Development of sensor for measuring the aircraft metal parts contact potential difference

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Abstract. The article is devoted to solving the problem of determining the electron work function of aircraft metal parts of aviation technology by the Kelvin probe method. The features of the application of the Kelvin probe method for contact potential difference measurement for aircraft metal parts are considered. Requirements for the Kelvin probe developed for measuring the contact potential difference of metal parts are formulated. A comparative analysis of materials for the manufacture of the measuring electrode of the sensor is carried out. A technique is proposed to ensure the stability of the measurement results of the contact potential difference, and the factors influencing it are assessed. Practical recommendations are given for the Kelvin probe development of the contact potential difference measuring on the aircraft metal parts surface.

1. Introduction
Structural alloys based on Fe, Al, Ti, Cu, Mg and other metals are widely used in modern aircraft construction. In the manufacture, operation and repair of aircraft metal parts, knowledge of their technical condition is necessary, which can be successfully determined by non-destructive testing methods [1, 2].

The known method of contact potential difference related to the electrical type of non-destructive testing of machines metal parts. Its other name is the Kelvin probe method [3, 4]. The Kelvin probe is a capacitive sensor with a reference measuring electrode (tip), which is applied to the controlled area of the metal parts surface. However, in this case, the measuring electrode touches the surface of the metal parts, being at a certain distance from it. In this case, a capacitor is formed, the plates of which are the surfaces of the measuring electrode and metal parts. Between the plates of such a capacitor, the contact potential difference is formed, which is registered by the measuring device. At its core, contact potential difference is voltage, the unit of its measurement is Volt.

The advantages of such capacitor sensors for contact potential difference measuring are:

- ensuring a sufficiently high accuracy of sensor manufacturing;
- the capacitor formed during the measurement of the contact potential difference has low losses, since the passage of electric current through the capacitive resistance is not accompanied by heat losses and high efficiency;
- little influence of electrical forces on the mechanical parts of the capacitor;
• the shape of the capacitor-type sensor can be easily adapted to the various surface shapes of the metal part.

The disadvantage of capacitor methods for measuring the contact potential difference is the small values of the capacitance between the capacitor plates. Therefore, it is necessary to use power amplifiers of an electric signal, or high-frequency oscillations of the capacitor plates, which does not always ensure the stability of the readings of the contact potential difference measuring device. In addition, the measurement error of the contact potential difference can be increased by electromagnetic interference arising in the electrical circuit as a result of the remote location of the signal amplifier from the measuring electrode.

Thus, the sensor is an important part of the contact potential difference measuring device, on which the quality of non-destructive testing of aircraft metal parts at various stages of their life cycle largely depends.

The known publications on the development of Kelvin probes do not fully take into account the factors affecting the accuracy and stability of the results of measurements of the contact potential difference on the surface of aircraft parts made of multicomponent metal alloys [3–5]. It is required to develop a methodological approach to the construction of the sensor that increases the accuracy and stability of the contact potential difference measurement results.

2. Research and instrumentation

Features of the Kelvin Probe Method Application. The solution to the problem of ensuring high accuracy and stability of the measurement results of the contact potential difference on the surface of the aircraft metal parts is associated with the Kelvin probe method essence. The Kelvin probe method is based on comparing the work function of the electron from the metal of the measuring electrode and the metal part. The work function is the minimum work done to remove an electron from a metal part at a distance where no metal forces act on it. In reality the electron work function is understood as the work of transferring an electron from a metal part beyond its surface. The unit of measure for the electron work function is Joule or electronVolt. The electron work function from a metal characterizes its electronic, energy state. The values of the electron work function correlate with many parameters of the part - elasticity, strength, corrosion and wear resistance, surface energy and others, which must be taken into account in the production, operation and repair of aircraft metal parts [3],[4],[5].

Equation (1) defines the electron work function $\phi$ as the difference between the electrostatic potentials inside and outside the metallic one and its Fermi energy [6]:

$$\phi_{mp} = (\phi_{in} - \phi_{ex}) - E_F = 4\pi \cdot P_s - E_F,$$

(1)

where $\phi_{in}$ and $\phi_{ex}$ is, respectively, the electrostatic potential inside and outside the metal part; $E_F$ is the Fermi energy of the metal part; $P_s$ is the unit dipole moment of the double electric layer on the surface of the metal part, per unit area of its surface.

