Показані існуючі проблеми в галузі контролю товщини ізоляції циліндричних оправ в процесі автоматичного намотування. А також проаналізовано методи контролю товщини ізоляції сталевих і пластмасових оправ, що застосовуються в електротехнічній промисловості.

Контроль товщини ізоляції після намотування призводить до збільшення технологічних відходів теплоізоляції з дорогих матеріалів (наприклад, склоізоляції), усунення виявлених порушень є досить трудомісткою роботою і може привести вироби в непридатний стан. Тому автоматизація процесу контролю товщини ізоляції в процесі намотування завжди була складним, але актуальним завданням. Рішенням цього завдання можна виключити ручну працю, зменшити відходи і підвищити якість промислової продукції, що застосовується в електротехнічній та радіотехнічній промисловості. Розглянуто принципи роботи, фізичні моделі, області застосування різних типів електромагнітних перетворювачів неелектричних величин в електричні. Розглянуто особливості та проаналізовано характеристики основних типів електромагнітних перетворювачів товщини ізоляції оправ. Наведено порівняння характеристики основних типів електромагнітних перетворювачів товщини склоізоляції оправ, показані їх відносні переваги і недоліки. На основі аналізу відповідних методів контролю товщини різних елементів виявлені проблеми, що виникають при автоматизації контролю товщини ізоляції пластмасових і сталевих оправ в процесі намотування. Порівняльний аналіз конструкцій і характеристик існуючих перетворювачів показує, що необхідно удосконалити конструкції лінійних індукційних підвісів з левітаційними екранами і створити ефективні способи передачі переміщень на левітаційний екран. Тоді отримані нетрадиційні конструкції можуть бути успішно використані для автоматичного контролю товщини ізоляції в процесі намотування її на обертові оправи. З цією метою рекомендуються диференціальні індуктивні і трансформаторні перетворювачі з левітаційними екранами і рухливими вимірювальними обмотками. Зазначені перетворювачі забезпечують необхідну точність вимірювань, однозначне безперервне перетворення товщини ізоляції в електричний сигнал в процесі намотування

Ключові слова: електромагнітний перетворювач, магнітна провідність, магнітне опір, магнітне поле, чутливість перетворювача

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THE CHOICE OF THE METHOD AND TECHNICAL MEANS FOR THE AUTOMATIC CONTROL OF THE INSULATION THICKNESS OF THE FRAMES IN THE WINDING PROCESS

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1. Introduction

In the radio engineering and electrical industries, fiberglass and steel elements of a cylindrical profile with external insulation are widely used. Controlling the thickness of insulation winding on rotating frames is a more difficult task than controlling the linear dimensions of non-moving parts. Mass production of such frames requires automation of control of linear dimensions (frame diameter) in the winding process.

Measurement of the insulation of frames after winding by non-electric methods is inaccurate and leads to a decrease in the quality of industrial products based on fiberglass elements.

Detection and elimination of deviations of the linear dimensions of the frames from those established after the completion of the process (after hardening of the expensive insulation material) lead to additional material costs. Therefore, automation and, therefore, continuous, accurate control of the process is an urgent task.

When using non-electric methods in the winding process, relative inaccuracy is preserved, adjustment and matching of the transducer design with the object are complicated.

One of the solutions to the problems is the development of contactless electromagnetic and electromechanical automation devices, among which primary electromagnetic displacement transducers of inductive and transformer types are of great importance. However, existing linear induction suspensions used as electromagnetic displacement transducers have the disadvantages listed below. Therefore, it becomes necessary to determine the optimal method and design to solve this problem.

2. Literature review and problem statement

Known capacitive, inductive and other types of transducers provide satisfactory thickness control of non-moving products up to several micrometers [1]. Steel and fiberglass frames used in the electrical industry have insulation thicknesses of up to (5–15) millimeters. Linear capacitive transducers are easy to manufacture and have a wide range of applications due to some performance advantages [2]. At the same time, these transducers have disadvantages associated with low measuring capacitance, such as the influence of stray capacitances. In addition, linear capacitive transducers have a limited measurement range and low sensitivity.

Ultrasonic displacement transducers are characterized by a wide range of measurements [3]. However, these transducers are inaccurate for this purpose and have a high deadband value of more than 50 mm.

