Представлені дослідження контактного індукційного датчика переміщення на малі відстані. В якості датчика застосований феритовий сердечник з обмоткою та рухомим якорем. Між сердечником та якорем існує повітряний зазор.

Для вирішення завдання підвищення точності вимірювання датчик ввімкнутий в мостову вимірювальну схему, яка живиться змінним струмом високої частоти. Для підвищення чутливості вказаного датчика до переміщення запропонована диференційна схема його включення. Також, з метою підвищення чутливості, використаний резонансний режим роботи мостової схеми вимірювання. Для підтримання сталої напруги генератора живлення застосована схема фазового автоматичного підстроювання частоти.

В результаті дослідження індукційного датчика переміщення отримані практичні результати при максимальній величині переміщення в ±0,6 мм. На більші переміщення датчик не досліджувався, так як при збільшенні вказаного переміщення з являється нелінійність перетворення переміщення-струм.

Отримана максимальна чутливість диференційного датчика в вказаному діапазоні переміщення в 2,44 мкА/мкм без застосування системи фазового автоматичного підстроювання частоти.

Застосування системи фазового автоматичного підстроювання частоти дозволила підвищити чутливість до 3,48 мкА/мкм.

В ході дослідження була визначена залежність чутливості датчика від частоти генератора живлення, що дозволило визначити оптимальну частоту живлення вимірювальної мостової схеми.

Проведені дослідження показали, що використання контактних індуктивних вимірювачів мають перспективу застосування і резерви по вдосконаленню. А використання диференційного включення датчика та резонансний режим роботи дає суттєве підвищення чутливості первинного перетворювача на малих переміщеннях.

Розроблений недорогий датчик буде корисний для багатьох застосувань, де необхідно вимірювати переміщення і лінійні розміри контактними методами

Ключові слова: лінійність перетворення, контактний датчик переміщення, індуктивний датчик, феритовий магнітопровід

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DEVELOPMENT OF A HIGH SENSITIVE INDUCTIVE MOVEMENT SENSOR

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1. Introduction

The modern development of technical systems is closely connected with the need to accurately measure the movement of objects and measure the linear dimensions to them. The variety of applications for linear displacement and distance meters, the constant growth of requirements for the accuracy of sensors, the range of measured values, as well as focus on solving specific practical problems, the number of which is constantly growing. This suggests that the development and research of new meters of linear displacements and distances, as well as the improvement of existing sensors is an important and urgent task.

Practical examples of problems solved by existing linear meters are: monitoring and measuring the geometric characteristics of the product (measuring dimensions, measuring deviations in shape and location of surfaces). It also provides accurate positioning of individual units of assembly units when compiled in precision instrumentation, accurate functional positioning of the moving elements of precision systems, calibration and alignment of mechanical metrological instruments, etc.

Today, technical industries require micron and submicron precision to the quality of manufacturing of individual parts of products and to control the spatial position of their nodes. This creates the need for the development and research of new types of linear measurement sensors; they are distinguished by their simplicity of design and low price.

Among the known high-precision methods for measuring linear displacements, inductive contact sensors can be distinguished.

Inductive sensors are parametric primary converters, the principle of which is based on a change in the inductance or mutual inductance of the winding with a ferromagnetic core, due to a change in the magnetic resistance of the magnetic circuit of the sensor into which the core enters. They are widely used in metrology and industry for measuring displacements. Inductive sensors cover a measuring range from 0.1 μm to 20 mm. It is also possible to use inductive sensors to measure pressure, force and fluid, etc.

Inductive sensors are used both at the production stage and during the operation of devices.

All this allows to say that the development and research of new linear displacement meters and distance meters, as well as the improvement of existing sensors, is an urgent task.

2. Literature review and problem statement

Linear displacement measurement has been given a lot of attention. So, in [1], an inductive displacement sensor based on a flat spiral coil is presented. The proposed sensor uses a fixed flat coil and a movable U-shaped magnetic circuit. As a result of its improvement, the author developed a differential sensor using two sets of coils. The differential sensor, according to the authors, has high sensitivity in the entire range, unlike the first prototype. But in this paper, the influence of the shape of the magnetic circuit on the operation of the differential circuit is not noted.

