The crankshaft position sensor based on magnetoelectric materials

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***Abstract*— This paper is devoted to the research of possibilities of applying of the magnetoelectric material as the sensing element of a crankshaft position sensor. Proposed magnetoelectric crankshaft position sensor would have several advantages against the traditional sensors such as smaller size and weight. Magnetostrictive-piezoelectric layered structure based on piezoceramic PZT plate with dimensions 0.5 mm of thickness, 30 mm of length and 10 mm of wide was used as an element of a sensor. The designed sensor showed the peak voltage pulse of 1.4 V. Proposed design with using the magnetoelectric material may be applied to creation of position and displacement sensors.**

Keywords—sensor; magnetoelectric sensor; magnetoelectric crankshaft position sensor

I. Introduction

Industrial progress in the modern era places the task in the invention of new technical devices and components to them. The automotive industry is one of the important sectors of the economy also undergo unceasing updating, in looking for competitive advantages even in small things, and more so using breakthrough technology. Electronics, computers and sensors have become an integral part of any modern car. For example, almost every auto is equipped with a crankshaft position sensor (CKP sensor) or sometimes also a camshaft position sensor (CMP sensor) [6]. CKP sensor is used to determine the angular position of the crankshaft of the engine, synchronization of the control unit with the workflow engine and determining the rotational speed of the shaft. This gives significant advantages such auto and generally has a consumer demand. The principle of operation of the CKP and CMP sensors is based on the phenomenon of electromagnetic induction or the Hall effect. Magnetoelectric sensors developed recently are a good alternative to inductive sensors and Hall sensors. Magnetoelectric (ME) effect is an effect that is manifested in the change of the electric polarization of the material P under the action of an external magnetic field H (the direct effect) or in the change in the magnetization of the material M under the influence of an electric field E (opposite effect) [1] and can be used to register position of the crankshaft. The dimensionality of ME coefficient which accepted in most modern publications about ME effect is V/(cm·Oe). That is, it is the ratio of the voltage on ME element electrodes to ME element thickness and the alternating magnetic field. We have used in the paper this dimensionality of ME coefficient for correct comparison of study results with other works. The magnitude of a constant magnetic field will also be given in Oersteds. The magnetic field sensor described earlier [2] can be used as the basis for such sensor. As an advantage over inductive sensors, it is worth noting a more simple construction, smaller size and weight. In addition, the advantage over the sensors based on the Hall effect is the absence of a special power source required for operation of the sensor. As a prototype of ME CKP sensor and for further improvement of characteristics can be used a current sensor, previously proposed in the papers [3-5]. The principle of operation of ME CKP sensor provides accurate level information about the position of the crankshaft. In principle, proposed the idea of measuring the angular position or the speed of rotation of the shaft with ME element can be used for various devices and designs where there is any movement.

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II. MAGNETOELECTRIC MATERIAL PROPERTIES

A. Structure

We applied for the manufacture of CKP sensor magnetostrictive-piezoelectric layered structure. Layered structure based on piezoceramic PZT plate in our case had 0.5 mm of thickness, 30 mm of length and 10 mm of wide. Piezoelectric was polarized in the thickness direction. The electrodes are applied on two sides of the piezoelectric plate. The electrodes are made from three layers of Metglas and correspond in size the PZT plate. Thickness of one layer of Metglas was about 0.02 mm. Joint of layered design was done by gluing. Thus, the total number of thin layers Metglas was 6 with a total thickness of magnetostrictive phase about 0.12 mm. The layered structure is symmetrical. The electrical signal is taken from the surface of Metglas plates. Low-frequency magnetoelectric coefficient in this ME magnetostrictive-piezoelectric structure measured at the frequency about 20 Hz was 0,75 V/(cm·Oe). The size of ME element, technology, materials and manner of fastening have a significant influence on the value of ME coefficient.

B. Specifications

ME coefficient is an important characteristic of ME material. It is measured as the ratio of the magnitude of the voltage at the output structure to the structure thickness and to the alternating magnetic field value. The bias of ME material in permanent magnetic field is used to get the best characteristics. Low-frequency and resonant ME coefficients are distinguished. In our case we use the mode of operation of the sensor outside of the resonance at a low frequency. Typical value of ME coefficient for the structures described above will be from tens to hundreds mV/(cm·Oe) when the thickness of a piezoelectric material of about half a millimeter and the magnitude of the alternating magnetic field in the range of a few Oe. Bias field should be tuned to the maximum ME coefficient for layered structures using Metglas which is from 50 to 80 Oe. Fig. 1 shows the dependence of ME coefficient α_E on the magnitude

