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ANALOG INTERFACE FOR EDDY CURRENT DISPLACEMENT SENSOR

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Abstract. *In the following article we describe interface for analog inductive displacement sensor and possible scope of its application (both aviation industry and civil domestic production taking rotary washing machines as example). The is also an there's overview of main sources of destruction and failure of rotary washing machines, advantages and disadvantages of inductive sensors of movement and embodiment of such a sensor. Also presented a graphic model as a result of research of a sensor.*

Keywords: analog system; displacement sensor; eddy current; rotary washing machine

1. Introduction

Requirement to measure displacement occurs in many industrial sectors. In most cases these are critical diagnostic and monitoring tasks aiming to control a condition of a device or a machine.

Measuring displacement in aircraft industry is vital and improvement of currently existing measuring systems can save lives. The simplest system is usually the most applicable and reliable, hence analog interface presented in this article could be used in aircraft industry as well as in civil production.

However, the most striking example of such measurements is a use of displacement sensors in gas turbine compressor units, in which deviations from specified limits of displacement may result in huge financial losses. But this is only one of the best examples. We should not forget the household sector as well. The practical value of sensors sufficiently simple in their design for mass production, cheap enough in order to not inflate the overall price of the product and sufficiently reliable to justify their use and to meet requirements is obvious.

2. Overview

In 2012, at the St. Petersburg has been opened a factory for the production of Bosch washing machines, which according to official plans should produce 350,000 washing machines per year. According to the same information, the total number of washing machines from different manufacturers is approximately 35 million copies only to be sold in Russia. Considering these figures, any, even minor savings in the production process reaches such amounts, which takes into account even by the industry giants. Also, structural reliability and the ability to control the functioning of the machine allow manufacturer to reduce the incidence of failure of the product during the warranty period, which also eliminates the unplanned expenses for a manufacturer.

It should be noted that manufacturing of washing machines for household use is a striking example through mass and proximity of examples to every listener, but let's not forget the industrial washing machines used in commercial and public laundries. The price and size of these machines are much larger, and the consequences of a serious breakdown may even lead to human victims.

From the definition of the differences between consumer and industrial machines follows a fundamental difference in approach of improvement of a design. Both ergonomic-design and commercial factors affect it.

First of all, particularly production of household washing machine imposes certain limitations on physical parameters – possibly counterweight of two tons might be a solution of some problems, but this is obviously impossible. Recently, when the basic form factor of washing machines has been formed, there's a problem for all manufacturers – it's competition in all possible ways (last but not least – using changes of ergonomic options). Manufacturing of "thin" washing machines imposes special restrictions not only regarding some basic technical support staff, but also regarding additional structural elements that limit the maximum allowable size and taking into account the special needs of physical parameters improve existing solutions and encourage finding of new ideas. Obviously there is also a commercial aspect – embedding too expensive sensor will increase not only the reliability of the system, but also its price, which, as already noted, the scale of production and given the high competition (only in Ukraine there are about twenty major manufacturers and distributors of washing machines) are not allowable.

Manufacturing of industrial washing machines have fundamental differences in most of the above aspects, but inflated price is still a factor which should be avoided. Size of industrial machines does not limit the range of technical capabilities, but instead of this – the requirements for system built into these machines is much higher. One of the best examples is a requirement for an emergency stop in case of a failure of the rotating mechanism (excessive loosening or breakout of a drum). Detection of such failure shall take seconds and response to such an event must be immediate , because in case of an explosion or fire such a machine (or, for example, in the case of uncontrolled bias of a drum hyped up to 1000 rpm with 90 kg of stuff in it) casualties and significant losses are highly possible.

3. Task formulation

The main source of kinetic energy, and hence the mechanical movement of the washing machine is a drum. Control over his movement and the response to it can be done in different ways.

Differences in control of the movement lies in the chosen type of sensor and data processing methods derived from it. The most common type is a piezoelectric sensor and an inductive sensor.