Optoelectronic displacement transducers are widely used in modern control and monitoring systems. This is due to such advantages as high accuracy, speed and manufacturability [4, 5]. However, when solving a number of applied problems, including in the field of insulation thickness control in the winding process, these transducers have the following disadvantages:

– sensitivity to the ingress of foreign elements on the sensitive elements of the source and receiver of optical radiation;

– sensitivity to extraneous light sources;

– increased tuning accuracy.

Contact profilometers, micrometers and minimeters of capacitive and inductive type, as well as inductosins partially provide continuous control of linear dimensions (insulation thickness) [6]. These transducers do not provide appropriate measurement accuracy and linearity of the static characteristic, especially when the thickness of the controlled insulation is greater than one millimeter. In addition, these transducers require complex auxiliary parts for coordination with the object. The linear induction suspensions developed by the author of [7, 8] were used as displacement sensors, which differ from analogues in high accuracy of operation, but these devices have the following disadvantages:

– due to unstable conductivity in the magnetic system, the basic characteristic of the thickness gauge $U_C(\delta_{ins})$ is significantly nonlinear and the residual signal at the gauge output is large;

– the transducer design forms a rigid contact system, which creates additional errors in the gauge output signal U_C;

– due to design flaws, the electrically conductive ring of the transducer can overheat and form a “thermal drift”.

Therefore, it is advisable to conduct a study on improving induction levitation-screen (LS) suspensions and creating effective methods of transferring displacements to LS.

3. The aim and objectives of the study

The aim of the study is to select the method and type of transducers that simplify automatic control of insulation thickness and increase their accuracy in the winding process.

To achieve the aim, the following objectives were set:

– to formulate requirements for frame insulation thickness gauges during winding;

– to determine the characteristics of the main types of linear electromagnetic transducers of cylindrical frames;

– to select designs of electromagnetic displacement transducers to accurately measure the insulation thickness of steel and plastic frames.

4. Analysis of characteristics and design features of various types of electromagnetic displacement transducers

4. 1. Requirements for transducers to ensure automatic insulation thickness measurement in the winding process

In the radio engineering and electrical industries, fiberglass elements of cylindrical profile with external insulation are widely used. Such products have found application in electrical equipment, communications, radar systems, on-board system systems, etc. Steel and plastic frames can have straight and stepped shapes, with the length and thickness of the cylinders varying widely. For example, the length is (10–200) mm and the wall thickness is (1.5–20) mm.

Controlling the thickness of the insulation winding on rotating frames is a more difficult task and further complicates the automatic control in the insulation winding process.

It should be noted that the measurement of the insulation thickness of steel and fiberglass frames after winding by non-electric methods, such as mechanical sensing, ultrasound, pneumatic and microwave methods are inaccurate. Application of these methods increases the amount of waste insulation and manual labor and decreases the quality of industrial products based on fiberglass elements. Mass production of such frames requires automation of insulation thickness control in the winding process.

Thickness control of the insulation of steel and plastic frames during automatic winding is associated with a number of features that can be reduced to the following problems [8, 9]:

1) required degree of accuracy;

2) unambiguous continuous conversion of insulation thickness into an electric signal in the winding process;

3) control of uneven winding requires the automatic movement of the measuring device along the frame with the simultaneous conversion of insulation thickness into an electric signal;

4) different behavior of the individual measuring system and the same system integrated into the measuring unit.

In most cases, the thickness measurement system consists of an insulation thickness transducer, an electrical measuring circuit and an auxiliary device. Auxiliary devices are design solutions for matching the thickness transducer with the controlled object. To transfer the thickness dimension to the working element of the transducer, rollers, supports, guides, limit stops, etc. are used. Auxiliary devices introduce their errors to the overall measurement error of the insulation thickness [10]. Thus, automatic control of the insulation thickness during the insulation winding along the frame requires two tasks to be solved. The first of them relates to the selection of the appropriate control method or type of insulation thickness transducer, and the second task relates to the problem of matching the thickness transducer with the object (frame). In this case, the following basic requirements apply to the thickness transducer:

– the transducer should have high sensitivity and linearity of the static characteristic, the least residual signal at the output;

– the influence of auxiliary elements and external factors on the transducer characteristics should be minimal;

– matching of the insulation thickness transducer with the frame should be simple, and the number of matching elements should be minimized;

– the power of the output electric signal of the transducer should be sufficient to automatically stop the winding process;

– the error of controlling the thickness of expensive insulation of about 1.0–150 mm should be no more than 0.5–1.0 % of the upper measurement limit.