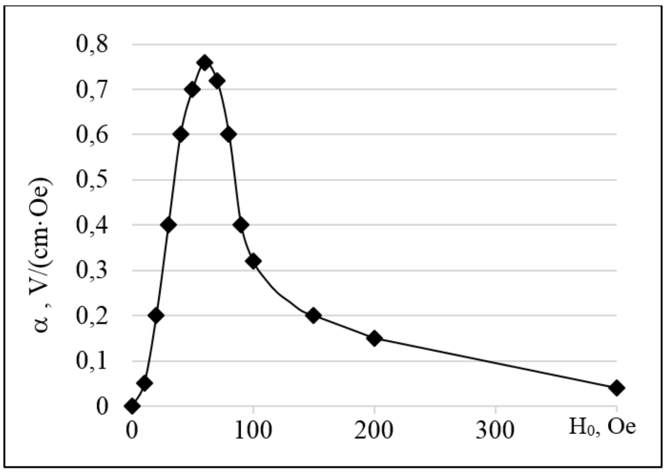

Fig. 1. Dependence of ME coefficient α_E on the magnitude of constant magnetic field at the frequency of alternating magnetic field of 20 Hz.

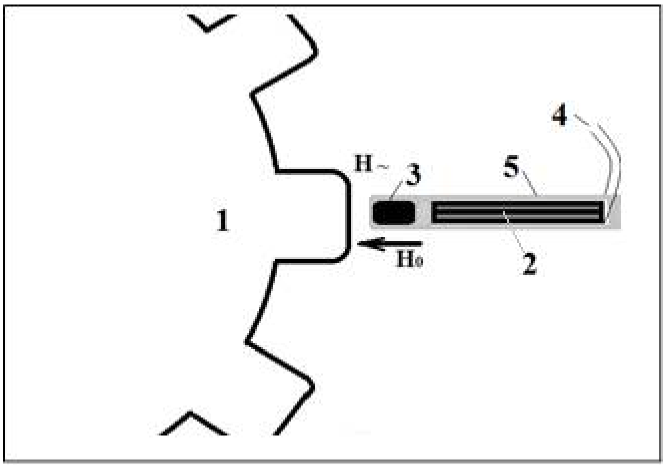

Fig. 2. Scheme of ME CKP sensor.

of the constant magnetic field at the frequency of alternating magnetic field of 20 Hz for the structure described in the previous section.

The choice of optimal AC and DC magnetic fields are very important task for designing sensors.

III. OPERATING PRINCIPLE

The crankshaft position sensor based on magnetoelectric effect works as follows. Fig. 2 shows the scheme of ME CKP sensor. ME element (2) should be located in the immediate vicinity of the steel toothed ring (1). The constant magnetic field H_0 (bias field) is created using the permanent magnet (3) located near ME element. $Nd_2Fe_{14}B$ magnet with dimensions of 20 mm × 10 mm × 2 mm with a residual flux density of 1 T was used for the prototype. Steel toothed ring has one type of label determined by successive identical combinations of "tooth/interval between the teeth" and the distinguishable labels with increased intervals between the teeth. The magnetoelectric element is experiencing the action of alternating magnetic field $H_\sim$, caused by the rotation of the steel toothed ring (1) due to the alternation during the rotation of plots with high magnetic

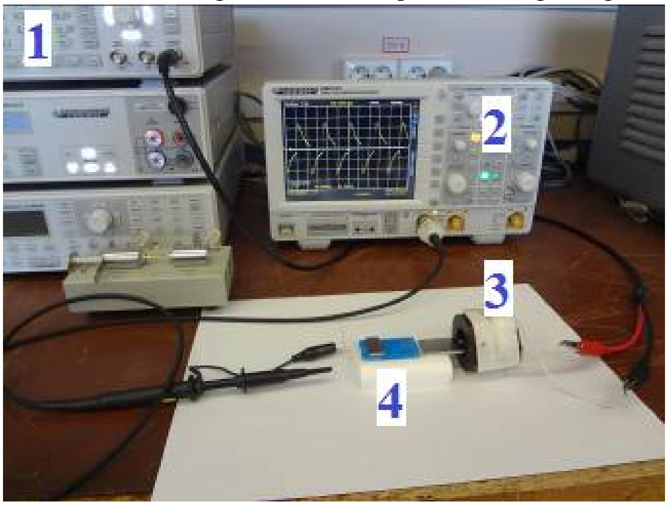

Fig. 3. Simulation stand. 1 is the generator; 2 is the oscilloscope; 3 is the solenoid coil with the core; 4 is ME sensor.