Reaction to the value obtained during a work of a sensor depends on the structural features of the machine and basic decisions that being made further are to turn off a power of a machine to make it stop completely or also making adjustment to depreciation system if such possibility is available.

Turning power off is a simple task that does not require detailed consideration and can be solved by many methods. Additionally it's possible to envisage interference to the process with a temporary stopped mechanism, for example using physical rotation in the opposite direction to a current movement of a drum or a controlled reduction of speed of a drum, however, this method has its drawback – it takes more time.

Adding a correction to amortization systems is quite effective in the case of a wide range of possible loading of a machine and when it's required to reduce, for example, the amplitude of movement of the rolling element urgently. The basic idea of the system is processing data from sensors that check moving drum and transfer control signal to amortization springs to increase their rigidity. Such systems mainly required in industrial machines but this decision finds its application also for everyday use too.

4. Main points of the research

Currently, differential inductive sensor is the most used in displacement measurement in washing machines. However, it does have one undeniable problem – need for mechanical contact with the object.

In any design of the sensor, if sensor is not connected to an object of measurement there's a need to return this pin to its original position in the absence of measured displacement. For example, in case of the simplest solution of this problem, usage of springs, it is obvious that spring creates some counteract to displacement of a measured object and thereby distort measurement results. Also constant loading of a spring leads to changes of spring's characteristics, first of all, change of an initial stiffness, which again leads to a distortion of results and, under the influence of external mechanical forces accelerate the failure of the spring itself. It also leads to a failure of machine itself what is obviously an undesirable effect, resulting in warranty or non-warranty repair, which in its turn has negative financial and reputational consequences for the manufacturer. It is also worth mentioning that failure of a displacement sensor only can lead to the need to not only repair of the sensor itself, but also to more serious breakdowns in the system, which was left without supervision.

Another way of using differential inductive sensor is an inseparable connection of control object and a sensor pin. This method is devoid of the above shortcoming; however, is effective only in case of strictly linear movement of the object. Any deviation from the specified path leads to the displacement of the pin itself, which in its turn causes more pressure on one side of the sensor, and, most likely, deformation and mechanical damage of elements that bind the pin and the sensor. In case if deviation is happening in more than one side – pin is loosening, this obviously leads to a distortion of the measurement and a failure of a sensor.

A common disadvantage of both systems is the need of mechanical movement of the mentioned pin – any option of mounting it (using bearings, etc.) faces a need either to manufacture ideally identical elements, or to the need to amend the measurement result (if you consider the use of the sensor over time it is inevitable and changes in the characteristics on which such adjustments are deducted which brings us to corrections of corrections).

Considering mentioned above, the need of non-contact measurement method that would not only avoid mentioned drawbacks, but would also have required characteristics for the complete replacement of contact sensors is quite obvious. A possible universal solution in terms of not only these factors, but also the reliability and efficiency may be inductive displacement sensor with ferrite core. Simple construction (allowing mass production of it and usage in domestic machines); resistance to the main destabilizing factor that is specific for washing machines – temperature; efficiency and high sensitivity to the slightest movement, it can be used not only for the above purposes, but also to measure not only drum displacements in machines. Usage of only one type of machine sensors also brings financial benefits and technical and structural simplicity (and ease of installation and technical maintenance).

An offered sensor consists of a metal conducting plate attached to the moving part of the machine, displacement of which should be measured; and a coil with ferrite core directed perpendicularly to a plane of a plate. Inductivity value of a coil is proportional to a distance between the plate and the core. This device, as already mentioned, can measure the slightest movement of the measurement object and mass production of parts that are used in it is trivial and financially simple task.

