The linear sizes tolerances and fits system modernization

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Abstract
The study is carried out on the urgent topic for technical products quality providing in the tolerancing process of the component parts. The aim of the paper is to develop alternatives for improving the system linear sizes tolerances and dimensional fits in the international standard ISO 286-1. The tasks of the work are, firstly, to classify as linear sizes the elements additionally linear coordinating sizes that determine the detail elements location and, secondly, to justify the basic deviation of the tolerance interval for the element's linear size. The geometrical modeling method of real details elements, the analytical and experimental methods are used in the research. It is shown that the linear coordinates are the dimensional basis of the elements linear sizes. To standardize the accuracy of linear coordinating sizes in all accuracy classes, it is sufficient to select in the standardized tolerance system only one tolerance interval with symmetrical deviations: Js for internal dimensional elements (holes) and js for external elements (shafts). The main deviation of this coordinating tolerance is the average zero deviation, which coincides with the nominal value of the coordinating size. Other intervals of the tolerance system are remained for normalizing the accuracy of the elements linear sizes with a fundamental change in the basic deviation of all tolerance intervals is the maximum deviation corresponding to the limit of the element material: EI is the lower tolerance for the of the internal elements (holes) sizes and es is the upper tolerance deviation for the outer elements (shafts) sizes. It is the sizes of the material maximum that are involved in the of the dimensional elements mating of the shafts and holes and determine the fits type.

Keywords – Technical products, size elements, linear coordinating sizes, tolerance intervals, basic limit deviations.

1. Introduction
The most common dimensional elements, which comprise the details of technical products, are cylindrical and plane-parallel prismatic elements (elements of the "cylinder" type and the "two parallel planes" type, according to the international ISO standards for the geometrical product specification GPS). The sizes of these elements are expressed in units of length and are standardized as linear sizes [1]. The accuracy of linear sizes is normalized by the International System of limits and fits [2, 3]. High efficiency of the system is confirmed by almost a century of its application without significant changes for the technical products design. Based on the numerical values of linear sizes tolerances and F W Taylor principles, half a century ago, a system of limit gauges was created to control the accuracy of dimensional elements [4] and is still used today [5].

The location of the dimensional elements of the part in the GPS standards is determined by the linear distances [6], which do not belong to linear sizes and do not have a tolerance system. Therefore, linear distances are used as theoretically exact dimensions (TED), and their accuracy is normalized towards the part datums [7] using positional tolerances [8], which do not have standardized numerical values either and are set by the project designer. The control of design documentation shows that the projects quality is mainly reduced by inconsistencies in the accuracy standardization of the linear
distances between dimensional elements. A lot of researchers face this problem when calculating dimensional chains and estimating the cost of assemblies [9], analyzing size tolerances in technological processes [10] and assembling products [11], investigating the influence of the location tolerances on the maximum material size of dimensional elements in automotive and aircraft industry [12,13], developing new algorithms for setting dimensions and geometric tolerances [14], creating software packages for computer-aided design [15], developing the models for three-dimensional linear sizes tolerances and geometrical tolerances [16], including those which take into account the forces of gravity and friction in assembling units [17].

2. Statement of the problem

Modern automated design of technical products and technological processes is carried out in a rectangular coordinate system. However, in the ISO standards for geometrical products specification GPS, coordinate systems are not applied. The reason is simple: in the matrix GPS model [18] there are no coordinate systems for reading the parts geometrical specification.

When designing products, the position of each geometric element in the generalized coordinate system of the workpiece is specified using the linear coordinates $x$, $y$, $z$.

Consequently, the first task of the study is the transition from the sizes of linear distances to the mathematical linear coordinates of the parts elements and the development of a tolerances system for the normalization of coordinating sizes accuracy.

The second task is to refine the functional purpose of the concept of "basic deviation" of linear sizes tolerance intervals for dimensional elements in the system of tolerances and fits ISO 286-1.

3. Accuracy of the parts linear coordinating sizes

Each part has a generalized $OXYZ$ coordinate system, which is identified by a set of main design datums that constrain the detail of six degrees of freedom - three linear and three angular. The coordinate planes of the rectangular $OXYZ$ coordinate system have different informativeness: 3, 2, and 1. The coordinates axes of the rectangular $OXYZ$ coordinate system also have different informativeness: 4, 2 and $\theta$ (zero) [19]. The coordinating dimensions of the part geometric elements should be specified with respect to the coordinate planes and axes of coordinates with the maximum informativeness. The more such coordinates the part has, the higher will be its quality in positioning accuracy of geometric elements, including size elements.