4. 2. Study of characteristics of electromagnetic transducers for measuring the dimensions of cylindrical frames

The widespread use of measurement of non-electric quantities (including linear dimensions) by electrical methods is due to the advantages over other methods. These advantages may include:

– the ability of remote measurement and control of non-electrical quantities;

– automatic control of the measurement process;

– automatic conversion of signal parameters and measurement results;

– wide range of measured values;

– measurement of rapidly changing non-electrical quantities, etc.

Analysis of the characteristics and design features of various types of transducers of non-electric quantities into electrical ones showed that only some designs of electromagnetic displacement transducers of inductive and transformer type meet the relevant requirements [11–13]. They are easy to match with the frame in both horizontal and vertical positions. The advantage of inductive transducers is simple design, good noise immunity, possibility to obtain high metrological characteristics and simplicity of secondary transducer elements.

We study the most typical designs of electromagnetic transducers of insulation thickness and note a number of their features [8, 9, 14, 15].

The surface inductive transducer (SIT) (Fig. 1, *a*) is structurally quite simple and is powered by the measuring bridge (MB). Such a transducer can be freely moved by fluoroplastic rollers along the insulation surface. As the insulation thickness changes, the rollers lift up the magnetic core of the transducer, so that winding inductance decreases.

Winding inductance is determined as [7]:

$$L = W_1^2\left[\Lambda_s + \Lambda_b\left(\delta_{ins}\right) + \mu_0 \frac{S_n}{2\delta_{ins}}\right]\cos^2\theta, \qquad (1)$$

where Λ_s and $\Lambda_b\left(\delta_{ins}\right)$ are the magnetic conductivity of winding leakage and magnetic conductivity of pole buckling; S_n is the pole cross-sectional area; θ is the loss angle in the frame steel, which is a function of the gap $\delta=\delta_{ins}$. For small values of δ_{ins}, the angle θ substantially depends on the gap δ, and the conductivity of buckling Λ_b is small. Therefore, the dependence $L(\delta_{ins})$ is essentially non-linear and the transducer has low sensitivity at large values of the gap $\delta=\delta_{ins}$. At small gaps δ_{ins}, the magnetic resistance of steel can be greater than the magnetic resistance of air gaps of poles, and this increases the nonlinearity of the output voltage of the transducer U_c from the insulation thickness δ_{ins}. The main characteristic of the transducer $U_c(\delta_{ins})$ is non-linear and only the middle part of this characteristic is more or less linear (Fig. 1, *c*). Therefore, the SIT can be used to control the insulation thickness in the case when the insulation thickness corresponds to a given limit of the linear part of the characteristic. Matching the SIT with the frame does not present any difficulty.

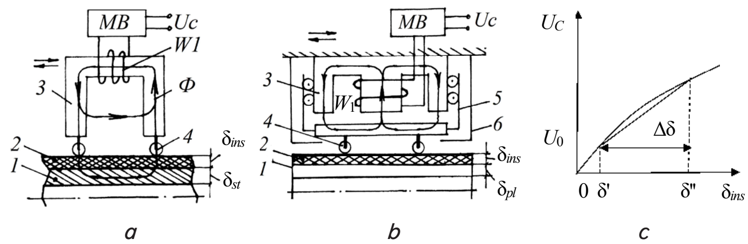

Fig. 1. Control of the insulation thickness of frames by inductive transducers: *a* — steel frame; *b* — plastic frame; *c* — transducer output characteristic

The inductive movable-core transducer (ICT) (Fig. 1, *b*) has an armature. The armature in the initial position ($\delta=\delta_{ins}=0$) rests on the L-shaped limit stop 6 and can freely move upwards during the insulation winding. Transverse displacements of the armature are limited by the rod 5, which slides by means of the fluoroplastic roller on the surface of the magnetic core 3. The inductance of the winding depends on the insulation thickness and is determined by the formula (1), i. e., the dependence $L(\delta_{ins})$ is nonlinear. The nonlinearity is also considerably affected by losses in magnetic core steel if the gap $\delta=\delta_{ins}$ is small. But the sensitivity is satisfactory. With large gaps ($\delta\geq 4$–6 mm), the sensitivity falls. The main characteristic $U_c(\delta_{ins})$ is nonlinear.

