Improvement of piezoelectric vibration sensors’ performance characteristics via optimization of details’ functional surfaces roughness

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Abstract. Method of improvement of piezoelectric vibration sensors’ performance characteristics via optimization of the details’ functional surfaces roughness is presented in this paper. Effect of the functional surfaces roughness of the vibration sensor's details on the relative coefficient of transverse conversion has been studied. Description of the surfaces roughness has been fulfilled using graphical criteria. Optimum procedures and technological parameters of the mechanical treatment of the details' functional surfaces roughness providing the best relative coefficient of transverse conversion for the piezoelectric vibration sensor have been determined. Full-scale experiments pertinent to the surfaces mechanical treatment have been designed using Taguchi method, which allowed reducing substantially the number of the performed experiments.

1. Introduction

A piezoelectric vibration sensor (hereinafter referred to as the "vibration sensor") is the multipurpose precision instrument, which enjoys wide application almost in all fields of measurements and analysis of mechanical vibrations (oscillations) [1, 2]. Operation of piezoelectric vibration sensors (PVS) is connected with the extreme conditions, including extremely high and extremely low temperatures. Accordingly, rather strict requirements in respect of operational reliability and stability of metrological characteristics, as well as in respect of their survival in conditions of external destabilizing factors effect, are imposed on PVSs.

Currently improvement of piezoelectric vibration sensors operational characteristics is realized mainly via development of new designs of piezoelectric transducers [3]. Such approach is characterized by performance of the design and engineering preproduction, which are time-consuming procedures, requiring large financial expenditures incurred by the enterprises.

An alternative method of the output products quality improvement and upgrading of their operational characteristics is based on the engineering provision of optimal functional surfaces roughness of the details [4]. However, application of this method is aggravated by insufficient studies of the surfaces roughness effect on the piezoelectric vibration sensors operational characteristics.

In this paper the results of relationship investigation between the functional surfaces roughness of the PVS's detail "Base" and relative coefficient of transverse conversion (RCTC), $K_{RTC}$, are presented. The performance diagrams characterizing the surface roughness profile irregularities deviations have been used as the criteria for estimation and control of the functional surfaces roughness [5, 6].
2. Design and operation principle of the vibration sensor

PVS operation is based on piezoelectric effect, that is occurrence of electric potential on piezocrystal in the process of its mechanical deformation. The investigated sensor (Figure 1) was designed based on the modular piezoelectric element containing five active layers (pos. 1). The piezoelectric element is located between the base (pos. 2) and load (pos. 3) and is screwed down by the nut (pos. 4). The sensor's sensor is manufactured from piezoceramics and the metallic details within the sensor's design are manufactured from the steels of different grades.

![Figure 1. PVS appearance.](image)

Strict requirements in respect of roughness are imposed towards the "Base" detail functional surface (Figure 2).

![Figure 2. The drawing segment (a) and appearance (b) of the PVS's detail "Base".](image)

In this study, an optimal roughness of the surface highlighted in Figure 2 was determined. There are a lot of methods used for treatment of this surface, among which there is lathe work, milling, grinding, finishing, etc. [7]. In turn, the surface roughness depends on the used equipment, cutting tools, machine-tool attachments, cutting/cooling medium, cutting modes, treatment policy, work material and others. Therefore, after finding the optimal surface roughness, it is necessary to ascertain those processing factors, which will provide it.
3. Investigation of effect of the surface roughness of the vibration sensor’s detail on the relative coefficient of transverse conversion

At the first stage of this study, three groups of the detail "Base" (three samples per each group) were manufactured from the stainless steel AISI 321, differing by the initial roughness of the functional surfaces. The lathe machining of the studied surface within each group of the details was performed using different cutting modes. After manufacturing the samples, their surface roughness has been measured using a Hommel Tester T8000 section gage. The assembled PVS with manufactured bases have been tested on the test bench designed for RCTC measurement. The results of these measurements and treatment schedules are presented in Table 1 (s – feed, mm/rev; t – cutting depth, mm; ν – cutting speed, m/min).