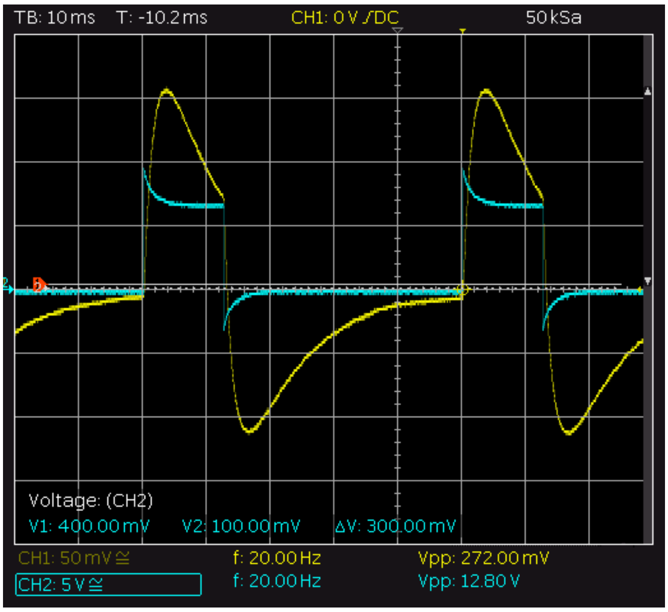

Fig. 4. Dependence of the sensor output voltage on the pulse signal in coil when the gap between sensor and steel core of 1 mm.

permeability – "tooth" and low magnetic permeability – the "interval between teeth". ME sensor for each passing combinations "the tooth/interval between the teeth" generates a pulse with the different levels. The signal has a high level in the locations of teeth, and low level at the locations of all intervals between teeth. The alternating magnetic field $H_{\sim}$ and the bias field H_0 collinear to each other and perpendicular to the polarization vector P of the piezoelectric layer of ME elements. The conversion of magnetic energy into electric potential in ME element is due to the magnetoelectric effect as result from the interaction of magnetostrictive and piezoelectric components of ME material. Alternating electrical signal proportional to the rotational speed of the crankshaft and depending on the angle of rotation occurs at the electrodes (4)

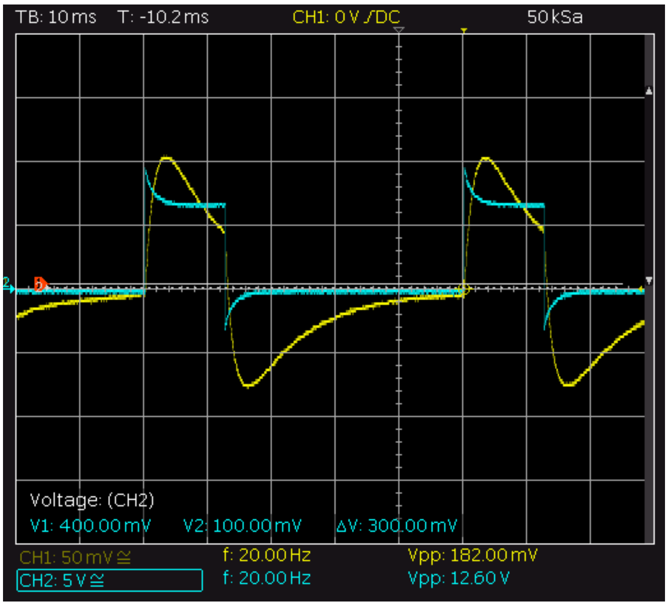

Fig. 5. Dependence of the sensor output voltage on the pulse signal in coil when the gap between sensor and steel core of 3,5 mm.