The transformer movable signal winding transducer of large linear displacements (TWT) (Fig. 2, *a*) has an elongated open E-core with a uniform magnetic field of the working gap. In this design, the signal winding W_s can move up freely. Due to the large magnetic resistance of the working air gap between the parallel rods, the magnetic resistance of steel slightly affects the sensitivity and linearity of the characteristic $U_c(\delta_{ins})$. The transducer allows satisfactory control of thicknesses of about 2–100 mm.

The terminal voltage of the concentrated signal winding of the transformer transducer can be determined as

$$\dot{U}_c = -j\omega W_S\left[\Phi_e + 2b\int_0^x B_\delta dx\right] =$$

$$= -j\omega W_S F_1\left[\Lambda_e + 2\int_0^x \lambda dx\right] = \dot{U}_e + \dot{U}_x, \qquad (2)$$

where $F_1=I_1W_1$ is the amper-turns of the winding exciting the magnetic flux; Φ_e and Λ_e are the end magnetic flux and magnetic conductivity; B_δ is magnetic induction and λ is the specific magnetic conductivity of the working air gap along which the signal winding moves; x is the displacement coordinate of the signal winding; b is the magnetic core thickness; U_e is the initial voltage of the signal winding caused by the end magnetic flux; U_x is the useful voltage proportional to the insulation thickness $\delta_{ins}=x$.

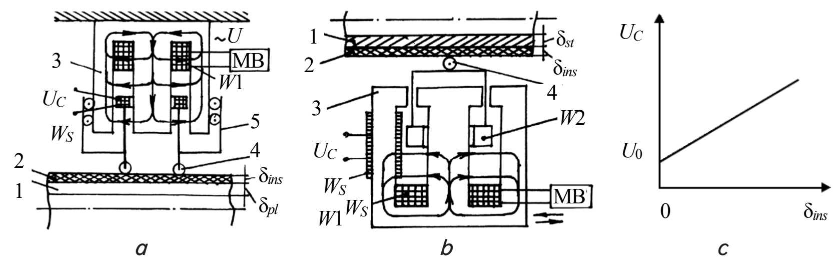

Fig. 2. Control of the insulation thickness of frames with transformer transducers: *a* — movable-winding; *b* — levitation-screen; *c* — transducer output characteristic

For a uniform magnetic field of the gap, B_δ=const and λ=const, and the voltage U_e is compensated by the reference voltage. In this case:

$$\dot{U}_C = \dot{U}_X = -j2\omega W_S B_\delta b \delta_{ins} = -j2\omega W_2 F_1 \lambda \delta_{ins}, \qquad (3)$$

i. e., the dependence $U_c(\delta_{ins})$ when neglecting the magnetic resistance of steel and uniformity of the magnetic field of the working gap is linear.

In some cases, the output voltage U_c is conveniently expressed through the supply voltage U_1

$$\dot{U}_c = \dot{U} - j\dot{U}_1 \cdot \frac{W_S}{W_\sigma} \cdot \frac{X}{l_c}, \qquad (4)$$

where

$$\sigma = 1 + \frac{h_1}{3l_c}$$

– the leakage coefficient of the excitation winding.

For differential transformer displacement transducers:

$$\dot{U}_c = -j\dot{U}_1 \frac{W_S}{W_1\sigma} \cdot \frac{X}{l_c}. \qquad (5)$$

Hence, the sensitivity of the transducer is directly proportional to the supply voltage U_1 and the number of turns of the signal winding W_s. But as the voltage increases above the permissible level, saturation of the section of the magnetic circuit where the excitation winding W_1 is located can occur. The transducer is structurally simple and easily matched with the frame and measuring system.

Transducers with inductive levitation of the moving part can be inductive or transformer (Fig. 2, *b*).

The transducer has an elongated E-core with alternating current winding W_1, levitation screen W_2 and signal winding W_s. The levitation screen abuts against the insulation surface through the fluoroplastic roller 4 under the influence of lifting force F_s [16]. The meter functions as an inductive linear displacement transducer (output signal – current I_c) or a transformer linear displacement transducer (output signal – voltage U_c).

For the linear part of the characteristics $I_c(\delta_{ins})$ and $U_c(\delta_{ins})$ (Fig. 2, *c*), we have

$$I_c = K_I\delta_{ins};\ U_c = K_U \times \delta_{ins}. \qquad (6)$$

A recording device that records the winding process is connected to the measuring circuit. The measuring circuit is relayed to the steel frame drive motor. This ensures automatic winding stop when the required insulation thickness is reached.