Analyzing the materials of [2], in which contact methods of displacements are considered, it is possible to conclude that despite the progress in the development of non-contact means of measuring displacements, in particular optical and laser ones, their complete replacement of means of measuring displacements by the contact method is impossible. This is due to the fact that non-contact measuring instruments do not allow excluding the influence on the measurement accuracy of surface sludge, oxide film, etc.

It is known that inductive coils have a magnetic core, through a non-linear characteristic of magnetization of the core material they have a non-linear current-voltage characteristic and generate higher current harmonics in the circuits into which they are connected [3]. Therefore, in practice, sensors with linear characteristics, which have non-magnetic gaps in the magnetic circuit (Fig. 1) [4], are most widely used. In this case, the magnetic resistance of the core is determined mainly by the magnetic resistance of the gaps, therefore, the nonlinearity of the magnetic characteristics of the core practically does not affect the current flowing through the coil, with a sinusoidal supply voltage it will also be almost sinusoidal. Therefore, inductive coils with an air gap have almost linear characteristics.

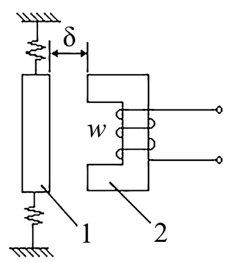

Fig. 1. The scheme of the inductive transducer with a movable armature

Variable inductance parametric sensors (Fig. 1) are an inductive coil with a ferromagnetic core 2. The inductance of the coil L changes depending on the movement of the armature 1, as a result of which the air gap δ in the magnetic circuit of the inductive coil changes.

In practice, various devices are used for measuring displacements by the contact method with various schemes for switching on inductive sensors. One of the most common switching schemes is a bridge circuit, which contains sensor windings in two arms, and balancing supports are located in two other arms [5]. As a rule, a signal indicator with a large input resistance is included in the measuring diagonal of the bridge circuit. To give the device properties of sensitivity to phase shift, the signal indicator (voltmeter or ammeter) is turned on, as a rule, through the rectifier circuit [2]. The issues of constructing and studying the operation of electromagnetic displacement sensors were covered in publications of a number of authors. At the same time, the influence of many factors that occur during the measurement of displacements was not investigated in these works.

The article [6] presents an inductive displacement sensor, which is used to detect small displacements (less than 0.5 mm) in one plane. The design, implementation, and measurement of the input inductance of the sensor are described. To increase the linearity of the sensor, longitudinal magnetic gaps are inserted inside each segment of one fixed coil. The authors indicate non-linearity with an increase in the air gap of more than 0.5 mm.

The source [7] systematizes reference materials on sensors of technological quantities: displacement, accelerations, and vibration parameters. But there is little coverage of the sensitivity of the sensors to the measured values. In the source [8], the authors present a new effective displacement sensor using flat coreless coils that have magnetic coupling. The sensor consists of two flat stationary coils and one movable coil. The mutual inductance between the fixed coils and the moving coils is measured and the displacements are calculated. But in this paper, questions of design features necessary for the design of the mechanical part of the sensor are not considered. In [9], a device is proposed that differs from the standard circuits of the inductive sensor in that the sensitive coil is excited by the electromagnetic field created by the executive coil, and not by an external generator. The electromagnetic flux associated with the sensitive coil operates in the mode of changing the distance between the sensor and the object that needs to be measured. So the design of the sensor is very sensitive to external electromagnetic interference.

In [10], the authors consider issues of assessing and calculating the sensitivity and speed of only elastic elements of mechanical sensors. In [11], the theoretical foundations, operating principles, described designs and characteristics of sensors of physical quantities are described in general terms, without highlighting the detailed features that must be taken into account when designing inductive displacement sensors.

Let's note that in the sources reviewed, little attention is paid to the issues of the dependence of sensitivity on the material and shape of the core. The question of the resonant modes of operation of the measuring circuit and the effect of instability of the frequency of the supply voltage of inductive displacement sensors on the measurement results also remained open.