| Group | Sample | Cutting mode | Ra, μm | RCTC, % |
|-------|--------|--------------|--------|---------|
| 1     | 1      | s = 0.01     |        | 3.2     |
|       | 2      | t = 0.05     | 0.1    | 3.1     |
|       | 3      | ν = 110      |        | 3.1     |
| 2     | 1      | s = 0.03     |        | 3.5     |
|       | 2      | t = 0.10     | 0.2    | 3.8     |
|       | 3      | ν = 110      |        | 3.7     |
| 3     | 1      | s = 0.10     |        | 6.7     |
|       | 2      | t = 0.10     | 0.6    | 6.9     |
|       | 3      | ν = 110      |        | 6.4     |

As seen, RCTC is less for the samples with the lowest roughness, which is characterized by a Ra value. The values of this parameter for the third group of samples are out of 5% tolerance (following the specifications for studied vibration sensors $K_{RTC} < 5\%$). Thus, the surface roughness of the PVS detail "Base" exerts an effect on its RCTC, and therefore the operational characteristics of the instrument may be improved via changing the surface roughness type.

4. Determining the manufacturing conditions of the functional surface for the vibration sensor’s detail using Taguchi method

At the second stage of this study, the cutting parameters providing an optimal roughness of the functional surface during its manufacturing have been determined. Determining the minimum number of samples and treatment schedules within the design of experiment and analysis of the results were performed using Taguchi method [8, 9].

Within the scope of the performed experiments, 45 samples in the form of the plane-parallel cylinders having the diameter of 18 mm and height of 4 mm were manufactured. The samples were manufactured from the same material as the detail "Base". Pursuant to Taguchi method, four factors have been selected, namely: feed (A), cutting depth (B), cutting speed (C) and tool nose angle (D). Three levels have been established for each factor: minimum, medium and maximum cutting modes recommended by the tools manufacturer. Treatment was performed on the lathe machine equipped with a HAAS SL-10 computer numerical control system (CNC). Initial cutting parameters applied in the performed experiments following the Taguchi method are presented in Table 2.
| Table 2. Factors studied in the experiment and their levels |
|---------------------------------|---------------|------------|------------|
| Factor                          | Treatment level |           |            |
| A Feed, mm/rev                  | 0.03 0.09 0.15 |           |            |
| B Cutting depth, mm             | 0.1 0.3 0.5   |           |            |
| C Cutting speed, m/min          | 140 190 240   |           |            |
| D Tool nose angle, °            | 35 55 80      |           |            |

Pursuant to standard GOST R ISO 4287-2914, the following surface roughness parameters were selected: Ra, R_max, Pt, Rp_k, Rv_k, R_ku, Rd_q. During experiment designing within this study, L9 Taguchi orthogonal matrix has been selected. After performing of experiments on three different sections of each manufactured sample, their profiles have been measured and parametric estimation criteria have been calculated. Based on these values, the signal-to-noise ratio (RSN), η, for all selected parametric estimation criteria of the surface roughness and for the selected levels of each factor have been calculated. RSN for the factors exerting an effect on the Ra parameter is presented in Figure 3.

The more scatter the points are, the greater the effect exerted by the factor. From the data in Figure 3 it follows that for the Ra parameter, the optimal set of factors levels is A1B3C2D1, which may provide the highest value of the η generalized response or the lowest Ra value.

Without presenting similar relationships for the rest roughness parameters, let us present the results of the performed experiments. An optimal set of cutting modes, A1B1C1D1, has been found, which provides the plateau profile of the treated surface characterized by the least height of projections. It was established that the main factors exerting an effect on roughness of the manufactured surface are the tool nose angle and the feed.

5. Determining the surface roughness for the detail "Base" providing the least value of the relative coefficient of transverse conversion
At the third stage of this study, optimal surface roughness for the specific manufacturing conditions, providing the required value of the instrument's operational characteristic, that is the least value of
RCTC of the sensor has been determined. Several samples of the detail "Base" were manufactured on the lathe. The first sample was manufactured using previously determined cutting modes based on the Taguchi method, that is: \( s = 0.030 \text{ mm/rev}, \ t = 0.1 \text{ mm}, \ v = 140 \text{ m/min} \) (for the second sample, \( s = 0.015 \text{ mm/rev}, \) for the third sample, \( s = 0.008 \text{ mm/rev} \)). RCTC for PVS assembled on bases 1, 2 and 3 amounted to 2.4; 2.2 and 1.6%, respectively. Using "Lemming" software, graphical estimation criteria for the surface profile have been plotted, namely: plots of profile ordinates density distribution and plots of profile slope ratio density distribution (Figure 4: 1 – the best sample after the lathe work, 2 – sample after finishing operation, 3 – sample after milling; \( H \) – number of ordinates of the considered value-to-general number of the ordinates ratio, \( Y \) – profile ordinate, \( R_q \) – root-mean-square deviation of the initial profile ordinates, \( \tan \alpha \) – profile slope ratio). The least value and hence the best result was obtained for the third sample, and therefore the graphical criteria for this sample have been accepted as the reference ones. In order to provide possibility of applying the reference values during the details control within the serial manufacturing, the tolerance was designated for these reference values. Methods and parameters of treatment pertinent to the best sample should be introduced into the detail's manufacturing process.