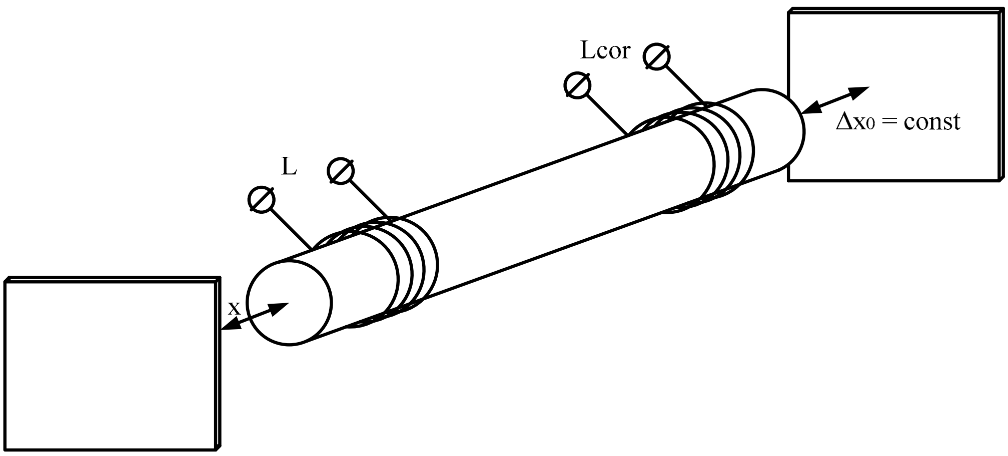

Fig. 1. Functional diagram of the proposed inductive displacement sensor with ferrite core

To get rid of errors caused by temperature changes (effects which are most essential for this type of sensors) proposes the use of two identical coils (production of which is a real task at the moment) on one ferrite core. One end of this rod is directed perpendicular to the plate on a moving subject, while the other - perpendicular to the similar plate, but fixed (as the sensor itself) motionless by a known distance. Thus, at any given time in the system we have two parameters - the current rate of inductor coil and directly measured static metric of a model coil, which changes only under the influence of external factors, and thus allows using elementary arithmetic operations to make an amendment to the resulting value. It's easy to implement this design and get rid of the need to memorize specific reference values and compare them with current parameters of movement and external factors that have influence on a system, in order to get rid of the need to support and handle a method standardized by the Institute of Electrical and Electronics Engineers as Transducer Electronic Data Sheet (TEDS), which takes a lot of software and hardware costs for solving cubic equations, which in its turn improves performance and simplifies system design.

Currently widespread bridge circuits require rate increase of quality factor, which is achieved by increasing the frequency, but increased frequency in its turn leads to increased influence of parasitic capacitance and inductance, especially in the conductors. This prevents the use of bridge circuits for remote measurements. The proposed scheme decrease the frequency of the test signal and is possible due to compensation of in-phase component of the impedance of the sensor, which can reduce the impact of parasitic capacitance and inductance of conductors.

Testing of a test model of such sensor was performed using 8-sectional coil with 240 turns around ferrite core M400NN and aluminum plate with thickness of 1.5 mm. Based on these values the following characteristic has been built, which shows considerable sensitivity of the sensor even on small offsets.

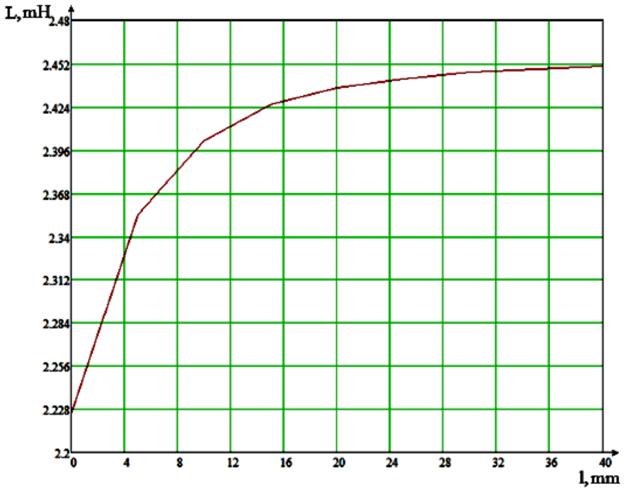

Fig. 2. Empirical experimental characteristic of inductive displacement sensor with a ferrite core

The proposed system can also be used with serial inductive displacement sensors of differential type.