3. The aim and objectives of the study

The aim of the study is studying the effect of a nonmagnetic gap on the conversion sensitivity of an induction linear displacement sensor. This will make it possible to increase the sensitivity of a contact induction linear displacement sensor for mechanical measurement systems.

To achieve the aim, the following objectives are set:

– apply a differential switching circuit and a resonant mode of operation of the induction sensor to increase the sensitivity of the induction sensor to movement;

– apply a bridge measuring circuit powered by high frequency alternating current;

– use a phase locked loop (PLL) to maintain a stable resonant mode of operation of the measuring circuit in its power circuit

4. Materials and methods for studying a differential linear displacement sensor

Differential (reversible) inductive sensors are a combination of two single sensors with a common armature. Differential inductive sensors have a reversible static characteristic and there is mutual compensation of the electromagnetic force of attraction of the armature.

The mechanical part of the proposed sensor is shown in Fig. 2.

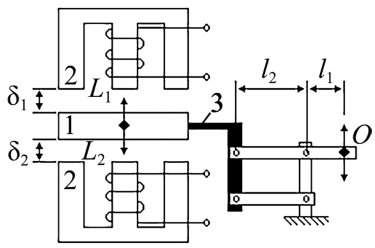

Fig. 2. The mechanical part of the differential inductive sensor

Inductors $L1$ and $L2$ are placed on two E-shaped core ferrite magnetic circuits 2 installed with a gap. An armature 1 made in the form of a plate of ferromagnetic material is placed in the gap between the magnetic circuits. Armature 1 is mechanically connected to the beam 3, which moves under the action of forces applied to point B from the side of the measurement object. The rocker mechanism for transmitting movement from point O to the rocker 3 is constructed so that the armature 1 moves strictly perpendicular to the E-shaped magnetic circuit 2. The wings of the wings have a high intrinsic stiffness, which makes it possible to construct a transmission transfer multiplier from the measurement object (point O) to the movement of the armature 1 as a ratio shoulders l_1 and l_2.

5. The use of a differential switching circuit and a resonant mode of operation of the induction sensor

Inductive sensor coils $L1$ and $L2$ are included in the arms of the AC measuring bridge. Capacitors are included in the opposite shoulders of the bridge. The design scheme of the measuring bridge is shown in Fig. 3.

The device operates as follows. In the equilibrium position of the sensor armature, when the resistance of the windings is level, the bridge circuit is in a state of balance and the current value I_0 in its measuring diagonal is zero.

Under mechanical action from the side of the measurement object applied to point B, through the levers and rocker 3 of the sensor (Fig. 2), the armature 1 moves, which lead to a change in non-magnetic gaps and inductance of the windings, and these changes will be asymmetric:

$$\begin{cases} \delta_1 = (\delta_2 \pm \Delta\delta), \\ \delta_2 = (\delta_1 \mp \Delta\delta). \end{cases}$$

When the non-magnetic gaps between the coils and the armature change, the eddy magnetic currents of the cores 1, 2 change. This causes a change in the impedance of the coils Z_1 and Z_2:

$$\begin{cases} Z_1 = R_{1\delta}(\delta_1 \pm \Delta\delta) + \mathrm{j}\omega L_1(\delta_1 \pm \Delta\delta), \\ Z_2 = R_{2\delta}(\delta_2 \pm \Delta\delta) + \mathrm{j}\omega L_2(\delta_2 \pm \Delta\delta), \end{cases}$$

where $\omega=2\pi f$ (f – the frequency of the bridge supply voltage, R – the active resistance of the coil).

Moreover, with an increase in impedance Z_1, the impedance Z_2 decreases and vice versa. This constructive solution theoretically, as can be seen from (1), makes it possible to increase the sensitivity of the measuring circuit to displacement by doubling the current I_0.