Transducers with induction levitation of the moving part simply match the frame and do not require complex parts to transmit displacements to the measuring system. Transducers of this design allow controlling thicknesses of about 2–150 mm and have high sensitivity and linearity of the characteristic $U_c(\delta_{ins})$.

4. 3. Selection of designs for automatic control of the insulation thickness of frames

Analysis of numerous designs of electromagnetic displacement transducers showed that inductive and transformer transducers can be successfully used to automate the control of the insulation thickness of frames. Structural diagrams of the main types of electromagnetic transducers for controlling the insulation thickness of frames are shown in Fig. 3.

Comparisons and evaluation of the parameters of these transducers revealed their relative advantages and disadvantages. This allowed compiling Table 1, where a comparative analysis of the characteristics of various electromagnetic transducers is given. The relative advantages and disadvantages of them are indicated by the numbers 1–3, which show the places attributed to the transducer by each considered parameter. For example, the mass of the movable element in the form of a screen is the smallest and indicated by the number 1, and the mass of the movable core is indicated by the number 3. The most sensitive are DTCT, DTST, DTLST and TWT transducers.

Based on Table 1, it can be concluded that the ILST, TWT and DTLST transducers are applicable when it is necessary to control large insulation thicknesses. The advantage of ILST, DIST, DTST and DTLST transducers is the weak influence of external conditions (magnetic and temperature fields, iron parts, etc.) on their characteristics [17]. Deviation of the output signal from zero at zero input is the least for movable-screen transducers. These transducers are insensitive to the displacement of the moving element in the transverse direction and simply consistent with the object.

In addition, differential inductive and transformer levitation-screen transducers due to the springy property of the moving part and self-centering of the latter do not require special parts or elements for these purposes. This greatly simplifies the matching of the transducers with the object of study.

Table 1

Comparison of characteristics of electromagnetic transducers of insulation thicknesses of frames

No.	Parameters	Transducer type								
		SIT	ICT	ILST	DICT	DIST	DTCT	DTST	TWT	DTLST
1	Sensitivity	3	2	2	2	1	2	1	1	1
2	Linearity	3	2	2	2	1	2	1	1	1
3	Residual signal	1	2	2	3	3	2	3	2	3
4	Sensitivity in non-working directions	1	2	3	1	3	1	3	2	3
5	Mass of the moving element	–	1	1	1	1	1	1	1	3
6	Reactive force	1	1	1	1	1	1	1	1	1
7	Complexity of production	3	1	3	3	3	3	3	3	3
8	Difficulty of matching the transducer with the frame	3	1	3	3	3	3	3	3	3
9	Travel	1	3	1	3	1	3	1	1	1
10	Travel range ratio to the total transducer length	1	3	1	3	1	3	1	1	1
11	Permissible influence of external conditions on characteristics	3	2	1	2	1	2	1	2	1

