Model of selective assembly process of rod-piston group parts of internal combustion engines

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Abstract. Functioning of conrod-piston group of internal combustion engine is considered. It is shown that the main method of assembly of this unit is selective assembly, which provides the required accuracy of parts joints. The scheme of the assembly set-making is given, a mathematical model of the process of its selective assembly with the selected strategy is built. As a strategy, a single-variant set-making is proposed, in which the assembly is carried out from the groups of the same numbers. The constructed model allows to determine the process indicators, in particular, the probability of obtaining suitable assembled sets, the probability of incomplete elements, forming work in progress and preliminary scrappage. The task of optimal assembly of rod-piston group at specified values of extended tolerances and arrangement of tolerance intervals by rational selection of boundaries of selective groups is set. The solution of this task is given.

1. Introduction
The conrod-piston group together with the crankshaft are the main working mechanism of the piston internal combustion engine. Translational motion of piston is converted into rotary motion of crankshaft by means of conrod coupled with upper head by piston pin and lower head with neck of shaft crank. The conrod-piston group consists of a cylinder, piston, piston rings, piston pin, details of seal, connecting rod, crank head cover with parts of attachment and conrod bearings. A fragment of the unit of this group and its individual elements are shown in Figures 1, 2.

Piston pin 1 serves for pin joint of piston with connecting rod. It is in the form of a hollow cylinder, made of chromium-nickel steel, undergoes cementation and hardening, followed by grinding and polishing. When using piston pins of floating type, bushes 3 are pressed into piston head of connecting rod 4. Holes or slots are made in upper, less loaded part of head to lubricate piston pin. Locking of the bush from turning can be provided by screws or tubular pins.

Connection of pin with bush of upper head of connecting rod is characterized by clearance, and with bosses of piston - by interference. These clearances and interferences are quite small, so the piston pins are selected to the pistons and connecting rods by selective assembly to maintain accurate fit.

Pistons 2 are distributed into 3 groups along bosses holes diameters as size increases. A similar number of groups have piston pins on the outer diameter as the size increases. The task of selective assembly of the given unit is the task of single-parameter assembly of three parts. Note here that piston pin 1 mates simultaneously with two parts (piston 2 and connecting rod bush 3) that do not form mating.
The main stages of selective assembly of mechanical engineering products are discussed in detail in [1-3]. Further development of studies related to single- and multi-parameter selective set-making and taking into account the influence of various random factors on this process is described in works [4-15].

The purpose of the work is to build a model of selective assembly of parts of the connecting rod-piston group unit to determine and optimize the indicators of the assembly process.

2. Model of selective assembly of the unit
The scheme of set-making in accordance with the designations adopted in [1] is shown in figure 3.

![Figure 3](image_url)

Figure 3. The scheme of set-making of the unit.
The parameters $x_i$ ($i = 1, 3$) by which the mating occurs are independent random variables that have distribution densities $f_i(x_i)$, as well as the final initial and central moments of the distribution of at least the first two orders.

When constructing a model, the following are accepted as assumptions.
1. The sizes of holes 1 and 2 in the piston, mated to the piston pin and manufactured independently of each other, fall into the same selective group (figure 2,a) and are considered one parameter $x_2$.
2. The dimensions of the surfaces of the piston pin (1, 2, 3) measured in several sections (I, II and III) perpendicular to the axis, the arithmetic mean of which is taken as the real value of the parameter $x_i$, are in the same selective group (figure 2,b).

Let each parameter $x_i$ have an extended manufacturing tolerance $X_i$. Before assembly, parts are sorted by specified parameters by groups with group tolerances intervals $X_{ki}$, where $i$ - part number, $k_i$ - selective group number. Boundaries of selective groups $a_{ki}$ divide the entire region of parameter values $X_i$ into $l_i$ intervals $X_{ki}$. For our task $l_1 = l_2 = l_3 = 5$. Tolerance intervals for all three types of parts, taking into account their rejection and the number of selective groups equal to three for suitable parts, are presented in Table 1.