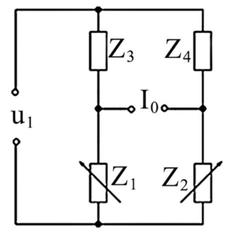

Fig. 3. The design scheme of the measuring bridge

The current value I_0in the measuring diagonal of the bridge circuit is determined by the following expression:

$$I_0 = u_1 \frac{Z_2 Z_3 - Z_1 Z_4}{Z_1 Z_2 Z_3 + Z_2 Z_3 Z_4 + Z_3 Z_4 Z_1 + Z_4 Z_1 Z_2}, \qquad (1)$$

where u_1 – voltage of the power source; Z_1, Z_2 – resistance of the sensor windings; Z_3, Z_4 – impedance of the balancing arms of the bridge circuit (Fig. 3).

And

$$Z_1 = R_{L1} + jX_{L1}, \quad Z_2 = R_{L2} + jX_{L2}, \quad Z_3 = Z_4 = R_C + jX_C,$$

where R_C – the active resistance of the insulator between the plates, on which the leakage current of the capacitance depends.

6. The use of a bridge measuring circuit powered by high frequency alternating current

Let's study the operation of the circuit of Fig. 3 when powered by alternating current.

Expression (1) can be written as follows:

$$I_0 = \frac{u_1(r_2 - r_1) + j(x_2 - x_1)}{A + jB}, \qquad (2)$$

where A and B are the coefficients:

$$A = \mathrm{Re}\{Z\} = \left[(r_1 + r_2) + j(x_1 + x_2)\right] + 2(r_1 r_2 - x_1 x_2); \qquad (3)$$

$$B = \mathrm{Im}\{Z\} = \left[(r_1 + r_2) + j(x_1 + x_2)\right] + 2(r_1 x_2 - r_2 x_1), \qquad (4)$$

where x_1, x_2 – reactance of the sensor windings; r_1, r_2 – active resistance of the sensor windings.

Multiplying the numerator and denominator of formula (2) by the complex value (A–jB), let's obtain:

$$I_0 = u_1 \begin{bmatrix} \dfrac{A(r_2 - r_1) + B(x_2 - x_1)}{A^2 + B^2} + \\ + j\dfrac{A(x_2 - x_1) - B(r_2 - r_1)}{A^2 + B^2} \end{bmatrix}. \qquad (5)$$

Further, multiplying the numerator and denominator of the real part by $1/B$, and the imaginary part by $1/A$, let's obtain:

$$I_0 = u_1 \left[\begin{array}{l} \dfrac{\frac{A}{B}(r_2 - r_1) + (x_2 - x_1)}{A^2 + B} + \\ + j\dfrac{(x_2 - x_1) - \frac{B}{A}(r_2 - r_1)}{A + B^2/A} \end{array} \right]. \quad (6)$$

Moving the sensor armature mainly causes a change in the reactance of the windings x_1 and x_2. But there is also a change in active losses in the sensor windings. It is characterized by the presence of the difference ($r_2 - r_1$) in formulas (2), (5) and (6) and leads to the appearance of an error in the measurement of displacement.

The error can be reduced by an appropriate choice of the values of the shoulder balancing resistances Z. When choosing such a value Z, B>>A is an order of magnitude larger, the active component of the current in formula (6) is proportional to the difference ($x_2 - x_1$), since the term $\frac{A}{B}(r_2 - r_1)$ can be neglected due to its smallness.

For values of the quality factor of the sensor windings greater than unity, that is, for (($x_2 x_1$)>>($r_2 r_1$), when the difference ($r_2 r_1 - x_2 x_1$) in formula (3) is negative, then to reduce the value of coefficient A, the second term in formula (3) have a positive. This can be achieved by using as resistance balancers Z the active resistances R. Formulas (3) and (4) in this case take the following form:

$$A = R(r_1 + r_2) + 2(r_1 r_2 - x_1 x_2), \quad (7)$$

$$B = R(x_1 + x_2) + 2(r_1 x_2 - r_2 x_1). \quad (8)$$

In most cases, the numerical value R is sufficient to determine by formula (7), minimizing coefficient A, taking into account the real resistances of the sensor windings r_1, x_1, r_2 and x_2 in the equilibrium mode of the bridge with the sensor armature not deflected. Equating in the formula (7) A=0, let's obtain the expression for R:

$$R = \frac{2(x_1 x_2 - r_1 r_2)}{r_1 + r_2}. \quad (9)$$

The error in measuring displacements caused by the instability of the values of r_1 and r_2 decreases the more, the greater the coefficient value B in comparison with coefficient A, it follows directly from formula (6).