The electric double layer formed on the metal surface has a thickness of about 0.5 Å, and is formed with negative charges directed outward, and with positive charges directed to the inside of the layer. The reason for the formation of an electric double layer is that electrons moving in the metal with sufficient kinetic energy are ejected from its surface. Electrons are held above the surface by positively charged ions. In this case, the electrons escaping from the metal form a spatial negative electric charge above its surface. In order to escape from the metal, the electron must do the work of overcoming the forces of the electric field inside the metal and the electric double layer. This work is the electron work function [7, 8].

Equation (2) determines the value of the contact potential difference of two metals in vacuum as the difference between their electron work functions [9]:

$$U = (\phi_{me} - \phi_{mp}) / e,$$

(2)
where $U$ is the contact potential difference between the measuring electrode and the metal part, $V$; $\phi_{me}$ is the electron work function from the Kelvin probe measuring electrode, $J$; $\phi_{mp}$ is electron work function from a metal part, $J$; $e$ is unit charge of an electron, $C$.

Let us assume that we know the electron work function value from the measuring electrode $\phi_{me}$. Now you can measure the contact potential difference with a Kelvin probe on the surface of aircraft metal part. And according to Equation (2), one can determine the electron work function value from the metal part $\phi_{mp}$. As can be seen from Eq. (2), a decrease in the contact potential difference $U$ indicates an increase in the electron work function of the controlled aircraft metal part. However, the condition of stability of the electron work function from the metal of the measuring electrode of the sensor of the device for measuring the contact potential difference must be met.

Thus, the sensor is a kind of transfer link between the value of the electron work function from the aircraft metal part and the measuring circuit of the device for measuring the contact potential difference.

When measuring the contact potential difference on air, the medium of the gap in the capacitor formed by the measuring electrode and the surface of the controlled metal part is of great importance. Therefore, Equation (2) is not exactly suitable for determining the electron work function from a metal in air by the Kelvin probe method.

We use a mathematical model of a capacitor that forms a metal surface and a reference measuring electrode of a Kelvin probe installed on it. Eq. (3) shows the value of the contact potential difference in the capacitor formed by the surface of the metal part and the measuring electrode of the Kelvin probe applied to it [9]:

$$U = \frac{q}{C},$$

where $U$ is the metals contact potential difference, $V$; $q$ is the charge on the capacitor plates formed by the measuring electrode and the of the aircraft metal part surface, $C$; $C$ is the capacity of such a capacitor, $F$.

Based on Eq. (2) and (3) we can derive the final Eq. (4) showing the value of the electron work function from the metal part surface [10]:

$$\phi_{mp} = \phi_{me} - e \cdot \frac{q}{C}$$

where $\phi_{mp}$ is the electron work function from a metal part, $J$; $\phi_{me}$ is the electron work function from the Kelvin probe measuring electrode (tip), $J$; $e$ is unit charge of an electron, $C$; $q$ is the charge of the capacitor formed by the surface of the metal part and the measuring electrode, $C$; $C$ is the capacity of such a capacitor, $F$.

A variation of the Kelvin probe method is the Kelvin-Zisman method or the dynamic capacitor method, in which the measuring electrode oscillates with a certain frequency and amplitude above of the metal part surface to be inspected, also without touching it. The dynamic capacitor method increases the accuracy of the contact potential difference measurement. However, this reduces the stability of measurements of the contact potential difference.

Thus, the Kelvin probe method is a relatively simple tool for determining the value electron work function from a metal. The electron work function values correlate with many strength and performance of aircraft metal parts characteristics [11]. Let us consider the features of the development of a Kelvin probe for the contact potential difference measuring for aircraft metal parts surface.

Developing Requirements for the Kelvin Probe. It is advisable to present the following basic functional requirements to the developed sensor of a specialized device designed to measure the contact potential difference on the aircraft metal parts surface:

- The use of an easy-to-analyze form of the dependence between the input and output characteristics, preferably linear. However, it is possible this to implement exponential, power, logarithmic and other dependencies.
• Sufficient sensitivity ensuring. In our opinion, due to the energy inhomogeneity of the surface of the metal parts of the aircraft, it is necessary to ensure of the Kelvin probe sensitivity when measuring the contact potential difference not worse than 1 mV.

• The output characteristics stability ensuring, including the least influence on the Kelvin probe of humidity, temperature, atmospheric pressure, gas composition, electromagnetic fields [12]. In order to fulfill this requirement, it is necessary to use shielding of the sensor from parasitic pickups, and, in addition, as a material for the measuring electrode of the Kelvin probe, use a conductive material with stable characteristics over time.

• The minimum time achievement for the contact potential difference measuring. In devices for measuring the contact potential difference, it can reach several tens of seconds.

• Simplicity of manufacture and operation.