| Group number $k_i$ | Part number | $1$ | $2$ | $3$ |
|--------------------|-------------|-----|-----|-----|
| rejected parts     | $1$         | $X_1^{(1)} = \{x_i : -\infty < x_i < a_1^{(2)}\}$ | $X_2^{(1)} = \{x_2 : -\infty < x_2 < a_2^{(2)}\}$ | $X_3^{(1)} = \{x_i : -\infty < x_i < a_1^{(2)}\}$ |
| suitable parts     | $2$         | $X_1^{(2)} = \{x_i : a_1^{(2)} \leq x_i < a_1^{(4)}\}$ | $X_2^{(2)} = \{x_2 : a_2^{(2)} \leq x_2 < a_2^{(4)}\}$ | $X_3^{(2)} = \{x_i : a_1^{(2)} \leq x_i < a_3^{(3)}\}$ |
|                     | $3$         | $X_1^{(3)} = \{x_i : a_1^{(3)} \leq x_i < a_1^{(4)}\}$ | $X_2^{(3)} = \{x_2 : a_2^{(3)} \leq x_2 < a_2^{(4)}\}$ | $X_3^{(3)} = \{x_i : a_1^{(3)} \leq x_i < a_3^{(4)}\}$ |
|                     | $4$         | $X_1^{(4)} = \{x_i : a_1^{(4)} \leq x_i < a_1^{(5)}\}$ | $X_2^{(4)} = \{x_2 : a_2^{(4)} \leq x_2 < a_2^{(5)}\}$ | $X_3^{(4)} = \{x_i : a_1^{(4)} \leq x_i < a_3^{(5)}\}$ |
| rejected parts     | $5$         | $X_1^{(5)} = \{x_i : a_1^{(5)} \leq x_i < \infty\}$ | $X_2^{(5)} = \{x_2 : a_2^{(5)} \leq x_2 < \infty\}$ | $X_3^{(5)} = \{x_i : a_1^{(5)} \leq x_i < \infty\}$ |

In this case, the rejection removes parts from the extreme groups with large deviations of parameters (smaller $a_1^{(2)}$ or larger $a_3^{(5)}$) from the set-making and assembly processes. At that, number of types of assembly sets decreases by two ($L = 3$).

The arrangement of tolerance intervals for the part parameters to be assembled is shown in Figure 4.

Requirements to product output parameters:
1) the clearance $S$ in the mating of a pair of parts 1-3 must belong to the area $[S_{\text{min}}, S_{\text{max}}]$, where $S_{\text{min}}, S_{\text{max}}$ is the smallest and largest clearance values regulated by design documents;
2) the interference $N$ in the mating of a pair of parts 1-2 must be within $[N_{\text{min}}, N_{\text{max}}]$. 

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Table 1. Group tolerance intervals.
where \( N_{\text{min}}, N_{\text{max}} \) is the smallest and largest interference values regulated by the design documents.

\[
\begin{align*}
4
\end{align*}
\]

**Figure 4.** The arrangement scheme of tolerance intervals of parameters \( x_i \) \( (i = 1, 3) \).

For the formation of assembly sets in accordance with the technological process, a single-variant rule is used. The set-making rule is a method of forming assembly sets from parts of different selective groups. The set-making rule establishes the correspondence between the number \( k \) of the assembly sets and the vector \( (k_1, k_2, ..., k_m) \) of numbers of the selective groups of parts of the set. For a single-variant set-making, each \( k \) is assigned a corresponding vector that necessarily differs from the rest by the values of all its components, so each variable value is included in only one set.

Let's define quantity of the assembly sets received on an output of the set-making and assembly processes. In \( k_i \) selective group the parts of type \( i \) get with probability

\[
I_{i}^{(k_i)} = \int_{x_i^{(k_i)}} f_i(x_i)dx_i.
\]

The probability of obtaining assembly sets of type \( k \) can be determined by the formula

\[
I_{ck}^{k} = \min_{i \in [1, 3]} \left\{ I_{i}^{(k_i)} \right\}, k = 1, 3.
\]

The total probability of obtaining suitable assembly sets for all sets is

\[
I_{CK} = \sum_{k = 1}^{3} I_{ck}^{k}.
\]

The probability of incomplete parts forming incomplete production and preliminary scrappage is equal to

\[
P = 1 - I_{ck}.
\]

Having the received relations, it is possible to put a number of problems connected with the analysis, synthesis and optimization of processes of set-making and selective assembly.
3. Optimization of the unit assembly indicators

Under conditions of technological process of manufacturing and assembling of the considered unit the number of selective groups and extended tolerances for manufacturing of details of all types are set. At the given intervals of group tolerances the number of fully completed assembly sets is calculated by formula (1). One of the tasks of rational selection $a_{ik}^{(k)}$ is their optimal distribution to obtain as many complete assembly sets as possible. When distributing group boundaries, it should be borne in mind that the values obtained during the calculation of clearances $S'$ and interferences $N'$ must satisfy the conditions

$$S_{\text{min}}^{(k)} \geq S_{\text{min}}, S^{(k)} \leq S_{\text{max}}, N_{\text{min}}^{(k)} \geq N_{\text{min}}, N^{(k)} \leq N_{\text{max}},$$

which are due to the above product quality requirements.

