THE ESSENCE OF METHODS FOR CALCULATING DIMENSIONAL CHAINS IN DESIGNING DETAILS OF AGRICULTURAL MACHINERY

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ABSTRACT

The quality of machine and mechanism performance largely depends on the quality of manufacturing of parts and the assembly process. The assembly process, both after the direct production of components and after their restoration during repair, is based on the development of design and technological documentation, an essential element of which is the calculation of dimensional chains. The existing interstate, national, and industry regulatory documents define the procedure and rules for calculating dimensional chains. In Ukraine, when developing a technological assembly process at the design stage, interstate standards such as GOST 16319-80 and GOST 16320-80 are used. During the assembly stage, technological and design solutions are applied to achieve the required dimensional accuracy, which often leads to additional technological operations and costs. However, it is possible to reduce the total assembly error and the number of technological operations already at the design stage (Cherkashyna, 2013). GOST 16320-80 establishes methods for calculating dimensional chains using various approaches to achieve the accuracy of the closing link, in particular: the method of complete interchangeability, the method of partial interchangeability (probabilistic method), the method of group interchangeability (selective assembly), the fitting method, and the adjustment method. This article discusses the essence of calculating dimensional chains using the methods of partial and group interchangeability in the manufacture of agricultural machinery parts.

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СУТНІСТЬ МЕТОДІВ РОЗРАХУНКУ РОЗМІРНИХ ЛАНЦЮГІВ ПРИ ПРОЕКТУВАННІ ДЕТАЛЕЙ СІЛЬСЬКОГОСПОДАРСЬКИХ МАШИН

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АНОТАЦІЯ

Якість роботи машин та механізмів в значній степені залежать від якості виготовлення деталей та процесу складання. Процес складання як після безпосереднього виготовлення деталей, так і після процесів їх відновлення при ремонті], базується на розробці конструкторської і технологічної документації, обов'язковим елементом яких є розрахунок розмірних ланцюгів. Існуючи міждержавні, національні, галузеві нормативні документи регламентують порядок, правила розрахунку розмірних ланцюгів . В Україні, при розробці технологічного процесу складання на етапі конструювання використовуються міждержавні стандарти: ГОСТ 16319-80; ГОСТ 16320-80, а на етапі складання використовують технологічні та конструкторські рішення для досягнення необхідної розмірної точності, що потребує додаткових технологічних операцій та витрат. Але зменшення сумарної похибки складання та зменшення технологічних операцій можливо на етапі конструювання (Черкашина, 2013). ГОСТ 16320-80 встановлює методи розрахунку розмірних ланцюгів з використанням різних методів досягнення точності замикаючої ланки, зокрема: метод повної взаємозамінності; метод неповної взаємозамінності (ймовірнісний метод); метод групової взаємозамінності (селективної збірки); метод пригону; метод регулювання. У статті розглянуто сутність розрахунку розмірних ланцюгів методами неповної та групової взаємозаміни при виготовленні деталей сільськогосподарських машин.

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STATE OF THE ART AND PROBLEM STATEMENT

The method of complete interchangeability (maximum–minimum method) is an interchangeability approach in which the required accuracy of the closing link of a dimensional chain is ensured when any link can be included in or replaced within the chain without selection or dimensional adjustment. In this method, components are assembled without fitting. For any combination of part dimensions manufactured within the specified tolerances, the value of the closing link does not go beyond the established limits. The dimensional chain is calculated using the maximum–minimum method.

This method of calculation is typically used in individual and small-batch production; when the tolerance of the closing link is small and the number of constituent links is limited; or when the tolerance of the closing link is relatively large.

The advantages of the method include simplicity and cost-effectiveness of assembly, simplified organization of assembly processes, the possibility of extensive inter-plant cooperation, and a simplified spare-parts supply system. The disadvantages include higher product manufacturing costs, since the tolerances of the constituent links are smaller than those obtained using other methods.

The method of partial interchangeability (probabilistic method) ensures the required accuracy of the closing link not for all assemblies but for a predetermined proportion of them. To meet technical requirements in this case, additional processing operations are introduced. Parts are assembled, as a rule, without fitting, adjustment, or selection; however, in a small number of assemblies (the quantity is predetermined), the value of the closing link exceeds the established limits. The dimensional chains are calculated using a probabilistic approach. This method is applied in serial and mass production, when the tolerance of the closing link is small and the number of constituent links is relatively large.