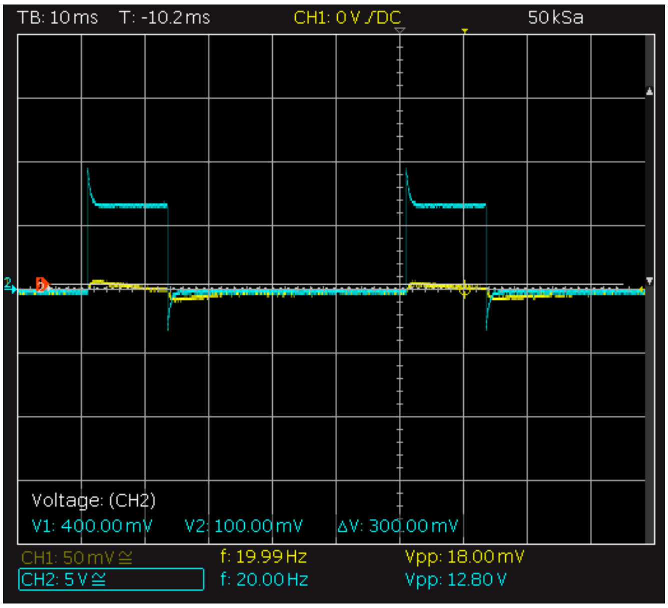

Fig. 6. Dependence of the sensor output voltage on the pulse signal in coil in case the absence of steel core.

of ME element. ME element and the magnet are placed in the case (5).

IV. Simulation Stand

Stand for simulation of the operation principle of CKP sensor is shown in Fig. 3. The simulation stand consists of HMF2550 generator; oscilloscope HMO722; magnetometer DX-180; solenoidal coil with the width of 3 cm, internal diameter of 2 cm, outer diameter of 4 cm, number of turns about 2000; the impedance of 120 Ohms; the core of a soft magnetic steel alloy; ME element.

Measurement of characteristics is performed as follows. The signal from the generator is fed to the solenoid coil. The alternating magnetic field is formed in the coil at a preset frequency. This alternating magnetic field through the steel core is supplied to ME sensor. The distance between ME sensor and the steel core can be adjusted. The simulation of the steel toothed ring is performed in this way. This method makes it possible to develop ME sensor design without using the actual hardware and to estimate limiting characteristics of the sensor. The signal generator with the frequency of 20 Hz and amplitude 10 V was supplied on the coil for study of the characteristics of ME prototype sensor. Solenoidal coil causes a slight distortion in the signal, simulating the work of real devices. ME sensor converts the signal and then this signal goes to the oscilloscope. The magnetometer measures the amplitude of constant and alternating magnetic fields. For the sensor described in section II, we obtained the following characteristics. Fig. 4 shows the characteristic of ME sensor for the case when the gap between the steel core and the sensor was 1 mm, Fig. 5 shows the same characteristic with a gap of 3,5 mm Fig. 6 shows the characteristic when steel core was absent in the coil. As can be seen from the figures, ME sensor has a high sensitivity to AC magnetic field. Maximum output

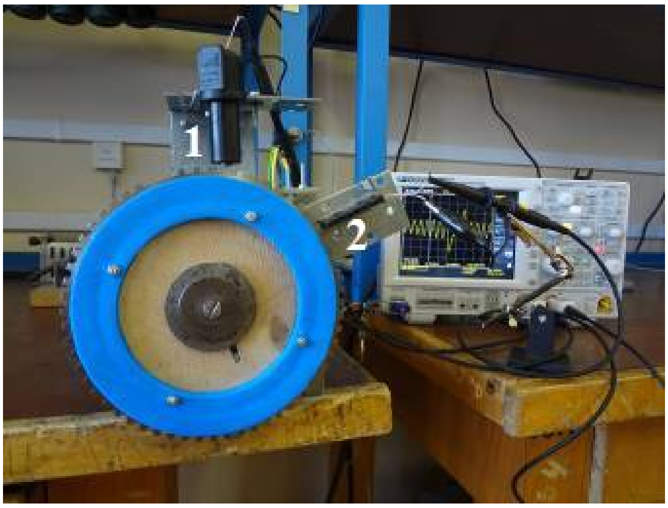

Fig. 7. Measuring stand. 1 is CKP sensor company "Start-Volts" type VS-CS0112, 2 is ME CKP sensor.

peak-to-peak value voltage was about 270 mV for the above parameters. Data obtained by measurements on this stand allowed us to refine the sensor design.

V. Measuring Stand

The stand shown in Fig. 7 was designed to test ME CKP sensor. Steel toothed ring that we used to for measuring stand is the crankshaft pulley damper for AVTOVAZ automobiles. The measuring stand also includes an electric motor with mounting system for a pulley, oscilloscope HMO722, CKP sensor company "Start-Volts" type VS-CS0112 (in Fig.7 marked 1), ME CKP sensor (in Fig.7 marked 2). Standard sensor VS-CS0112 and ME sensor were tested and obtained the comparative data.

Fig. 8 shows the oscillogram of the standard CKP sensor of type VS-CS0112 and Fig. 9 shows the curve shape of a crankshaft position marker.