Let's set the optimization task in the following form: define $a_{ik}^{(k)}$ which deliver the function maximum

$$I_{CK} = f(a_{ik}^{(k)})$$

under constraints (2).

This problem is a problem of nonlinear discrete programming due to the fact that the values $a_{ik}^{(k)}$ can take strictly defined values that are multiples of the discreteness of instruments $D_{i}$ that perform control and measurement operations.

The task of searching for maximum of the function (3) with the constraints (2) will be solved by full search of all possible variants. Since the dimension of the task is relatively small (there are 6 variable parameters limited by the final limits), this method will give a guaranteed result in a reasonable time.

Input data for solving the problem are as follows.

1. Laws of distribution of parameters of parts. Suppose that the distributions of the mating parameters of the type $i$ parts are Gaussian with distribution densities

$$f_{i}(x_{i}) = \frac{1}{\sigma_{i} \sqrt{2\pi}} e^{-\frac{(x_{i} - m_{i})^2}{2\sigma_{i}^2}},$$

where $m_{i}$ - means (mathematical expectations), $\sigma_{i}^2$ - standard deviation of a random variable $x_{i}$, ($i=1,3$), which are known, determined by accumulated empirical data with their subsequent processing.

Let's take $m_{1} = -6 \ \mu m$, $\sigma_{1} = 1.967 \ \mu m$; $m_{2} = -9 \ \mu m$, $\sigma_{2} = 2.400 \ \mu m$; $m_{3} = -0.5 \ \mu m$, $\sigma_{3} = 2.143 \ \mu m$.

2. Values of maximum clearances $S_{\text{max}}, S_{\text{max}}$ and interferences $N_{\text{min}}, N_{\text{max}}$, determined by the requirements for the quality of the product in the assembly. For our case in accordance with the technical documentation:

$$S_{\text{min}} = 0 \ \mu m, S_{\text{max}} = 12 \ \mu m; N_{\text{min}} = 0 \ \mu m, N_{\text{max}} = 12 \ \mu m.$$

3. The number of sorting groups $l_{1} = l_{2} = l_{3} = 5$, the number of types of assembly sets $L = 3$, the set-making rule is single-variant.

4. Values of extended manufacturing tolerances $E_{i}$, coordinates of the midpoints of tolerance intervals $X_{i}$, ($i=1,3$) (deviations of the midpoints of tolerance intervals from the nominal size $\varnothing 20 \ \text{mm}$). Let's take $X_{1} = X_{2} = X_{3} = 12 \ \mu m$, $E_{1} = -6 \ \mu m$, $E_{2} = -10 \ \mu m$, $E_{3} = 0 \ \mu m$.

5. Discreteness values of reading of measuring instruments $D_{i}$.

The results of the problem solution are summarized in Table 2.
Table 2. Optimization problem solution results.

| The part | $D_i$ | The boundaries $d^{(k)}_j$ for groups, μm | $I_{CK}$ |
|----------|-------|----------------------------------------|----------|
|          |       | 2          | 3          | 4          |          |
| 1        | 2     | 0          | -4         | -4         | -8        | -8        | -12       | 0.780     |
| 2        | 2     | -4         | -8         | -8         | -12       | -12       | -16       |          |
| 3        | 2     | +6         | +2         | +2         | -2        | -2        | -6        |          |
| 1        | 1     | 0          | -4         | -4         | -8        | -8        | -12       | 0.813     |
| 2        | 1     | -4         | -8         | -8         | -12       | -12       | -16       |          |
| 3        | 1     | +6         | +1         | +1         | -3        | -3        | -6        |          |
| 1        | 0.5   | 0          | -4         | -4         | -7.5      | -7.5      | -12       | 0.880     |
| 2        | 0.5   | -4         | -7.5       | -7.5       | -12       | -12       | -16       |          |
| 3        | 0.5   | +6         | +1.5       | +1.5       | -2.5      | -2.5      | -6        |          |

4. Conclusions

Thus, on the basis of the constructed model of the selective assembly process, the problem of optimal assembly of the conrod-piston group is solved at the given values of extended tolerances and the location of tolerance intervals by rational selection of the boundaries of the selective groups.

The results presented in Table 2 clearly show that reducing the discreteness of measuring equipment in this particular case gives a tangible result. However, it should be remembered that increasing the accuracy of measurement by replacing existing instruments with new ones should be accompanied by calculations that confirm the economic efficiency of such an operation.

Acknowledgments

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