Evaluation of probabilistic characteristics of measurement results during parts inspection

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Abstract. The features of control of linear dimensions in repair production have presented. The main factors influencing the measurement results have identified. Possible consequences of the influence of the measurement error in the control of linear dimensions have indicated. The analysis of existing methods for assessing the probabilistic characteristics of measurement results has carried out. A diagram of the control of parts such as a hole, has been drawn up, which reflects the probabilistic characteristics of the measurement results, taking into account the influence of the error on the sorting results. The results of approbation of the developed technique have presented on the example of measuring the diameters of the restored main and connecting rod journals of the engine crankshafts.

1. Introduction
Repair of machines is a rather laborious and complex technological process [1,2], in which control plays an important role. During operation, most of the machine connections are subject to wear, there is an increase in clearances [3,4], preloads change [5,6], there is a complex process of degradation in the seals [7,8]. Increasingly high accuracy has required, which forms a margin for wear, to reduce assembly tolerances, methods of incomplete interchangeability have used [9,10]. With prolonged use, failures begin, and the car comes for repair. Incoming control during repair is the most important operation, which involves the acceptance or rejection of parts [11]. The metrological service of the enterprise deals with the quality of the input, production and acceptance control [12,13]. An increase in the accuracy of new and repaired parts, which has dictated by modern machine-building production, leads to the need to use new measuring instruments, while an increase in control costs is possible [14], and most importantly, it is necessary to justify the likelihood of losses from errors in measuring instruments [15, 16].

In repair production, when controlling linear dimensions, depending on the task at hand, two different goals can be pursued. To achieve one of them, as a result of measurement, the size of the controlled part has determined in absolute terms. To achieve another goal, the size of the controlled part has determined within the prescribed maximum deviations for it and, according to the measurement results, the part is classified as suitable or rejected.

Depending on the goal of control, the measurement error affects the results obtained in different ways. In the first case, the measurement error leads to the fact that the part has assigned a size, which, although it has called «valid», but its reliability depends on the error that manifested itself at the time of
measurement. The magnitude of the error introduced in this case depends only on the degree of manifestation of the measurement error at a given moment. With each single measurement, the influence of the part on the measurement error can manifest itself only when its dimensions have uneven, and the technique adopted during the measurement does not reveal this unevenness.

During acceptance inspection, the measurement error interacts with the actual dimensions and affects the final measurement results only for those parts whose dimensions are close to the boundaries of the tolerance field. In practice, this condition applies to parts that have actual deviations from the tolerance limit in the area of the corresponding measurement error.

Thus, the measurement results have influenced not only by the measurement error, but also by the actual size that the controlled part had at that moment.

Depending on the state and design of the measuring instrument and the conditions for conducting measurements, the measurement error manifests itself in a certain pattern. The actual dimensions of the machined parts also obey certain laws, that is, they have a certain distribution law. Consequently, the combination of the measurement error and the actual size of the controlled part is a random event and it is possible to determine the results of incorrect sorting and, with a certain combination, only by probabilistic means.

In any kind of control, the decisions made on the basis of measurements are due to the following set of random events that make up the entire group: $P_{FF}$ – the probability that a randomly taken product controlled by this parameter is fit and recognized as fit; $P_{DD}$ – the probability that the controlled product is defective and recognized as defective according to the results of the control; $P_{FD}$ – the probability that the tested product is fit, but recognized as defective – an error of the 1st kind; $P_{DF}$ – the probability that the controlled product is defective, but recognized as suitable - an error of the 2nd kind.

At the moment, the most common method for determining the probabilistic characteristics of the grading parameters has given in RD 50–98–86 [17]. According to these recommendations, the influence of the measurement error has assessed by the parameters: $m \ (m_1)$ - the number of incorrectly accepted products as a percentage of the total number of measured (number of accepted); $n \ (n_1)$ - the number of incorrectly rejected products as a percentage of the total number measured (the number of good ones); $c \ (c_1)$ – the probabilistic value of the output of the measured parameter for each tolerance limit for incorrectly accepted products (from the number of parts received).

Parameters $m$, $n$ and $c$ have determined from nomograms.

The proposed method has applicable to specific laws of measurement of the measured parameter and measurement error. The large number of combinations of distribution laws and the inconvenience of using the calculation methods themselves prompts the search for simpler methods.

Another significant drawback of the considered methods is that the probabilities of determining the number of incorrectly accepted and incorrectly rejected parts have summed up. This approach does not take into account the different nature of the economic and technological consequences of determining the parameters for sorting out parts with correctable and irreparable defects.

Based on the study of the state of the problem, the following goal was set – to develop a methodology for assessing the influence of measurement error on the probabilistic characteristics of sorting parts, taking into account the specifics of repair production. To achieve this goal, it is necessary to develop a mathematical model describing the influence of the measurement error on the probabilistic characteristics of sorting parts, develop a computer program for calculating the probabilistic characteristics, and test the technique on a specific object.