• Maintainability ensuring.

• High economic efficiency. Including high performance and low cost of measurements of contact potential difference.

These functional requirements for the Kelvin probe are developed formulated to improve the efficiency of measurements of the contact potential difference on the aircraft metal parts surface.

3. Results and discussion

Measuring Electrode Material Selection. The measurement of the contact potential difference of aircraft metal parts is influenced by the environment [12]. Therefore, the Kelvin probe measuring electrode must be made of a conductive material that is least exposed to the influence of the environment and retains its characteristics constant over time.

The most popular among developers are the following metals and alloys used for the manufacture for the Kelvin probes measuring reference electrode [6], [12], [13], [14], [15], [16]: gold, platinum, nickel, copper, brass, and stainless steel.

The main property of the metal selected for the manufacture of the measuring electrode is the stability of the oxide layer of its surface and its corrosion resistance, since the oxide layer significantly increases the electron work function from the metal. An increase in the work function of the electrode from the metal of the controlled part is recorded by an increase in the contact potential difference measured on its surface by a Kelvin probe.

A great influence on the measurement accuracy of the contact potential difference is the quality of the surface treatment of the measuring electrode, in particular, its roughness. The smaller the roughness of the measuring electrode surface, the smaller the error in measuring the contact potential difference. The device developed by us for measuring the contact potential difference [16] on the surface of aircraft parts made of multicomponent metal alloys has an error of 15 mV. For Kelvin probes, this is considered a good result.

Measuring Electrode Oscillation. In a dynamic capacitor according to the Kelvin-Zisman method, the electrical signal of the contact potential difference arises due to the conversion of the mechanical energy of the vibrational motion of the measuring electrode of the sensor into the energy of an electric current. Electric current in a dynamic capacitor is generated due to periodic changes in the screening conditions for electrostatic charges above the aircraft metal part surface [17].

Figure 1 shows an elementary input circuit diagram describing how the Kelvin-Zisman method works. Figure 1 indicates: U is voltage compensation of the signal of the contact potential difference; \( C(t) \) is capacitance of a variable dynamic capacitor; \( \omega \) is the cyclic oscillation frequency of the measuring electrode; MP is metal part; ME is Kelvin probe measuring electrode; R is a load resistor from which the signal of the contact potential difference is taken.
Equation (5) describes the value of the capacitance of a dynamic capacitor $C_d(t)$, the plates of which are a measuring electrode vibrating at a certain frequency and the metal part surface, as shown in Figure 1 [18]:

$$C_d(t) = \frac{\varepsilon_0 \cdot \varepsilon \cdot S}{d_0 + d_1 \cdot \sin(\omega \cdot t)},$$  \hspace{1cm} (5)$$

where $d_0$ is the distance between the measuring electrode and the metal part surface at a static position of the measuring electrode; $d_1$ is the vibration amplitude of the measuring electrode; $\omega$ is the measuring electrode cyclic oscillation frequency; $t$ is the measurement time of the contact potential difference on the aircraft metal part surface.

Equation (5) shows that the capacitance of a dynamic capacitor according to the Kelvin-Zisman method when measuring on air the contact potential difference of aircraft metal parts depends on the distance $d_0$, as well as on the area of the Kelvin probe measuring electrode, its frequency and vibration amplitude.

In practice, in a dynamic capacitor, the area of the measuring electrode is selected to be several tens of square millimeters, but there are also measuring electrodes of a smaller area, designed for point measurement of the contact potential difference on the part surface. But in this case, in the design of the Kelvin probe, an amplifier of the electrical signal from a dynamic capacitor with a high gain should be used, since the signal of the contact potential difference is too weak. A stronger filtering of the electrical signal from noise is also required [19].

The shape of the measuring electrode is usually chosen symmetric, most often round in plan. However, there are also square measuring electrodes, as well as made in the form of a string. The main condition for choosing the shape of the measuring electrode is the effectiveness of non-destructive testing of aircraft metal parts by the Kelvin probe method.

According to Eq. (5), the distance $d_0$ between the measuring electrode and the metal part surface with the sensor pressed against it is fractions of a millimeter. Most often, the measuring electrode in the Kelvin-Zisman method is set in oscillatory motion by piezoelectric elements [16] or electromagnetic inductance coils [20]. However, a pneumatic drive [21], a musical tuning fork [22], and a flexible membrane of a sound speaker [23] can be used to set the measuring electrode in oscillatory motion. The oscillation frequency of the measuring electrode according to the Kelvin-Zisman method is used from several hundred hertz to several kilohertz.