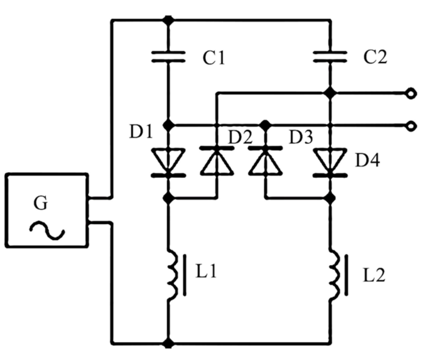

Fig. 4. The block diagram of the displacement meter

Structural electrical diagram of the device shown in Fig. 4 and contains a differential inductive sensor, the windings of which are $L1$, $L2$, as well as balancing impedance $Z1$ and $Z2$ (capacitances $C1$ and $C2$, respectively). Power source is a sinusoidal waveform generator G, included in the diagonal of the bridge power supply. To generate the measurement signal, a converter on diodes $D1$...$D4$ (ring detector) is used [13, 14]. The selection of resistance values minimizes the measurement error of displacements by reducing the effect of instability of the active resistances of the sensor windings and balances the bridge circuit at zero.

The measuring part of the device, which converts the displacement into an electrical signal, contains a differential inductive sensor. The sensor windings $L1$ and $L2$ are included in the two arms of the bridge circuit. The capacitances $C1$, $C2$ (impedance $Z3$ and $Z4$) are included in the other two arms. The power source G is a sinusoidal signal generator included in the diagonal of the bridge power supply [11, 12].

When the bridge circuit is unbalanced, a current I_0 starts flowing in the measurement diagonal, which is proportional to the change in the non-magnetic gaps on the cores $L1$ and $L2$.

A study is made of the dependence of the sensitivity of the sensor to displacement when the frequency of the reference supply voltage of the bridge changes at a constant oscillation amplitude u_1=5 V, which is set by the generator G. The results of the study are shown in the graph in Fig. 5.

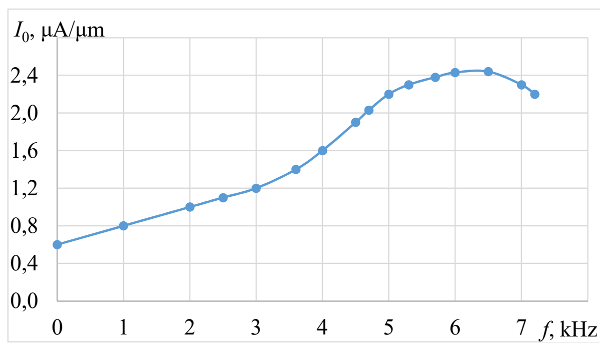

Fig. 5. The dependence of the meter sensitivity when the frequency of the supply voltage

As can be seen from the graph (Fig. 5), the dependence of the sensitivity of the sensor on the frequency of the reference voltage is almost linear in nature with some increase starting from 4.5 kHz. This can be explained by the presence of volumetric capacitance circuitry. Also, the sensitivity has a decline at frequencies greater than 6.5 kHz, which can be explained by an increase in the reactance of the inductive windings L1 and L2 of the sensor. The optimal frequency of the reference voltage in this implementation is the frequency of 6.5 kHz.

Analyzing the operation of this measurement circuit for continuous operation, its dependence on the supply voltage and temperature is traced.

It should be noted that, for comparison, a study is conducted of the dependence of the sensitivity of the mono sensor (Fig. 1) to displacement when the frequency of the reference supply voltage changes at a constant oscillation amplitude u_1=5 V. The maximum sensor sensitivity obtained at a generator frequency of 5.3 kHz is 1.37 μA/μm.

7. PLL use in the power supply circuit of the measuring bridge

The measuring bridge of alternating current with LC elements has the greatest sensitivity in the resonant mode of operation. That is, when the frequency of the supply voltage coincides with the natural resonant frequency of the bridge circuits. Since the bridge circuit power generator operates on LC load, there is a phase shift between voltage and current.