The advantages of the partial interchangeability method are the same as those of the complete interchangeability method. The manufacturing cost is significantly lower due to the expansion of the tolerance fields of the constituent links (compared with complete interchangeability). The disadvantage of the method is the need to employ highly skilled workers to fit certain parts in those assemblies where the closing link exceeds the specified limits.

The method of group interchangeability (selective assembly) is a method in which the required accuracy of the closing link of a dimensional chain is ensured by including in it constituent links that belong to one of the groups into which they have been previously sorted. The pre-sorted parts are assembled without fitting, and the required value of the closing link is thus achieved. This method is used in mass and large-scale production for dimensional chains with a small number of links.

The advantage of this method lies in the possibility of achieving high accuracy of the closing link with economically feasible tolerance fields of the constituent links. The disadvantages include the presence of unfinished production ("excess parts"), additional costs for pre-sorting the parts into groups, increased complexity of the assembly organization, and difficulties in spare-parts supply management.

The fitting method is a technique in which the required accuracy of the closing link of a dimensional chain is achieved by modifying a special (compensating) link included in the chain through the removal of a material layer. The amount of material to be removed is determined after preliminary assembly and measurement. The calculation of the dimensional chain is performed using either the maximum–minimum method or the probabilistic method. This method is applied primarily in individual production.

The advantage of this method lies in the fact that economically feasible tolerances can be assigned to all constituent links. The disadvantages include a significant increase in assembly cost and a decrease in labor productivity during assembly, as well as difficulties in spare-parts supply.

The adjustment method ensures the accuracy of the closing link of a dimensional chain by changing the compensating link without removing any material. This method is widely used in all types of production when a high degree of accuracy of the closing link is required.

The advantages of the adjustment method include the possibility of regulating the dimension of the closing link to achieve the required accuracy, the ability to compensate for wear during operation, and the possibility of assigning economically feasible tolerance fields to the constituent dimensions. The disadvantages are the increased complexity of the assembly unit design and greater difficulty in assembly processes *(Prykhodko, 2021; Deribo et al., 2024; Rud et al., 2008; Tsvirkun et al., 2022).*

MATERIALS AND METHODS

The maximum–minimum method guarantees the complete absence of defective products (technological failures), requires less information about the constituent links, and therefore involves lower computational complexity. However, this method allows for any, often undesirable, combination of the extreme dimensional values of the chain's constituent links. The probability of such combinations occurring during the machining of workpieces is low; nevertheless, it necessitates the assignment of tighter tolerances for technological dimensions *(Ivanov, 2013).*

The probabilistic method eliminates this drawback. It takes into account the regularities in the distribution of machining dimensional deviations. The tolerances calculated by this method do not include excessive accuracy reserves, which allows for a reduction in machining costs.

At the same time, the probabilistic method permits the possibility of defects, is more complex (requiring a greater amount of information about the constituent links), and therefore is more labor-intensive.

The choice of method for solving technological dimensional chains depends on the number of constituent links (*n*) in the chain. When the number of links is n ≤ 4, the calculation is performed using the maximum–minimum method. In cases where n ≥ 5, the probabilistic method is applied.

RESULTS AND DISCUSSION

The method of group interchangeability (selective assembly) is mainly used for dimensional chains consisting of three constituent links and for assembly joints that are not subject to disassembly and reassembly during the operation of the product but are instead replaced as a complete unit — for example, plunger pairs or rolling bearings.

When calculating tolerances and limit deviations for the dimensions of the constituent links of a dimensional chain, the accuracy of the closing link, ensured by the method of group interchangeability, is determined using the following formulas:

$$\delta_{\Delta} = \sum_{i=1}^{n_j} \delta_j + \sum_{i=1}^{n_q} \delta_q = \sum_{i=1}^{n_i} \delta_i \, , \tag{1}$$

where δ_{Δ} – is the tolerance of the closing link; δ_j – is the tolerance of the increasing links; δ_q – is the tolerance of the decreasing links; δ_i – is the tolerance of any constituent link.

$$\Delta_{0\Delta} = \sum_{i=1}^{n_j} \Delta_{0j} - \sum_{i=1}^{n_q} \Delta_{0q} \, , \tag{2}$$

where $\Delta_{0\Delta}$ – is the coordinate of the midpoint of the tolerance field of the closing link; Δ_{0j} – is the coordinate of the midpoint of the tolerance field of the increasing links; Δ_{0q} – is the coordinate of the midpoint of the tolerance field of the decreasing links.