2. Mathematical model of probabilistic characteristics of measurement results

In the repair production, the parts, the size of which is controlled at various stages of the technological process, are conventionally divided into parts such as holes and parts such as shaft. To assess the influence of the measurement error on the results of inspection of parts such as a hole, consider the diagram shown in figure 1. Parts such as a hole, coming for inspection, are sorted into three groups: correctable defect, irreparable defect.
Figure 1. Scheme of inspection of parts of the type hole. ±Δlim – maximum measurement error; $T_D$ – controlled hole tolerance; $x_D^u$, $x_D^l$ – upper and lower limits of the tolerance field of the controlled hole; $P^i_{DF}$ – the probability that the inspected holes with actual dimensions within the tolerance range will be assigned to the group of suitable parts; $P^c_{DF}$ – the probability that the controlled holes with actual dimensions within the tolerance range will be referred to the group of parts with a correctable defect; $P^i_{DFD}$ – the probability that the inspected holes with actual dimensions within the tolerance range will be assigned to the group of parts with an irreparable defect; $P^c_{DD}$ – the probability that the controlled holes with actual dimensions outside the upper limit of the tolerance range will be classified as suitable; $P^c_{DD}$ – the probability that the controlled holes with actual dimensions outside the lower limit of the tolerance range will be classified as suitable; $P^c_{DD}$ – the probability that the inspected holes with actual dimensions that go beyond the lower limit of the tolerance field will be classified as parts with a correctable defect; $P^c_{DD}$ – the probability that the inspected holes with actual dimensions outside the upper limit of the tolerance range will be classified as parts with an irreparable defect.

Due to the influence of the measurement error on the control result, it is likely that part of suitable parts such as a hole, will fall into a correctable defect $P^c_{DF}$, and some into an incorrigible one $P^i_{DF}$. Likewise, for defective parts, there is a possibility that they will be considered good – $P^i_{DF}$, $P^c_{DF}$.

In accordance with the diagram shown in figure 1, we will compose integral dependencies that describe the probabilistic characteristics of the results of inspection of parts such as a hole.

The probability of occurrence of parts such as a hole, the actual size of which is within the tolerance range and which will be recognized as suitable, has described by the integral
The probability of the appearance of parts such as a hole, the actual size of which is less than the minimum allowable size (correctable defect) has described by the integral

\[ P_{D_{FF}}^c = \int_{x_D^l}^{x_D^u} f(x) \int_{x_D^l}^{x_D^u} \phi(\gamma) d\gamma dx . \]  

The probability of occurrence of parts such as a hole, the actual size of which exceeds the largest allowable size (irreparable defect) has described by the integral

\[ P_{D_{DD}}^i = \int_{x_D^l}^{x_D^u} f(x) \left( \int_{-\infty}^{x_D^l-x} \phi(\gamma) + \int_{x_D^u-x}^{+\infty} \phi(\gamma) d\gamma \right) dx . \]  

The probability that, during inspection, a part of suitable parts such as a hole, the actual size of which is in the tolerance field, due to the influence of the measurement error, will fall into the group - correctable defect, has determined by the following integral

\[ P_{D_{FD}}^c = \int_{x_D^l}^{x_D^u-x} f(x) \int_{-\infty}^{x_D^l-x} \phi(\gamma) d\gamma dx . \]  

The probability that, during inspection, a part of suitable parts such as a hole, the actual size of which is within the tolerance field, due to the influence of the measurement error, will fall into the group - an unrecoverable defect has determined by the integral

\[ P_{D_{FD}}^i = \int_{x_D^l}^{x_D^u} f(x) \left( \int_{x_D^u-x}^{+\infty} \phi(\gamma) d\gamma \right) dx . \]  

The probability that, during inspection, a part of suitable parts such as a hole, the actual size of which is less than the minimum allowable (correctable defect), due to the influence of the measurement error, will be recognized as suitable, has determined by the integral

\[ P_{D_{DF}}^c = \int_{-\infty}^{x_D^l} f(x) \int_{x_D^l}^{x_D^u-x} \phi(\gamma) d\gamma dx . \]  

The probability that, during inspection, a part of parts such as a hole, the actual size of which exceeds the maximum allowable size (irreparable defect), will be recognized as fit has determined by the integral

\[ P_{D_{DF}}^i = \int_{x_D^l}^{x_D^u-x} f(x) \left( \int_{x_D^l}^{x_D^u-x} \phi(\gamma) d\gamma \right) dx . \]  

Formulas (1) - (7) are a mathematical model that describes the influence of the measurement error on the probabilistic characteristics of the distribution of the controlled parameters of parts such as holes.
Expressions (5) represent the product of two definite integrals. Moreover, the boundaries of the second integral depend on the variable of the function of the first integral. The calculation of the required probabilistic characteristics has determined by some accuracy.

To solve expressions (5), a computer program for calculating probabilistic characteristics by a numerical method in the Delthe 7 environment was written.

Let us consider the calculation of the probabilistic characteristics of the grading parameters using the example of the diameters, restored main and connecting rod journals of the crankshafts of YaMZ-238 engines.

The sorting parameters are more dependent on the distribution law of the controlled parameter and the length of the distribution. Therefore, to determine them, it is necessary to have a priori information about the control object.