Developed ME CKP sensor was installed at an angle of 45°

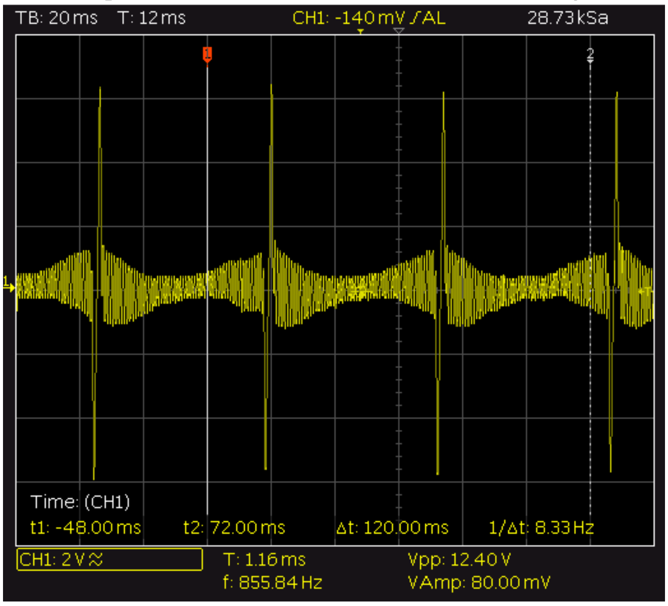

Fig. 8. The oscillogram of sensor VS-CS0112.

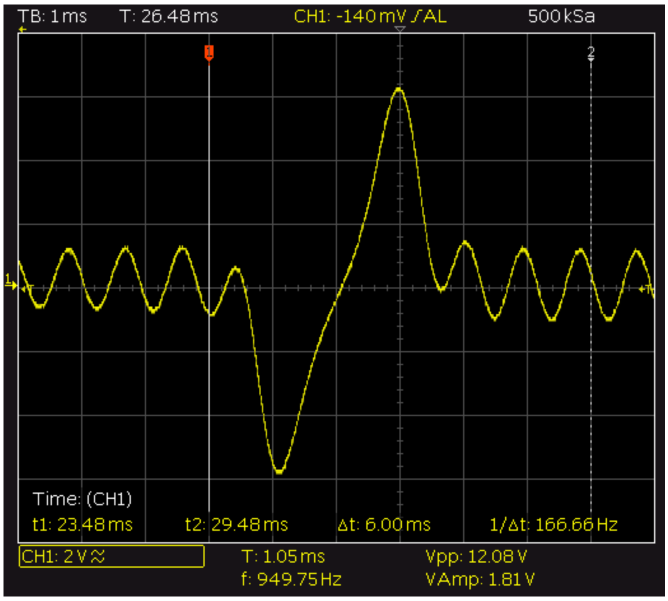

Fig. 9. The shape of the curve marker of sensor VS-CS0112.

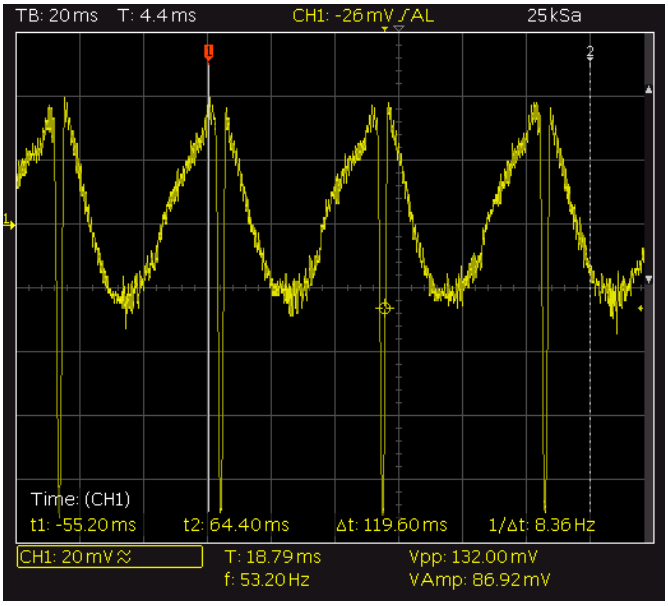

Fig. 10. The oscillogram of ME sensor.