Let us consider the following case. The dimensional chain consists of two constituent links, and the initial equation has the form:

$$A_{\Delta} = A_j - A_q , \tag{3}$$

where A_{Δ}, A_j, A_q – are the nominal dimensions of the closing, increasing, and decreasing links, respectively..

To satisfy the above conditions, it is necessary to assign tolerances for A_j і A_q in such a way that

$$\delta_{\Delta} = \delta_j - \delta_q \quad \text{і} \quad \delta_j = \delta_q$$

Then, such values of Δ_{0j} і Δ_{0q}, re selected so that condition (2) is satisfied. The limit deviations of the links A_j і A_q are determined according to the following formulas:

$$\left.\begin{aligned} \Delta_{bj} &= \Delta_{0j} + \frac{\delta_j}{2}; \\ \Delta_{нj} &= \Delta_{0j} - \frac{\delta_j}{2}; \\ \Delta_{bq} &= \Delta_{0q} + \frac{\delta_q}{2}; \\ \Delta_{нq} &= \Delta_{0q} - \frac{\delta_q}{2} \end{aligned}\right\} \tag{4}$$

This completes the constructive calculation.

Since the tolerances δ_j і δ_q obtained during the calculation are difficult to maintain under actual production conditions, they must be increased by *k* times.

To achieve this, the following conditions must be met:

$$\delta_j' = m\delta_j \quad \text{і} \quad \delta_q' = m\delta_q , \tag{5}$$

where δ_j' і δ_q' – are the production tolerances..

The tolerances of the constituent links are increased by the same factor by which the constructive tolerances were enlarged; accordingly, the production tolerance of the closing link is determined as follows:

$$\delta_{\Delta}' = m\delta_{\Delta} . \tag{6}$$

The number of groups into which the finished parts must be sorted will also be equal to *k* and is determined by the following formula:

$$m = \frac{\delta_{\Delta}'}{\delta_{\Delta}} = \frac{\delta_j' + \delta_q'}{\delta_{\Delta}} . \tag{7}$$

The limit deviations of the links A_j і A_q for each group are determined as follows:

a) for the first group, the limit deviations of the links A_j і A_q are taken to be equal to the calculated values.

$$\left.\begin{array}{l}\Delta_{bj(1)} = \Delta_{bj};\quad \Delta_{нj(1)} = \Delta_{нj};\\ \Delta_{bq(1)} = \Delta_{bq};\quad \Delta_{нq(1)} = \Delta_{нq}.\end{array}\right\} \tag{8}$$

б) for the subsequent groups, the limit deviations of each next group are obtained by adding the calculated constructive tolerances δ_j or δ_q depending on which link (increasing or decreasing) the deviations are being determined for.

For the *p*-th group:

$$\left.\begin{array}{l}\Delta_{bj(n)} = \Delta_{bj(n-1)} + \delta_j;\quad \Delta_{нj(n)} = \Delta_{нj(n-1)} + \delta_j;\\ \Delta_{bq(n)} = \Delta_{bq(n-1)} + \delta_q;\quad \Delta_{нq(n)} = \Delta_{нq(n-1)} + \delta_q.\end{array}\right\} \tag{8}$$

In practice, during the manufacturing of parts, dimensional scatter occurs as a result of technological factors, followed by the random nature of dimensional combinations of the parts during assembly.

Using probabilistic estimates, it can be observed that if a small or very small risk (probability) of interchangeability violation during assembly is allowed, the tolerances of the constituent parts can be expanded.

If, in the calculation of dimensional chains, economic analysis indicates the need to apply a system of overlapping tolerances based on the random combination of parts, the tolerances should be determined statistically to control the proportion of defective parts within an acceptable level. The statistical determination of tolerances defines the amount by which tolerances may be increased, based on an acceptable degree of risk that only a small fraction of defective parts will be produced.

The calculation of statistical tolerances of the links in a dimensional chain is based on the application of probability theory theorems. Let us consider one of the summation methods — the method of independent scalar quantities. When summing independent scalar random quantities, the conclusions of several theorems are applied.