To solve the problem of normalizing the accuracy of linear coordinating sizes, we consider structural models of linear elemental sizes of two dimensional elements: prismatic plane-parallel with informativeness 3 (Fig.1, a) and cylindrical with informativeness 4 (Fig.1, b)

![Figure 1](image)

Figure 1. Structural models of linear element sizes of two dimensional elements: 

a) plane-parallel prismatic; b) cylindrical.

Both dimensional elements form their own rectangular coordinate systems $OX4Y2Z\theta$ and $OX2Y8Z4$ thanks to their maximum informativeness of the datums: flat datum A3 with informativeness 3 for the prism element and the reference axis B4 with informativeness 4 for the cylindrical element. The analysis of the models shows that the dimensional basis of the elements linear sizes is the linear coordinates $z_2 \pm E_{z_2}$ and $x_2 \pm E_{x_2}$ from the datums to the center C of the opposite plane for the prism element and to the center C of the opposing straight line forming the surface of the cylindrical element.
while its rotating about the datums axis. Therefore, if the nominal sizes are equal, the tolerance of the linear coordinating size is a part of the linear elemental size tolerance. Taking into account that up to 60% of the linear size tolerance is taken by deviations in the shape and location of its real surfaces [20], the tolerance of the linear coordinating size should be one grade exact than the accuracy of the linear size and depend only on the length of the normalized coordinate. This will allow to normalize the accuracy of the linear coordinating sizes according to the standards ISO 286-1 and ISO 286-2 for the system of tolerances and fits of linear sizes, because both sizes are varieties of one linear physical quantity "length", have a common measurement unit and comparable tolerances.

Three linear coordinates in the part generalized coordinate system specify the position of one point of the origin of the auxiliary coordinate system for the attached part or one point of the executive geometric element center that performs the work functions of the part. Linear coordinating sizes of $x$, $y$, $z$ points are the distances from the coordinates origin of the part generalized coordinate system to the projections of the positioning point on the linear scales of the $X$, $Y$, $Z$ coordinate axes [19]. Every linear coordinate has only one value, is one-dimensional and has a normal distribution, symmetric with respect to its nominal size. The accuracy of coordinating sizes is higher the more informativeness the axes of coordinates has; i.e.4 and 2. Therefore, linear coordinating sizes measured along the coordinate axes with zero informativeness $(\theta)$ should be avoided in the part design, or their nominal values should be reduced to zero $(\theta)$. The principle of the shortest dimensional chains requires the reduction of the values of all linear coordinating sizes in order to increase their accuracy.

The symmetry of the normal distribution law of linear coordinating sizes with respect to their nominal values requires, for the accuracy normalization, only one symmetric tolerance interval $J_s$ for holes and $J_s$ for shafts that have the same limit deviations $\pm IT / 2$ equal in absolute values to half the tolerance $IT$ in each accuracy grade (Fig. 5). The basic deviation of the linear coordinating size is the zero deviation $(\theta)$, which coincides with the nominal size value.

The zero nominal value of the linear coordinating size is its distinguishing feature from the linear size of the element. Therefore, the first interval of sizes in the system of tolerances $J_s$ and $J_s$ should start from zero: $\theta ... 3mm$.

The second distinguishing feature of the linear coordinating size is its grouping around the nominal size. Therefore, the most probable values of the coordinating size are located in the interval covering the nominal size. In this case, the value of the linear coordinating size may differ from the normal linear sizes.

Finally, linear coordinating sizes may have negative values if the direction of their reference from the origin is opposite to the positive direction of the coordinate axis.

4. Accuracy characteristics of linear element size

The accuracy in the linear coordinating dimensions, which belong to the structure of elements linear sizes (figure 1), determines the dimensional basis of the element's accuracy. The geometric accuracy of the size element is determined by the deviations of the shape and location of the element real surfaces. These deviations make the linear dimension of each element variable, limited by two functional boundary dimensions. The main functional element dimension - the maximum material size - is formed by the protrusions fit points of the real surface of the hole $D_{max}$ or the shaft $d_{max}$ (figure 2). participates in mating, determines the nature and forms an an envelope element that serves as a design datum.
Figure 2. The influence of surface shape deviations on different functional purpose of linear sizes of material maximum and material minimum in the mating of real cylindrical elements: 
a) mating model in longitudinal section; b) the cross-sectional mating model.