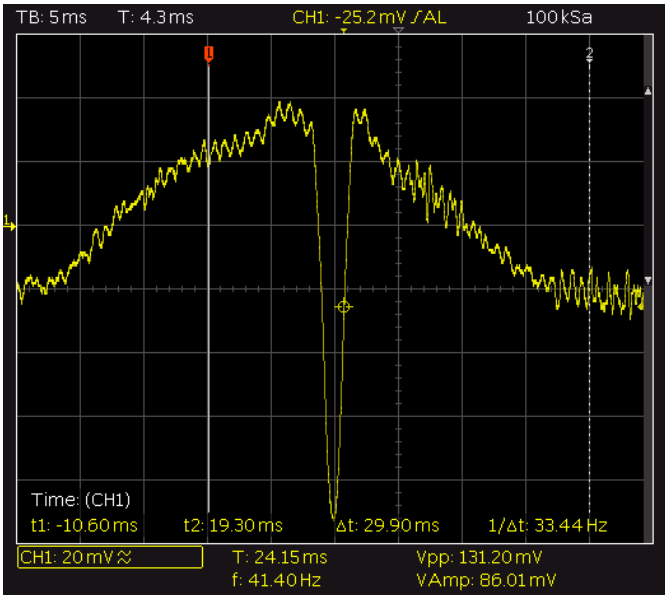

Fig. 11. The shape of the curve marker of ME sensor.

Fig. 12. The magnet position on the pulley.

to standard sensor. Its oscillogram is shown in Fig. 10. The shape of the curve pulse from the tag of the pulley is shown in Fig. 11. From these figures it is seen that the signal of ME sensor is significantly smaller in amplitude. If the signal of the standard sensor gave the value of the peak-to-peak voltage of 12 V, then ME sensor gave the signal value only 130 mV. Then, the curve shape of ME sensor is significantly different from the curve shape of the standard sensor. Although it should be noted that the experiments show the ability to change the shape of the curve in certain limits.

To obtain a more complete picture of the capabilities of ME sensor the following experiment was carried out. The permanent magnet which is part of ME sensor was moved from the design and fixed at the marker surface of the pulley in such a manner as shown in Fig. 12. Previous works on the development of ME alternator demonstrated the effectiveness of this design. Accordingly, Fig. 13 shows the oscillogram of work of ME sensor with magnet attached to the pulley, and Fig. 14 shows the curve shape of the marker from the rotating magnet. ME sensor reacts very clearly on the impact of

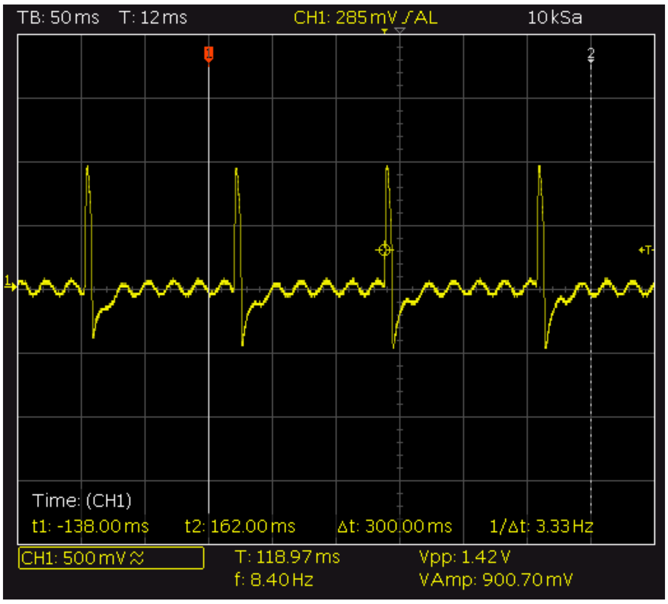

Fig. 13. Oscillogram of ME sensor.

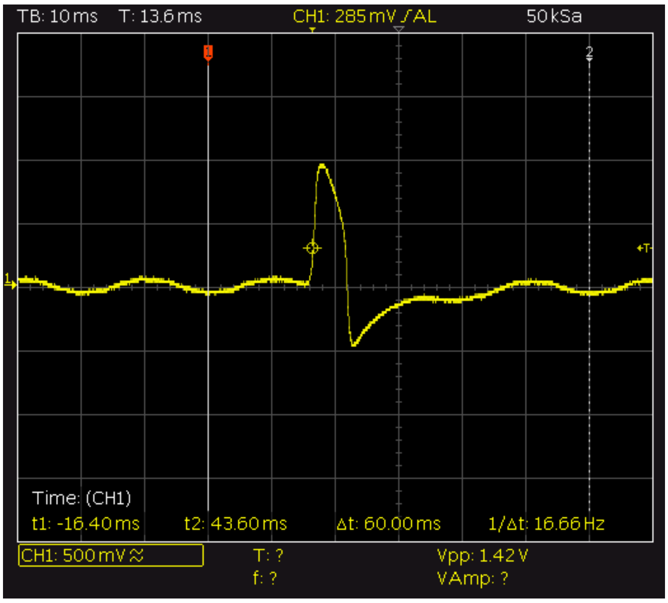

Fig. 14. The shape of the curve marker of ME sensor.