Figure 2 shows an example of an electrical circuit that sets the oscillation frequency of a piezoelectric element, leading to vibration of the measuring electrode of the Kelvin probe when measuring the contact potential difference [16].
The vibration amplitude of the measuring electrode is tenths of a millimeter. An important and rather difficult task for the developer of the sensor of the device for measuring the contact potential difference is to ensure the constancy according to equation (5) of the distance between the measuring electrode and the metal part, the frequency and amplitude of the oscillations of the measuring electrode above the surface of the aircraft metal part. Therefore, before measuring the contact potential difference on the surface of metal parts, it is important to check the health of the Kelvin probe.

Kelvin Probe Housing. An important part of the Kelvin probe is its housing. The Kelvin probe housing must have sufficient rigidity and strength, be ergonomic, and have the properties of a shield against the impact of external electromagnetic fields on the dynamic capacitor. The shielding housing of the device sensor for measuring the contact potential difference in this case is a kind of Faraday cup.

It is also advisable to shield the measuring electrode directly from the impact of the oscillatory system located in the same housing, which sets it in motion, since the inductors and piezoelectric elements are quite noisy.

For the shielding effect, stainless steel or other corrosion-resistant metal alloy can be used as the housing material. But it is also possible to choose plastic as the material of the sensor body, but with a shielding metal layer applied to it, for example, in the form of a foil. Figure 3 shows an example of the development of a Kelvin probe body [16] using a computer program and then printed on a 3D printer.
In most cases, the Kelvin probe is connected with electrical wires to a measuring device that quantifies the contact potential difference. It should be remembered that loops and bends of electrical wires change their capacitance, which can also affect the accuracy of measurements of the contact potential difference. Therefore, it is also necessary to screen the electrical wires connecting the Kelvin probe to the measuring device of the contact potential difference meter.

Method for Measuring Contact Potential Difference. An advantage and at the same time a disadvantage of the Kelvin probe method is its high sensitivity to contamination of the surface of a metal part, which is common in the environment during the production, operation and repair of aircraft. These circumstances can be an advantage when controlling the degree of cleaning of the surface of metal parts, for example, before applying protective coatings, gluing or soldering. In other cases, it is necessary to thoroughly clean the surface of the investigated metal part so that the existing contamination does not affect the accuracy of measurements of the contact potential difference on its surface.

The simplest, most inexpensive and effective cleaning of the metal parts surface by a chemical method, for example, with solvents. We have developed a method for cleaning the surface of metal parts [24], including cleaning with petroleum ether, and making it possible to effectively prepare it for measuring the contact potential difference.

The Kelvin probe method is characterized by fluctuation of measured values, that is, their fluctuation around a certain average value when several measurements of the contact potential difference are made. Therefore, it is desirable to carry out measurements of the contact potential difference of aircraft metal parts in a laboratory environment.

The methods for measuring the contact potential difference on the aircraft metal parts surface, depending on the tasks of non-destructive testing, are somewhat different from each other. Measurements of the contact potential difference can be carried out either pointwise, to determine the electron work function on some small area of the surface of an aircraft metal part, or by scanning a larger surface area of the part with a Kelvin probe.

But then it is imperative to process the results of measurements of the contact difference of potentials by methods of mathematical statistics [25].

If abnormally low or high values of the contact potential difference are found on areas of the metal part surface, it is advisable to investigate these areas of the part by eddy current or magnetic methods.

Further research on the development of the Kelvin probe should be carried out to improve its design and methods of its application in relation to specific aircraft parts.

4. Conclusion
In the course of the research, the following results and conclusions were obtained:

- To ensure the required accuracy and stability of the contact potential difference measurements, it is proposed to carefully screen the parts of the Kelvin probe both from external electromagnetic influences and from the effects of the elements of the probe itself, especially from electromagnetic inductance coils or piezoelements that vibrate the measuring electrode (tip).
- A prototype of the Kelvin probe has been developed, for which a patent for an invention has been obtained.
- A method aircraft metal parts preparing for measuring the contact potential difference has been developed, for which a patent for an invention has been obtained.
- A methods has been developed for measuring the contact potential difference on the aircraft metal parts surface.