To prevent this, a PLL is used in the bridge power circuit. The PLL block diagram is shown in Fig. 6.

The main elements of the PLL system is a phase detector (PD), the inputs of which through the comparator (triggered when the signal passes through zero), the control signals is fed. The difference between these signals is the phase shift between the voltage and the supply current. A PD generates a control signal and, through a low-pass filter (LPF), supplies it to a voltage-controlled oscillator (VCO). VCO under the influence of the control signal adjusts the power frequency. There is a balance of phases of voltage and current.

It should be noted that the low-pass filter, which is turned on between the PD output and the VCO input, determines in many respects the frequency properties of the PLL [14].

Fig. 7, 8 show the voltages in the measurement diagonal (waveform 1) and in the power circuit (waveform 2). In Fig. 7 circuit works without a PLL system

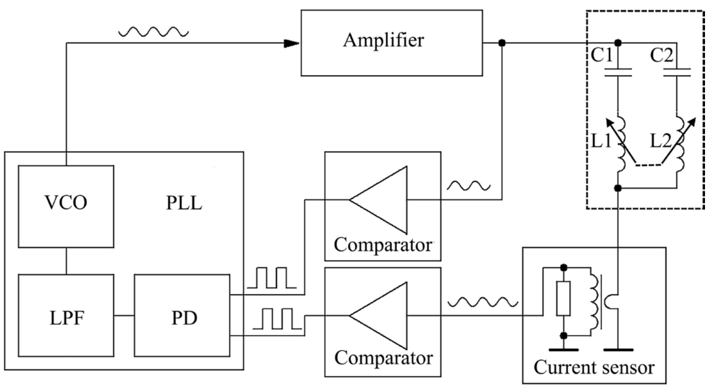

Fig. 6. PLL block diagram

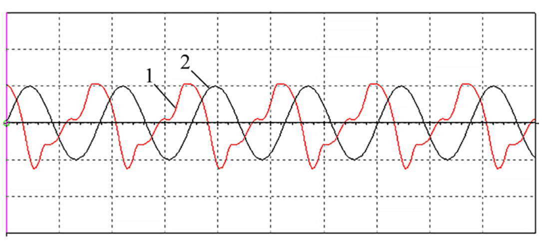

Fig. 7. Voltage in measurement circuit 1 and in supply circuit 2 without PLL

PLL system is presented in Fig. 8.

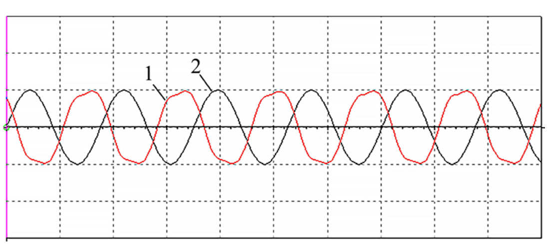

Fig. 8. Voltage in measurement circuit 1 and in supply circuit 2 with PLL

A study is made of the dependence of the sensitivity of the sensor to displacement when the frequency of the reference supply voltage of the bridge changes at a constant oscillation amplitude u_1=5 V, which is set by the G generator with a PLL. The results of the study are shown in the graph in Fig. 9.

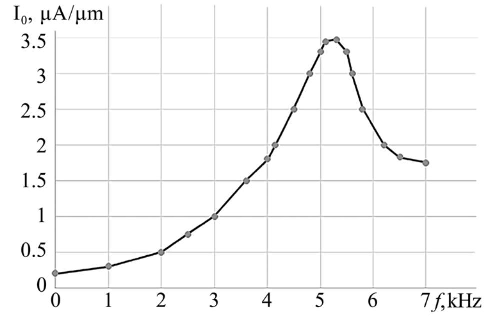

Fig. 9. The dependence of the meter sensitivity when changing the frequency of the supply voltage with PLL

Since the movement of the armature 1 (Fig. 2) from the neutral position causes an increase in the inductance of one of the windings and a decrease in the inductance in the other by the same value, the resonant frequency of the diagonal of the bridge power supply changes little. That is, the PLL system operates in a narrow corridor of phase shifts.