3. Research results and their analysis

To solve this problem, experimental measurements of the diameters of the restored main and connecting rod journals of the crankshafts of YaMZ-238 engines were carried out. The values of distribution parameters obtained as a result of processing are presented in Table 1.

Table 1. Parameters of the distribution of diameters of the restored main and shaft journals of the crankshafts of YaMZ-238 engines.

| Parameter                  | Connecting rod necks | Indigenous necks |
|----------------------------|----------------------|------------------|
| Scattering area, mm        | 0.075                | 0.063            |
| Shear value, mm            | +0.002               | +0.0025          |
| Risk factor (fatal defect) | 0.76                 | 0.95             |
| Risk factor (correctable defect) | 0.44              | 0.48             |
| Probable percentage of correctable defect, % | 22.36 | 17.11 |
| Probable percentage of unrecoverable defect, % | 33       | 31.56          |
| Total defect, %            | 55.36                | 48.67            |
| Probable percentage of suitable shafts, % | 44.64       | 51.33           |

As a result of the studies, it has revealed that the scattering of the diameters of the crankshaft connecting rod journals restored under the 1st repair size obeys the law of normal distribution with a probability of agreement of 0.72. Suitable crankshaft journals – 44.64%, necks with a correctable defect - 33%, an incorrigible defect – 22.36%. The scattering of the sizes restored under the 1st repair size of the main journals of the crankshafts obeys the law of normal distribution with a probability of agreement of 0.78. Suitable crankshaft journals – 51.33%, necks with a correctable defect - 31.56%, an incorrigible defect - 17.11%.

Using the obtained characteristics of the distributions of the diameters of the necks of the crankshafts and the proposed computer program, it has possible to determine the probabilistic characteristics of the sorting parameters for various measuring instruments. The calculation results have presented in Tables 2 and 3.

Table 2. The results of calculating the probabilistic characteristics of the sorting parameters of the restored main journals of the crankshafts of YaMZ-238 engines.

| Probability                      | Standard deviation measurement errors, mm |
|----------------------------------|------------------------------------------|
| 0.001                            | 0.0015                                   |
| 0.00325                          | 0.0075                                   |
| The neck is good and will be considered good | 0.4888   |
| 0.01                             | 0.4755                                   |
| 0.4290                           | 0.3270                                   |
| 0.2600                           | 0.2600                                   |
The neck is defective and will be deemed defective by inspection. From this:

| Defect Type       | Probability |
|-------------------|-------------|
| Defective defect  | 0.1689      |
| Correctable defect| 0.0754      |

The neck is good but will be found to be defective. From this:

| Defect Type       | Probability |
|-------------------|-------------|
| Defective defect  | 0.0237      |
| Correctable defect| 0.0100      |

The neck is defective but will be found to be good. From this:

| Defect Type       | Probability |
|-------------------|-------------|
| Defective defect  | 0.0212      |
| Correctable defect| 0.0136      |

Table 3. The results of calculating the probabilistic characteristics of the sorting parameters of the restored main journals of the crankshafts of YaMZ-238 engines.

| Probability                        | Standard deviation measurement errors, mm |
|------------------------------------|------------------------------------------|
|                                    | 0.001 | 0.0015 | 0.00325 | 0.0075 | 0.01 |
| The neck is good and will be considered good | 0.4057 | 0.3947 | 0.3554 | 0.2712 | 0.2168 |
| The neck is defective and will be deemed defective by inspection. From this: | 0.1552 | 0.2093 | 0.416 | 0.4601 | 0.4429 |
| Defective defect                    | 0.0618 | 0.0757 | 0.1304 | 0.1299 | 0.1248 |
| Correctable defect                  | 0.0933 | 0.1336 | 0.2861 | 0.3301 | 0.3181 |
| The neck is good but will be found to be defective. From this: | 0.0205 | 0.0315 | 0.0708 | 0.1550 | 0.2094 |
| Defective defect                    | 0.0083 | 0.0128 | 0.0299 | 0.0705 | 0.0983 |
| Correctable defect                  | 0.0122 | 0.0187 | 0.0409 | 0.0846 | 0.1111 |
| The neck is good and will be considered good | 0.0173 | 0.0277 | 0.0599 | 0.1105 | 0.1307 |
| The neck is defective and will be deemed defective by inspection. From this: | 0.0069 | 0.0107 | 0.0221 | 0.0383 | 0.0436 |
| Defective defect                    | 0.0104 | 0.0170 | 0.0378 | 0.0721 | 0.0870 |

Summarizing the results obtained, we can conclude that the dynamics of measuring the probability characteristics of sorting parameters is of a general nature for both connecting rod and main journals of crankshafts. The quantitative value of these parameters, other things being equal, largely depend on the characteristics of the distribution.

4. Conclusions
Thus, the proposed method for determining the probabilistic parameters of defect detection using modern programming methods allows performing complex mathematical calculations taking into account the real characteristics of scattering of the dimensions of the measurement object. In addition, due to the fact that in the proposed program the probabilities characterizing the number of incorrectly accepted and incorrectly sorted parts on the part of a fixable and unrecoverable defect are divided, the obtained values can be used to optimize the measurement error according to the economic criterion.

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