![Figure 4. Reference plots with tolerance of 10% for possible deviations: profile ordinates density distribution (a), profile slope ratio density distribution (b).](image)

These plots contain almost the complete information on angular and height profile characteristics. Based on the plots of profile ordinates density distribution, the following conclusions may be made. The peak of plot 1 essentially is not deviated from the central point, and therefore neither projections, nor bays prevail in the profile. Extreme points of graphical criteria for samples 2 and 3 are shifted to the left and hence the bays prevail in the profiles. The established graphical criteria make it possible to determine the profile excess that is a tilt angle of the irregularities. High values of peaks in plots 1 and 2 (the plots are narrow and higher than wide) are evidence on plateau profiles with irregularities of small height. The plot of profile ordinates density distribution for sample 3 is wider and hence the profile irregularities are more sharp and deep. In order to determine the profile excess, the plots of distribution of density of the profile slope ratio may be used as well.

Graphical criteria for the sample with the surface treated using finishing operations, as well as criteria for the other surfaces of serially manufactured details, which are within the limits of the designated tolerance, provide the surfaces roughness, which allows one to obtain the required value of RCTC. If the non-parametric criteria used for estimation of the controlled surface will exceed the tolerance limits, then the detail is not corresponding to the requirements towards the surface roughness.

6. Results
As a result of the performed studies, dependence of the relative coefficient of transverse conversion of the vibration sensor on the surface roughness of one of the most important details, which is the base, has been revealed. The preferred manufacturing method of the functional surfaces of the vibration
sensor's details – lathe work – has been determined. The most significant factors of the treatment process, exerting the largest effect on the surface roughness, have been detected. An optimal set of mechanical treatment modes has been determined. The base surface roughness providing the required value of the relative coefficient of transverse conversion of the vibration sensor has been determined as well. The expediency of carrying out the rating and control of the surface roughness has been demonstrated, using the graphical criteria for its estimation, which allow one rather completely to describe the required roughness.

The results of the performed investigation may be used at instrument-making plants during designing and manufacturing of the vibration sensors, the operation principle of which is based on the piezoelectric effect.

7. Conclusion

- Roughness of the functional surface of the detail "Base" exerts an effect on the relative coefficient of transverse conversion of the vibration sensor.
- In order to estimate roughness of the functional surface, it is necessary to use more informative graphical criteria.
- Usage of Taguchi method allows reducing quantity of the experiments performed for determining of the optimal cutting modes during manufacturing of the functional surface of the vibration sensor's detail.

References

[1] Walter P L 2007 *Journal of Sound and vibration* 84–92
[2] Laš V, Kroupa T and Bartošek J 2012 *Proc. Engineering* 48 367–74
[3] Bogush M, Abramenko T and Mitko V 2003 *Proc. of the 10th international congress on sound and vibration* 3 951–9
[4] Ivanov A Y and Leonov D B 2012 *Fundamental Sciences and Applications* 17 19 – 23
[5] Valetov V A 2015 *Journal of Instrument Engineering* 58(4) 250-67
[6] Yulmetova O S, Yulmetova R R and Matyzhonok V N 2011 *Proc. SPIE 7996 Fundamentals of Laser-Assisted Micro- and Nanotechnologies* 799604
[7] Andreev Y S, Demkovich N A, Isaev R M, Tselischev A A and Vasilkov S D 2017 *Proc. Engineering* 176 96–106
[8] Jagtap K and Pawade R 2014 *Int. J. of Advanced Design and Manufacturing Technology* 7(2) 53-8
[9] Gunay M and Emre Y 2013 *Measurement* 46 913–9