During the PLL operation in the power supply circuit of the measuring bridge, an increase in the range of linear displacement by ±0.1 mm is achieved.

8. Discussion of the research results of the differential inductive linear displacement sensor

High sensitivity and linearity of the conversion of the induction sensor obtained as a result of applying the differential switching circuit and the operation of the measuring bridge in resonance mode.

It should be noted the advantages of the E-shaped core used in the differential sensor (Fig. 2) instead of the *U*-shaped core (Fig. 1). The coil on the E-shaped core is placed on the central leg and the magnetic flux lines pass symmetrically through both side legs of the core balancing each other. This allows to form a symmetric magnetic effect on the armature. In the differential sensor switching circuit (Fig. 2), where the armature must move strictly normal to the cores, this positively affects the accuracy of soaking of non-magnetic gaps and, as a consequence, the measurement accuracy.

The obtained sensitivity values of the differential inductive linear displacement sensor achieved in the range of displacements of not more than 0...±0.6 mm. This is due to the fact that large displacements lead to non-linearity of the displacement-current transformation. This phenomenon is explained by the nonlinear law of magnetic flux scattering in the zone of non-magnetic (air gaps) of the differential sensor (eddy current loss).

The specified narrow range of movements in a certain way introduces restrictions on the scope of the sensor.

In addition, it should be noted that it is possible to supplement the mechanical part of the sensor with a lever system when transmitting the measured movement from the measurement object (Fig. 2). Lever circuits of sensors allow to design systems for multi-range measurements. The research results show that when measuring micron displacements, the lever circuits of the sensors introduce a large error into the measurement result. Therefore, most precision linkage sensor designs have a single transmission lever.

The error when using one lever is:

$$\Delta = \frac{\sigma + y}{n},$$

where $n = \frac{l_2}{l_1}$ – gear ratios of the first and second lever arm; σ – error in the geometric dimensions of the manufacture of the first and second shoulder; y – error of the contact pair (tuning error). This error will be an additive component in the total measurement error.

Based on the results of the experiment, it is also found that for different values of the supply voltage, the characteristics of the dependence of the output current on the movement of the armature intersect at a point that does not coincide with the origin. In the graph of Fig. 5, the initial current is 6 μA, and the graph in Fig. 9 initial current 2 μA. This suggests that with a symmetrical position of the armature, the current in the measuring diagonal of the bridge is not equal to zero. The main reason for the appearance of current in the neutral position of the armature – the asymmetry of the parameters of the windings *L*1 and *L*2, leads to an inequality of the active and reactive resistances of the coils.

Additional studies of the meter for temperature stability showed that the temperature error is $3E10^{-3}$ mm/°C in the temperature range (5...40) °C.

Therefore, in order to further improve the measurement accuracy, it is necessary to search for ways of temperature stabilization of the sensor. In the future, one should also carry out theoretical and experimental estimates of the speed (inertia) of the proposed differential sensor for the possibility of measuring low-frequency vibrations.

9. Conclusions

The proposed inductive linear displacement sensor differs from the known structural solutions of the mechanical part and application of the PLL system in the power supply circuit of the measuring bridge.

1. To increase the sensitivity of the electromagnetic circuit to movement, the sensor is constructed according to a differential circuit. The measurements of the device parameters showed that the differential sensor construction scheme increases its sensitivity by 1.78 times compared with a mono sensor according to the inductive transducer scheme with a movable armature.

2. The use of a bridge measuring circuit gives a maximum sensitivity of 2.44 μA/μm at a generator frequency of 6.5 kHz.

3. The use of a PLL in the power supply circuit of the measuring bridge gave an increase in sensitivity. The sensitivity obtained at a generator frequency of 5.3 kHz increased by 1.43 times and amounts to 3.48 μA/μm. Additionally, an increase in the linearity range by 1.2 times (up to ±0.6 mm) and increased stability in the operation of the circuit were noted. The rate of repeatability of measurement results has also improved.

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