The valleys of the real surface form the second functional dimension of the element - the minimum material size of hole $D_{LM}$ or shaft $d_{LM}$, which limits the deviation of the shape and location of the element surfaces.

In accordance with the principle of two-dimensionality of linear sizes [19], the maximum material size and the minimum material size of the real dimensional element are the sizes of two regular (ideal) elements of the same type as the dimensional element, nominally located relative to the coordinate system in which the dimensional element fulfills its functional purpose, and tangentially covering the real surface of the dimensional element: the first - outside the element material - forms the maximum material size, the second - from the element material - forms the minimum material size of the dimensional element.

Figure 3. Parameters of dimensional and geometric accuracy of single dimensional elements of holes and shaft (a) and their sets (b).
Thus, the linear size of the element has two boundary values that are counted in the part coordinate system and are constrained by two maximum and minimum material limits of the element according to the tolerance and fit system ISO 286-1 and ISO 286-2.

Two values of the linear size of a single real element make it possible to evaluate a number of accuracy characteristics that expand the functionality of every boundary size (figure 3a):

\( 0' - 0' \) and \( 0'' - 0'' \) are the reference systems for the indices of dimensional elements accuracy forming the limits of the material maximum \( D_{LMM} \) for hole and \( d_{LMM} \) for shaft;

\( ESD \) and \( ESDl \) are the indices of dimensional accuracy for hole and shaft:

\[
ESD = |D_{LMM} - D_{MM}|, \quad ESDl = d_{LMM} - d_{MM};
\]

\( EGD \) and \( EGd \) are the indices of geometrical accuracy for hole and shaft:

\[
EGD = |D_{MM} - D_{LM}|, \quad EGd = d_{MM} - d_{LM};
\]

\( ECD \) and \( ECDl \) are the complex indices of total, dimensional and geometrical accuracy for hole and shaft:

\[
ECD = |D_{LMM} - D_{LM}|, \quad ECDl = d_{LMM} - d_{MM};
\]

\( EWD \) and \( EWd \) are the values of accuracy margins for material wear for hole and shaft dimensional elements:

\[
EWD = D_{LMM} - D_{LM}, \quad EWd = d_{LMM} - d_{LM},
\]

where \( D_{MM} \) and \( d_{MM} \) are the maximum material dimensions for hole and shaft; \( D_{LM} \) and \( d_{LM} \) are the minimum material dimensions for hole and shaft; \( D_{LMM} \) and \( d_{LMM} \) are the minimum material sizes for hole and shaft.

For a single dimensional element, all the accuracy indices are systematic quantities with known uncertainties in the measurements. For a set of dimensional elements of a batch of parts, the accuracy characteristics become probabilistic quantities, consisting of systematic and random components (figure 3b).

Since the element accuracy reference point is the maximum material limit, the basic deviation in the linear sizes system of tolerances and fits must be the deviation of the element maximum material limit: the lower deviation \( EI \) for all tolerance intervals of the holes \( A \ldots ZC \) and the upper deviation \( es \) for tolerance intervals \( h \) to \( H \). This requirement in existing ISO 286 standards is maintained mating in the hole system and shaft system only for tolerance intervals from \( A \) to \( H \) holes and from \( a \) to \( h \) shafts. It should also be extended to the remaining tolerance intervals from \( J \) to \( ZC \) for holes and from \( j \) to \( zc \) for shafts. The main deviation, which is now the closest to the zero line, has no physical justification.

The symmetric tolerance interval \( Js \) refers to the linear coordinating dimensions and should be taken out in a separate matrix. Then the system of tolerances on linear sizes will indeed become a system without numerous corrections in it. The choice of fits for mating will be made only on the maximum material limits, i.e. on the basic deviations of all tolerances intervals for holes and shafts.

5. Experimental results

An experimental verification of the linear sizes accuracy of cylindrical elements was carried out at the production conditions on a circular grinding technological operation in a batch processing sequence \( N = 50 \) shafts (figure 4).
Figure 4. Dot diagrams and histograms of dimensional accuracy distribution of maximum material diameters, minimum material diameters and geometric accuracy of a cylindrical element for a batch of 50 shafts on a circular grinding operation.