If x_1, x_2, …, x_j, …, x_k are independent random variables with corresponding means M_1, M_2, …, M_j, …, M_k and variances σ_1^2, σ_2^2, …, σ_j^2, …, σ_k^2 і якщо a_1, a_2, …, a_j, …, a_k є 2 are constant coefficients, while *y* represents a linear combination of these variables x_j:

$$y = a_1 x_1 \pm \ \dots \ \pm a_j x_j \pm \ \dots \ \pm a_k x_k, \tag{9}$$

then y is also a random variable that possesses the following properties:

1) $M_k = a_1 M_1 \pm a_2 M_2 \pm \dots a_k M_k$;

2) $\sigma_y^2 = a_1^2 \sigma_1^2 \pm a_2^2 \sigma_2^2 \pm \dots a_k^2 \sigma_k^2$;

3) If each random variable x_1, x_2, …, x_k follows the normal distribution law, then y also follows a normal distribution law.

According to these conclusions, when determining the tolerance of the closing dimension under an arbitrary distribution law, a relative dispersion coefficient *k* is introduced.

The coefficient *k* characterizes the deviation of the distribution of dimensional-chain tolerances from the Gaussian (normal) distribution. For the normal distribution, $k = 1$; for the triangular (Simpson) distribution, $k = 1,22$.

The range of the distribution of *y* measures the dispersion of the linear combination of random variables x_j.

The range of deviations of the dimensions of the corresponding links, expressed by the values R_1, R_2 , …, R_k represents the respective tolerances that determine the qualitative characteristics of the deviations., The value R_y is the tolerance that defines the qualitative characteristic of the closing link in the dimensional-chain system.. The mean values M_1, M_2, …, M_k correspond to the nominal dimensions of the links in the dimensional chain M_y – while $\bar{y}$ corresponds to the nominal dimension of the closing link.. The standard deviation σ_y y is used as a measure of dispersion, since for the normal distribution law R_y, $6\sigma_y = R_y$. Similarly, σ_1, σ_2, …, σ_k will respectively be the estimates of R_1, R_2, …, R_k. The number of tolerances in the dimensional chain is denoted by *m*, which corresponds to *m* distributions of part deviations. From the above equation for determining the tolerance of the closing-link dimension, we obtain:

$$TA_\Delta = \sqrt{\sum_{j=1}^{m-1}(TA_j)^2}\ . \qquad (10)$$

For the tolerance of the closing-link dimension under an arbitrary distribution law, a relative dispersion coefficient *k* is introduced, and the previous equation takes the following form:

$$TA_\Delta = \frac{1}{k_\Delta}\sqrt{\sum_{j=1}^{m-1}(TA_j)^2 k_j^2}\ . \qquad (11)$$

By applying transformation procedures to the obtained equations, we derive an equation for calculating the tolerances of the constituent links of the dimensional chain based on a given tolerance of the closing link. For example, let us compare the tolerances of the constituent links TA_j in a dimensional chain consisting of four links, calculated using the method of complete interchangeability and the probabilistic (theoretical–statistical) method, under the condition $TA_\Delta = 4TA_j$.

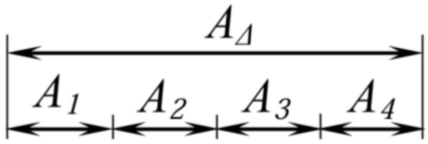

Fig. – Dimensional chain diagram

Calculation by the maximum–minimum method with additive tolerances:

$$TA_\Delta = 4TA_j,$$

from which it follows that

$$TA_j = \frac{TA_\Delta}{4}$$

The calculation performed using the theoretical–probabilistic method with random variables of overlapping tolerances gives:

$$TA_\Delta = \sqrt{4(TA_j)} = 2TA_j$$

from which it follows that

$$TA_j = TA_\Delta / 2.$$

CONCLUSIONS

In the case of selective assembly (for clearance and interference fits), the maximum clearances and interferences are reduced, while the minimum ones are increased. As the number of sorting groups increases, these values approach the mean clearance or interference for the given fit, making the joint more stable and durable.

The application of the probabilistic method for calculating the dimensional chain makes it possible to use the tolerances of the constituent links two grades coarser, which is of great importance for achieving the required machining accuracy of parts in various assembly unit designs.

From the comparison of both calculations using the method of partial interchangeability, it follows that applying the theoretical–probabilistic calculation allows, with the same closing-link tolerance *TAΔ*, to double the tolerance of the constituent links with a risk probability of only 0.27%.

In agricultural machine building, such a small level of risk is considered negligible, and machines are therefore designed taking this risk into account.

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