The approaches outlined in this article can be useful when used for other methods of non-destructive testing of machine parts.
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References

[1] Alymov M I and Averin S I 2020 Lower Limit Size of Pores in Metals under Sintering Inorganic Materials: Applied Research 11(3) 669-71 DOI: 10.1134/S20751132003003X
[2] Betsofen S Ya, Gordeeva M I, Knazyeva Yu A, Shibuneva S V, Panteleev M D and Bakradze M M 2018 Phase composition formation in a V-1469 alloy (Al–Cu–Li system) during friction stir welding Russian metallurgy 11 1059-66 DOI: 10.1134/S0036029518110046
[3] Ibragimov Kh I and Korol'kov V A 2002 Electron work function in physical-chemical investigations Internet Engineering
[4] Markov A A 2004 Electron work function and antifriction of metals Moscow State Institute of Radio Engineering, Electronics and Automation (Technical University)
[5] Goncharenko V I and Oleshko V S 2020 Energy Aspects of Technological Inheritance of Aircraft Metal Parts Russian Aeronautics 63(2) 323-9 DOI: 10.3103/S1068799820020191
[6] Aref'eva L P, Sukiyazov A G, Dolgachev Yu V and Shakhova L S 2020 Contact potential difference of alloyed steel after heat treatment Advanced Engineering Research 20(3) 289-94 DOI: 10.23947/2687-1653-2020-3-289-294
[7] Mousokhranov M V, Kalmykov V V and Malyshev E N 2017 Experimental Research of Variability of Surface Energy Value of Fe37-3FN, C45 and 41Cr4 Steels International Journal of Applied Engineering Research 12(17) 6428-33
[8] Loskutov S V 2003 Change of work function of the electrons under elastoplastic deformation of metals Physical surface engineering 1(3) 304-9
[9] Goncharenko V I and Oleshko V S 2019 The Method of Contact Potential Difference in Assessing the Energy State of the Surface of Metal Aircraft Parts MAI
[10] Malayer J R and Garner A L 2020 Theoretical assessment of surface waviness on work function AIP Advances 10(9) 095110 DOI: 10.1063/5.0016116
[11] Wang S G, Sun M, Liu S Y, Liu X, Xu Y H, Gong C B, Long K and Zhang Z D 2020 Synchronous optimization of strengths, ductility and corrosion resistances of bulk nanocrystalline 304 stainless steel Journal of Materials Science & Technology 37 161-72
[12] Yurov V M and Oleshko V S 2019 The impact of the environment on the contact potential difference of metal machine parts Eurasian Physical Technical Journal 16(1) 31 99-108 DOI: 10.31489/2019NO1/99-108
[13] Singh A K and Rani N 2019 Scanning Kelvin probe study of steel/oil interfaces for corrosion evaluation Materials and Corrosion 70(7) 1162-70 DOI: 10.1002/maco.201810577
[14] Shkilko A M and Kompaneets I V 2013 Factors limiting sensitivity of contact potential difference meter Fundamental and applied problems of engineering and technology 1(197) 103-7 URL: http://oreluniver.ru/public/file/archive/annot_1_2013.pdf
[15] Mousokhranov M V, Kalmykov V V and Malyshev E N 2017 Experimental Research of Variability of Surface Energy Value of Fe37-3FN, C45 and 41Cr4 Steels International Journal of Applied Engineering Research 12(17) 6428-33
[16] Oleshko V S, Tkachenko D P and Fedorov A V 2020 R.F. Patent 2717747
[17] Zharkikh Yu S and Lysochenko S V 2018 Conception of the Kelvin method on the basis of a mechanic-electrical transformation Ukrainian Journal of Physics 63(3) 269-75 DOI: 10.15407/ujpe63.3.269
[18] Danyluk S, Dubanevich A V, Gusev O K, Svistun A I, Tyavlovsky A K, Tyavlovsky K L, Vorobey R I and Zharin A L 2014 Kelvin Probe’s Stray Capacitance And Noise Simulation Devices and Methods of Measurements 1 948 DOI: 10.21122/2220-9506-2014-0-1-17-25
[19] Wicinski M, Burgstaller W and Hassel A W 2016 Lateral resolution in scanning Kelvin probe microscopy Corrosion Science 104 1-8 DOI: 10.1016/j.corsci.2015.09.008
[20] Retrieved from: http://www.kelvinprobe.info/technique-actuator.htm.
[21] Onishchenko A V and Korol'kov V A 1981 S.U. Patent 853514
[22] Kocharov E A and Markov A A 1969 S.U. Patent 255621
[23] Kocharov E A 2008 Physical methods in material control and high technology development Air Force Engineering Academy named after Professor N.E. Zhukovsky
[24] Oleshko V S 2013 R.F. Patent 2488093
[25] Oleshko V S 2019 Optimal Number of Duralumin Samples in Determining the Surface Energy Russian Engineering Research 39(3) 272-5 DOI: 10.3103/S1068798X19030183