magnet. Maximum pulse amplitude of 1.4 V, the resulting pulse shape is a single tooth (peak). So, this is the second possible option of ME CKP sensor design. This option has the explicit advantage over previous option where amplitude of the signal at the sensor output was essentially lower. The peak value of the voltage on the sensor was about 1.4 V, which is sufficient for reception and further processing of the signal in the electronic control unit (ECU) of the auto.

Simultaneous measurements of signals received from a standard sensor VS-CS0112 and ME sensor were made for comparison of the obtained characteristics. Fig. 15 shows the oscillogram corresponding to the carried out measurements. As the transducers are mounted at an angle of 45° relative to the axis of the shaft and to each other, the signal from one is ahead of another by one-eighth period, as can be seen on the oscillogram. In general it needs to note the prospects of the developed sensors. As a meaningful result it can be noted that succeeded in providing lower cost manufacturing ME sensors,

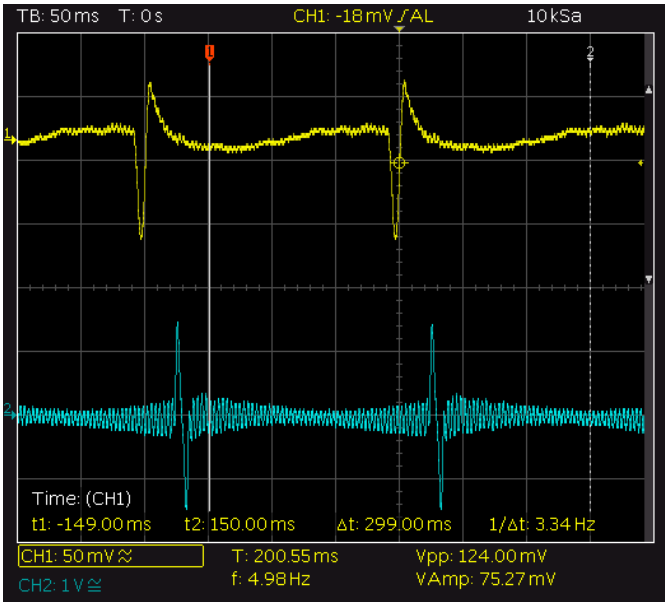

Fig. 15. Comparison of oscillogram of CKP sensors.

smaller size and weight of the sensor compared with standard sensors. It is obvious that the first results can be significantly improved and to obtain the sensors with more large output voltage and a more acceptable form of the output impulse.

VI. Theoretical Aproach

Fig. 16 schematically shows the distribution of the magnetic field passing through ME sensor. The well-known expression for the calculation of the magnetomotive force in the electrical devices can be used for approximate calculation of parameters of ME CKP sensor:

$$F=H_1l_1+H_2l_2+H_3l_3+H_4l_4+H_5l_5 \quad (1)$$

where F is the magnetomotive force, H_i is the magnetic field strength on the corresponding area of the magnetic circuit, l_i is the length of the magnetic circuit.

In this case, the magnetic flux is determined to the residual magnetic induction of the permanent magnet, which is used in the sensor. Magnetomotive force is defined as the product of the magnetic flux on the magnetic resistance of the subcircuit. The magnetic flux passes through the metal magnetic paths, the air and is redistributed between the layer of metglas of the sensor and the steel of pulley. The magnetic flux is closed on a steel pulley, when the pulley tooth will be next to sensor. The location of the tooth greatly increases the magnetic field strength in all parts of the magnetic circuit, as it shown in Fig. 16*a*. The gap between the pulley and the sensor is increased by approximately 3.5 mm at the moment of passing markers as shown in Fig. 16*b*. This causes significant changes of the magnetic flux, which passes through the sensor. For example, such a change can be estimated from Fig. 1 comparing the