Ferrites are used in modern inductive displacement sensors as magnetic materials of differential-plunger type. This greatly reduces the magnetic losses (loss in eddy currents (Foucault currents)) due to the smaller (approximately ten times) permeability than in conventional ferromagnetic alloys leads to increase of a number of turns in the windings of the inductors, causing an increase in parasitic capacitance in-between the turns that shunts each of windings. Assessment of capacity was made using precision microprocessor bridge R5083 (PA "Rostok", Kyiv) by measuring parameters of one half of the winding of a sensor by Swiss company TESA, which is similar to a sensor M-022, manufactured by LLC "Mykromeh" (St. Petersburg) [1] at several frequencies.

This value of capacitance is 500 pF, which is causing error (about 1 %, significantly higher than the accuracy class of inductive sensor, which is 0.05) using a two-element equivalent circuit of the sensor at a frequency of 10 kHz, or leads to reduce of frequency of a test signal, resulting in decrease in sensitivity. In addition, the high value of a capacity in-between turns limits the length of connecting cables. It should also be noted that as a measuring circuit for measuring differential inductive sensor used half-bridge diagram of the measuring voltage amplifier in the measuring diagonal [2, 3], the choice is dictated primarily to reduce the possibility of error that occurs because of the limited signal suppression factor of a general form by measuring amplifier - bipolar power of a bridge.

In Fig. 3 there's an embodiment of the proposed inductive displacement sensor with a ferrite core and analog-to-digital interface that processes the signal from it, where:

- L_1, r_1 and C_1 – scheme of replacement of a coil (respectively, inductance, active resistance and capacitance), which is used for displacement measurement.
- L_2, r_2 and C_2 - scheme of replacement of a coil (respectively, inductance, resistance and capacitance), which is used for measuring model input parameter of the sensor. Ideally its parameters remain unchanged.
- R_0 - model resistance, which is being used for correction of errors of measurement.
- R_{sh} - shunt.
- K_1 - analog switch using which the input system gets either measured signal or model one. Managed by microprocessor. Switching frequency synchronized with frequency of current network.
- r_{L1}, r_{L2}, r_{L3} – resistance of communication lines.
- I_0 – current source.
- "–1" – analog inverter.
- C_c and R_c – variable volume and resistance, which are used for initial and periodic calibration of a system.
- R_1 and R_2 – two identical resistors ($R_1 = R_2 = R$).
- K_2 and K_3 – analog switches, which allow virtually switch places of resistances R in scheme, which allows level their possible non–equality. Controlled by a microprocessor. Switching frequency is in two times greater than switching frequency of K_1.
- OA_1 and OA_2, R_3 – operational amplifiers and resistor together with resistors R_1 and R_2 and K_2 and K_3 keys form a measuring amplifier with differential current inputs (inverting input of OA_1 is a non–inverting input of the measuring amplifier, and inverting input of OA_2 is an inverting input) (hereinafter: the measurement amplifier).
- MUX – analog multiplexer, which has voltage from the first and second outputs of the measuring amplifier and also a common point of a scheme on its input.
- IIC_1 IIC_2 IIC_3 – iterative integrating converters.
- SD_1 and SD_2 – two half–periodical synchronous detectors.
- DPS – divider–phase splitter that is being controlled by microprocessor. Signal synchronized with signal of a power network (~50 Hz).
- ADC_S – analog–to–digital converter with simultaneous sample.
- μP – microprocessor.
- SNV – synchronization with the network voltage block.