The results of the experiments have fully confirmed the following theoretical conclusions of the research:

• the dimensional element of every part has two boundary linear sizes - the maximum material size $d_{MM}$ (the maximum diameter) and the minimum material size $d_{LM}$ (the minimum diameter);
• both the element boundary sizes have their own distribution laws within the tolerance interval; their grouping centers are displaced from each other by the average deviation of the cylindrical surface shape in terms of diameter;
• the geometrical accuracy of the $EGd$ element is determined by the difference in the maximum and minimum material size and its dispersion area occupies 40% of the diameter tolerance interval;
• the guaranteed accuracy margin for the wear of the element material is about 20% of the diameter tolerance interval.

6. Discussion
As a result of the work, two suggestions to improve the International System of Tolerances and Fits ISO 286 [2, 3] were updated.

The first suggestion relates to the introduction of the concept of a linear coordinating size and its accuracy normalization with the help of the tolerance interval $Js$ symmetric deviation for hole and $js$ for shaft in order to indicate the location of the parts geometrical elements. To do this, it is recommended to exclude this deviations $Js$ and $js$ as a separate matrix (figure 5) for linear coordinating element sizes from the tolerances and fits general system of ISO 286.
Figure 5. Symmetric tolerance intervals for linear coordinating sizes of external and internal geometrical elements of parts:
a) for the 6 accuracy tolerance grade of the coordination sizes range CS = 0 ... 500 mm;
b) for 6 ... 12 accuracy tolerance grades of the interval of coordinating sizes CS = 50 ... 80 mm.

Symmetrical deviations $J_s$ holes and $j_s$ for shafts have the same numerical values, in their tolerances grades and equal to half the standard international tolerance $\pm IT / 2$. Therefore, for the tolerances of the linear coordinating sizes of holes and shafts, a new general designation, for example $\pm CT / 2$ (Coordinate Tolerance), could be assigned.

Figure 6. Models of two systems of basic deviations of elements linear sizes tolerance intervals of 1-hole material; 2 - shaft material:
a) system of nearest deviations from the zero line;
b) system of functional deviations of the maximum material limit;

The second proposal relates to a change in the content of the "basic deviation" concept as the deviation of the maximum material limit in place of the deviation nearest to the zero line of the nominal size (figure 6).

The proposed model (b) does not contain symmetric deviations of the tolerance intervals $J_s$ and $j_s$.

7. Conclusion
The conclusion include the following findings:
1. In geometry, linear coordinates determine the position of a point in three-dimensional space. Likewise, linear coordinating dimensions are necessary for specifying the location of geometric elements in the space of the part material.
2. Linear coordinating dimensions are the dimensional basis of the geometric elements linear sizes, and their accuracy can be normalized by International system of linear sizes tolerances and fits ISO 286.

3. Linear coordinating dimensions have a normal symmetrical distribution with respect to the nominal size value. Therefore, for normalizing the accuracy of coordinating sizes, only one symmetric tolerance interval $J_s$ or $j_s$ from the ISO 286 tolerance system is required. The nominal values of linear coordinating sizes may differ from the normal values of linear sizes.

4. The accuracy tolerance grade of the linear coordinating size should be one grade more precise than the grade of the positioned element; at the same time, the tolerance should correspond to the nominal length of the coordinating size. The nominal length of the linear coordinating size can be equal to zero, so the first size interval in the tolerance system should start from zero: $\theta \ldots 3\text{mm}$.

5. In order to improve the international system of tolerances and fits of linear sizes ISO 286, it is recommended to consider the symmetric tolerance interval $J_s$ and $j_s$ in a separate matrix as a functional tolerance for linear coordinating sizes.

6. For the same purpose, it is recommended the deviation of the material maximum limit $E_I$ for holes and $e_s$ for shafts to consider the basic functional deviation for international system of linear sizes tolerances and fits ISO286, instead of the deviation that is nearest to the zero line as unreasonable.

7. The introduction of coordinating sizes will require a chain of changes in GPS standards, including a masterplan, coordinate systems for reading the dimensional and geometric specifications of parts, the informativeness of datums and datums systems, and the classification of dimensions according to a functional feature.

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