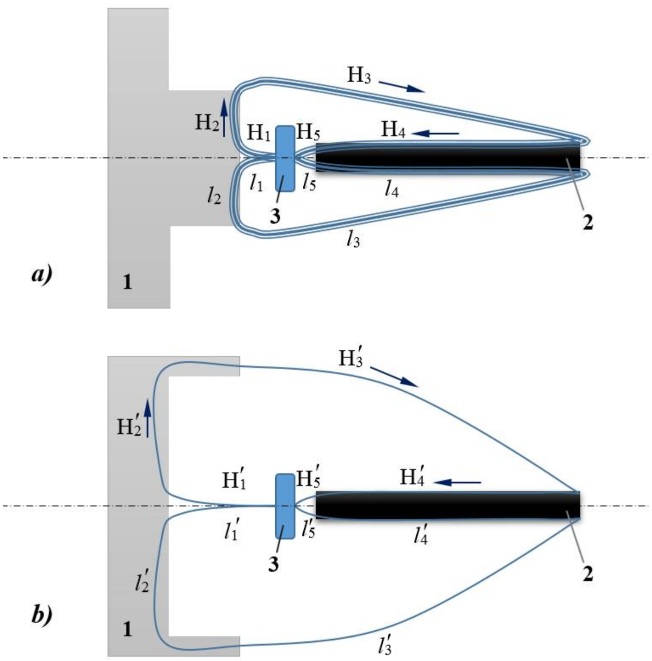

Fig. 16. Diagram of magnetic fields.

value of ME coefficient if the magnitude of the magnetic field changed from 100 Oe to 70 Oe. The flow is decreased and this causes a strong change of the characteristics of the sensor. Thus, the label of the pulley produces a strong voltage pulse on ME sensor. The value of the output voltage on ME sensor can be calculated by using an expression for ME coefficient [1]:

$$U=E\cdot d=\alpha_{ME}\cdot H_4\cdot d \quad (2)$$

where E is the electric field in the piezoelectric material, d is the thickness of the piezoelectric material, H_4 is the magnetic field strength at the location of the sensor, α_{ME} is the magnetoelectric coefficient.

A more accurate expression can be obtained taking into account the location of the sensor relative to the magnet and relative to the pulley, the properties of the materials used and design features of the sensor.

VII. Conclusion

In this paper it is proposed to use magnetoelectric material as the sensing element of CKP sensor. Proposed sensor would have the advantages against the traditional sensors such as smaller size and weight. The designed sensor showed the peak voltage pulse of 1.4 V. The design of ME sensor is made of mechanical solid components and provides greater reliability of the sensor. ME sensor is sensitive to strong magnetic fields, therefore, it is recommended to provide the magnetic shielding.

Acknowledgment

The research at Novgorod State University was supported by a Grant from the Russian Science Foundation: Grant No: 15-19-10036.

Authors would like also to acknowledge the Plovdiv University "Paisii Hilendarski" for funding the project agreement № НИ15-КС-016/24.04.2015 and project agreement № СП15-КС-010/24.04.2015.

References

[1] M. Bichurin and V. Petrov, "Modeling of Magnetoelectric Effects in Composites," Springer Series in Materials Science 201, 2014, 108 p.

[2] I.N. Soloviev, M.I. Bichurin, and R.V. Petrov, "Magnetoelectric Magnetic Field Sensors," PIERS Proceedings, Moscow, Russia, August 19-23, 2012, p. 1359-1362.

[3] R.V. Petrov, I.N. Solovyev, A.N. Soloviev and M.I. Bichurin, "Magnetoelectic current sensor," PIERS Proceedings, Stockholm, Sweden, Aug. 12-15, 2013, p. 105-108.

[4] I.N. Solovyev, A.N. Solovyev, R.V. Petrov, M.I. Bichurin, A.N. Vučković, N.B. Raičević, "Sensitivity of Magnetoelectric Current Sensor," Proceedings of 11th International Conference on Applied Electromagnetics - ПЕС 2013 September 01 – 04, 2013, Niš, Serbia, p. 109-110.

[5] Petrov, R.V., Yegerev, N.V., Semenov, G.A., Petrov, V.M., Bichurin, M.I., Aleksic, S., "Current sensor based on magnetoelectric effect," 18th International Symposium on Electrical Apparatus and Technologies (SIELA), 2014, 29-31 May 2014, Bourgas, Bulgaria.

[6] Slavcho Bozhkov, Ivan Milenov, Danail Danchev, Dimitar Tokmakov and Penko Bozhkov, "Researching the signals of the automobile electromagnetic sensors," 12th International Conference on Applied Electromagnetics - PEC 2015, ISBN 978-86-6125-145-0, O5-4, Niš, Serbia, 2015.