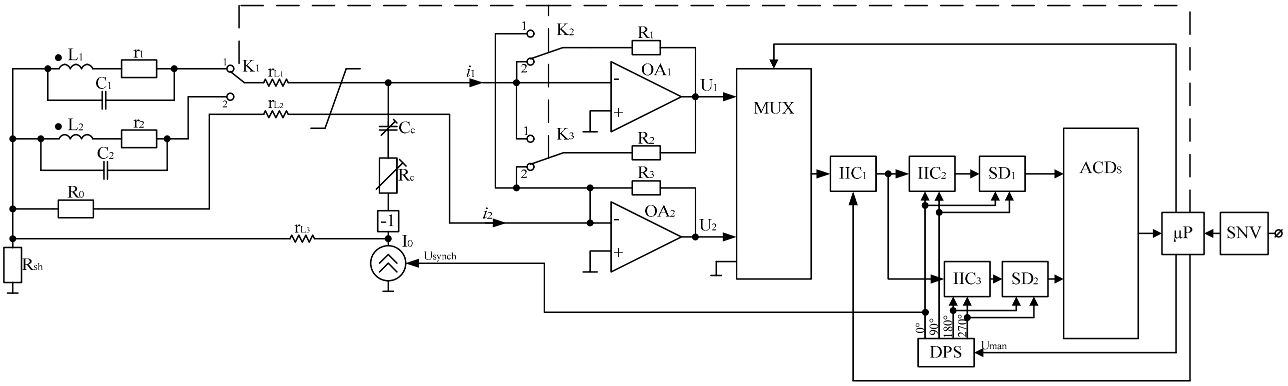

Fig. 3. Functional diagram of the sensor and the analog-to-digital interface for it

The output of the sensor has two signals at the same time: either the signal from the measuring coil or from a model one and a signal that has passed through a model resistor R_0. This makes possible both the consideration of the temperature error of the measurement coil using the model coil and correction of the temperature error of the sensor in general using the model resistor. It should be noted that this correction takes place in real time and does not require operator intervention. Also it's possible for operator to perform preliminary and periodic calibration of the system using variable resistor R and capacitance C_k. Automation of the calibration is also possible, but it complicates the system and requires specific set of pre-defined values e.g. the use of TEDS), which leads to structural redundancy of a scheme and have no exigent need.

IIC_1 gets rid of the impact of odd harmonics in a test signal through the formation of a synchronization frequency of IIC_1 three times less than frequency of IIC_2 and IIC_3.

A test signal of a transducer is being formed by the shunt R_{sh}.

On the first step of the work switch K_1 is set to 1, current in the first coil is fed to the non-inverting input of the measuring amplifier, and the current of a model resistor is fed to the inverting input of the measuring amplifier. The outputs we get

$$U_1 = \frac{U_ш R}{r_{Л_1} + r_1 + j\omega L_1},$$

where U_1 – the voltage at the first output of the measuring amplifier, U_{sh} – input voltage of the sensor, r_{L1} – resistance of corresponding connection line, r_1 – resistance of a corresponding coil, L_1 – inductance value of the sensor's coil at the particular moment, and

$$U_2 = R_C\left(\frac{U_ш}{R_0 + r_{Л_2}} - \frac{U_ш}{r_{Л_1} + r_2 + j\omega L_2}\right) = = R_C U_ш \frac{r_{Л_1} + r_2 - R_0 - r_{Л_2} + j\omega L_2}{(R_0 + r_{Л_2})(r_{Л_1} + r_2 + j\omega L_2)},$$

where U_2 – voltage at the second output of the measuring amplifier.

$$\frac{U_2}{U_1} = \frac{(r_{Л_1} + r - R_0 - r_{Л_2} + j\omega L_1)R_C}{(R_0 + r_{Л_2})R}.$$

Taking only the imaginary part of the relationship and implementing measurement signals from both coils get

$$\mathrm{Im}\left\{\frac{U_2}{U_1}\right\}_1 = \frac{R_C}{R}\frac{\omega L_1}{(R_0 + r_{Л_2})},$$

$$\mathrm{Im}\left\{\frac{U_2}{U_1}\right\}_2 = \frac{R_C}{R}\frac{\omega L_2}{(R_0 + r_{Л_2})}.$$

