаного на основі коливального контуру, та визначено добротність імітаційних моделей. Найбільш значущі важливі результати роботи полягають у наступному: а) запропонована методика дозволяє розробити оптимальний чутливий елемент для роботи у вакуумі та при підвищених температурах, та б) імітаційна модель дозволяє визначити найкращі електричні параметри елементів вимірювального перетворювача. Значимість отриманих результатів полягає у можливості підвищення точності та, відповідно, оперативності вимірювання товщини термостійкої металевої плівки лопаток турбіни.

Ключові слова: вихрострумовий датчик; лопатка турбіни; термостійке покриття; металева поверхня; товщина; вимірювальний перетворювач; коливальний контур