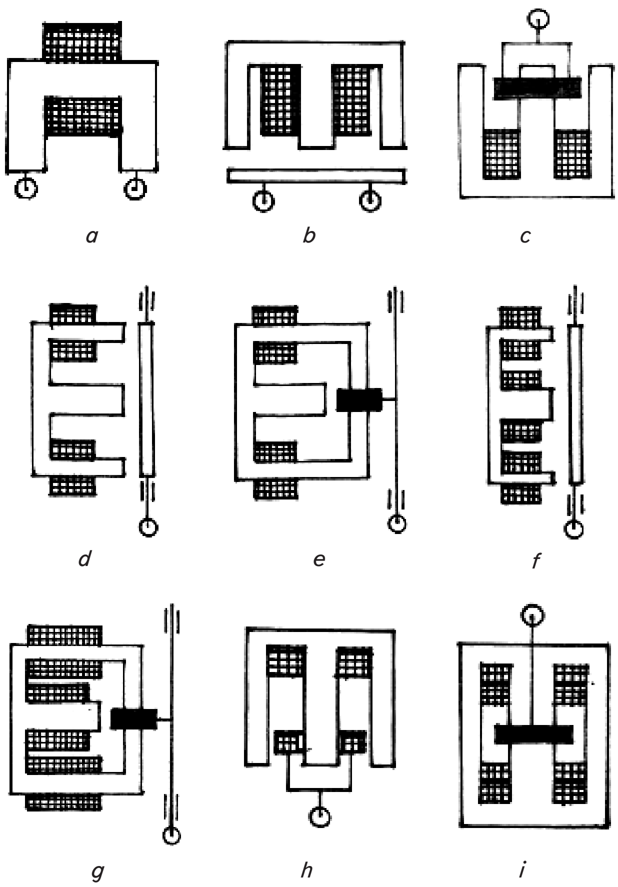

Fig. 3. Main types of electromagnetic transducers to control the insulation thickness of the frames:
a — surface inductive transducer (SIT);
b — inductive movable-core transducer (ICT);
c — inductive levitation-screen transducer (ILST);
d and *e* — differential inductive movable-core and screen transducers (DICT and DIST);
f and *g* — differential transformer movable-core and screen transducers (DTCT and DTST);
h — transformer movable-winding transducer (TWT);
i — differential transformer levitation-screen transducer (DTLST)

5. Discussion of the results of the study of the characteristics of electromagnetic displacement transducers for insulation thickness control

To ensure accurate control of the insulation thickness in the winding process, transducers are subject to the following requirements: linearity of the static characteristic, high sensitivity, minimum influence of auxiliary elements on transducer characteristics and the least residual signal at the output.

Characteristic features, disadvantages and advantages of different types of electromagnetic displacement transducers are determined. The surface inductive transducer is structurally quite simple and matching with the frame is not difficult. As the insulation thickness changes, the inductance of the winding decreases. The dependence $L(\delta_{ins})$ is essentially non-linear and the transducer has low sensitivity at large values of the gap $\delta=\delta_{ins}$. This transducer can be used when the insulation thickness corresponds to a given limit of the linear part of the characteristic.

For the inductive movable-core transducer, the dependence $L(\delta_{ins})$ and, accordingly, the main characteristic $U_c(\delta_{ins})$ is nonlinear. Nonlinearity is also markedly affected by losses in magnetic core steel. With small thicknesses, the sensitivity is satisfactory, with large thicknesses it falls.

The transformer movable signal winding transducer of large linear displacements allows satisfactory control of thicknesses of about 2–100 mm. The magnetic resistance of the transducer steel does not significantly affect the sensitivity and linearity of the characteristic $U_c(\delta_{ins})$. The transducer is structurally simple and easily matched with the measurement object.

Transducers with induction levitation of the moving part can be inductive or transformer. Transducers with induction levitation of the moving part are structurally simply consistent with the measurement object. Transducers of this design have high sensitivity and linearity of the characteristic $U_c(\delta_{ins})$.

Requirements for electromagnetic transducers of insulation thickness are met by inductive and transformer transducers. The inductive levitation-screen transducer, transformer movable-winding transducer and differential transformer levitation-screen transducer are applicable when it is necessary to control large insulation thickness. The advantage of levitation-element transducers is the weak influence of external conditions on their characteristics. Deviation of the output signal from zero is the smallest for movable-screen transducers. These transducers are structurally simply consistent with the measurement object.

In this study, the most suitable designs for controlling the insulation thickness of cylindrical frames are determined. However, the distribution of magnetic fluxes, the calculation of magnetic circuits and analytical expressions of the output characteristics of the transducers are not considered here. Further work on improving the selected designs should be aimed at improving the metrological characteristics of transducers, stability of levitation elements, practical elimination of the residual signal at the transducer output.

6. Conclusions

1. The basic requirements for insulation thickness transducers in the winding process are as follows:

– transducers should have high sensitivity, linearity of the static characteristic, the smallest residual signal at the output;

– the number of matching elements should be minimized;

– should be applicable in automatic control systems;

– should be protected from external factors.

These requirements are more met by electromagnetic displacement transducers.

2. Features and characteristics of the main types of electromagnetic transducers of the thickness of glass insulation of frames are analyzed. Comparative analysis showed that differential LS transducers are more suitable for controlling small displacements (or insulation thickness) of about $(1{,}0-10)\cdot 10^{-3}$ m, since the travel of LE in these designs is limited by coordinate levitation.

3. Comparative analysis of the parameters of electromagnetic transducers of insulation thickness of steel and plastic frames is made. The most suitable for these purposes are levitation-screen transducers, which are simply consistent with the frame and the measuring system, allow controlling thicknesses over wider intervals (2–150 mm) and have high sensitivity.

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