By following mathematical operations, we can change the ratio of the inductance of the coil to the original inductance value, which is directly proportional to the relative displacement of the object of measurement, if $L_2 = L = \text{const}$, and $L_1 = L + \Delta L$

$$\delta = \frac{\Delta l}{l} = \frac{\mathrm{Im}\left\{\frac{U_2}{U_1}\right\}_1 - \mathrm{Im}\left\{\frac{U_2}{U_1}\right\}_2}{\mathrm{Im}\left\{\frac{U_2}{U_1}\right\}_2} = \frac{\Delta L}{L},$$

where δ – measured relative displacement.

The most important parameter of the proposed scheme is its structural simplicity and economic advantage that comes out of it. Submitted operations may conduct with a simple and cheap microprocessor, reed switches allow you to toggle switches without loss of information or time (due to time delay of integration in the ADC for one period of the test signal), it's possible to actually produce coils and resistors with rather similar parameters nowadays; also their imperfection compensated by standard methods of prior calibration with usage of piecewise linear approximation.

5. Conclusions

From all that mentioned above we can conclude that the measurement of displacement in washing machines is necessary and actual task. Justification of it can be found both in industry and in private, domestic sphere. Contact inductive sensors that are being used at the moment have their advantages, but also have significant drawbacks, and main of them is inability to work at low frequencies because of need to increase value of a quality factor by increasing the frequency of the test signal because of the influence of the quadrature component (additionally piezoelectric transducers have significant errors at frequencies less than ten Hz) and an unreliable design considering their scope. However, it should be noted that this low frequency (0–20 Hz) is mainly required to control the movement of the drum machine.

An alternative resolution of remote measuring of movement is non-contact inductive displacement sensor with ferrite core which is mounted in a way to have also a model signal processing which can significantly simplify the design of the machine which reduces the cost of the product in general, that in its turn, is an important factor in our time.

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У статті описано датчики переміщення та важливість вимірювання переміщення як у авіаційній промисловості, так і у цивільній. У першій частині статті зроблено акцент на цивільному застосуванні описуваних датчиків як найбільш показовому. У межах цієї частини статті розглянуто різні типи пральних машин, важливість контролю різних параметрів у них та можливі результати поломок таких машин. Також оглянуто сучасні датчики переміщення у цій сфері, переваги та недоліки сучасних рішень, можливості для розвитку нових типів датчиків та відповідних аналогових інтерфейсів. Запропоновано новий аналоговий інтерфейс разом із індуктивним датчиком переміщення. Опис, схема, графік вихідного сигналу та формула підкріплюють запропоноване рішення. На основі наведеної інформації зроблені позитивні висновки щодо можливості корисного застосування запропонованої схеми.

Ключові слова: аналогова система; датчик переміщення; індуктивність; роторна пральна машина.

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В статье описаны датчики перемещения и важность измерения перемещения как в авиационной промышленности, так и в гражданской. В первой части статьи акцент сделан на гражданском применении описываемых датчиков как наиболее показательном. В рамках этой части статьи рассмотрены различные типы стиральных машин, важность контроля различных параметров в них и возможные результаты поломки таких машин. Также рассмотрены современные датчики перемещения в этой сфере, преимущества и недостатки современных решений, возможности развития новых типов датчиков и соответствующих аналоговых интерфейсов. Предложен новый аналоговый интерфейс вместе с индуктивным датчиком перемещения. Описание, схема, график исходящего сигнала и формула подкрепляют предложенное решение. На основании

приведенной информации сделаны положительные выводы относительно возможности применения предложенной схемы.

Ключевые слова: аналоговая система; датчик перемещения; индуктивность; роторная стиральная машина

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