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Dimensioning and tolerancing by the coloured contacts method

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The dimensions chain method, very used in mechanical design, makes it possible to determine the dimensions of the parts on which depend the clearances necessary in the mechanism they constitute. Unfortunately, no method can correctly determine the places in the mechanism in which these clearances must be introduced and configured. This remains dependent on the intuition of the designer who must, in addition, make a particular drawing of the mechanism that exaggerates these clearances. Errors are frequent. The presented coloured contacts method makes it possible to identify, in a systematic and exhaustive way, the functional clearances for the mechanism and then the dimensions of the parts on which they depend. This method represents a major advance for the functional dimensioning and tolerancing of the mechanisms. It is accompanied here by a method of calculating tolerance intervals of distances and dimensions on a relatively complex example.

Keywords: geometry, GD&T, dimensions chain, tolerancing

1 Introduction

For a mechanism to work, there must be clearances between the moving parts and clampings between the parts to remain bring together. These clearances and these clampings depend on the dimensions of the parts which are unfortunately subject to variation from a manufactured copy to the other and which therefore lead to clearances and clampings different between the copies of the mechanism. Therefore, the mechanism designer must calculate the tolerance intervals of these dimensions so that, despite their variations in these intervals, the mechanisms are all functional. This step of the mechanical design is called the "geometric dimensioning and tolerancing, (GD&T)". This step is very important because it can show, for example and if it is correctly conducted, that the mechanism is not feasible with the precision of the available manufacturing machines and that its design must be reviewed.

Unfortunately this stage is still poorly controlled by the design offices and eventually leads to very frequent industrial problems: parts conform to the tolerance indications and which however do not assemble, or the opposite: non-conforming parts having therefore to be discarded and which yet come together and work perfectly; resumption of the definition drawings to modify the tolerances ; and even lawsuits between companies for delivered batches of non-functional parts.

This is explained by the fact that the main method of dimensioning and tolerancing, and almost the only one used in industry, i.e. the dimensions chain method, is poorly formalized and is also incomplete as we will show it later.

In mechanical design, the mechanisms are initially modelled and drawn with exact geometries, i.e. without defects and generally without clearance (gap) or clamping (interference). We will say that this is the nominal geometry of the mechanism. For example, Figure 1 gives the nominal geometry of an assembly of a pulley at the end of a shaft without gap or interference between the parts.

This nominal geometry cannot be used by manufacturing because it would lead to a too large proportion of impossible assemblies because of the inevitable small deviations of the target geometry that generates any manufacturing on each part. The designer must therefore define, at least, a maximum geometry that must not exceed the manufactured parts to ensure assembly, and possibly a minimum geometry if he also wants to guarantee maximum clearance between parts. We will give a more precise definition of the maximum and minimum geometries in the last part of this paper. Let's just say here that they are relative to certain dimensions on parts that are critical for their assembly.

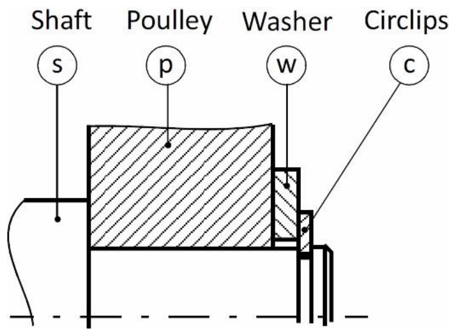

Figure 1 Drawing in nominal geometry i.e. without gap nor interference between parts, of the assembly of a pulley at the end of a shaft

To date, the only method that can determine the dimensions of the shaft, critical for assembly, is the dimensions chain. It is an essentially manual method, widely used in design, and whose origins are old and probably multiple.

It is based on the creation of a drawing showing, on the one hand, a particular configuration allowed by the clearances between parts in the future mechanism and, on the other hand, one or more of these clearances represented by exaggerated gaps.

For example, Graczyk [7] chose to push all parts of the pulley assembly to the left and to exaggerate a distance A between the circlips and the washer to allow, according to him, to assemble the future manufactured parts (Figure 2).

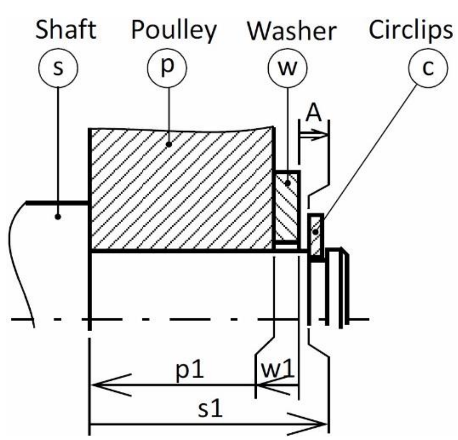

Figure 2 Drawing with an exaggerated gap between two parts

This technique of pushing the parts on one side or the other is described in one of the very first books on dimensioning and tolerancing due to Wade in 1967 [19]. In fact, it can lead to errors as is the case in this example.

Indeed, once this choice is made, the dimensions chain method consists in looking for the dimensions of the parts on which the exaggerated distance between the two parts depends. For this one starts from one of the faces separated by the distance and we try to join the other through the parts and their contacts. Each part crossed by this mental path provides a dimension on which the distance depends. The vector representation of the distance and the dimensions makes it possible to establish the algebraic relation between them (Equation 1 and Figure 2).

$$A = -w1 - p1 + s1 \qquad (1)$$

Nevertheless, for this example, even if the values of the dimensions w1, p1 or s1 led to a negative distance A, i.e. to a theoretical interference of the parts, the assembly would be possible anyway by pushing the circlips to the right (Figure 2).

The distance A is not functional and the dimensions that are deduced neither. The consequence is that some parts may be discarded because of their dimensions outside their tolerance intervals, even if they could fit together.

The technique of pushing the parts to the left or to the right is therefore inadequate and can lead to errors. Anselmetti has suggested in 2012 [1] another technique consisting of moving away or closer two parts in the aim to introduce a distance between them. This is indeed the correct technique and we will develop it because Anselmetti does not explain how parts are chosen, or whether the part must move them away or closer.

The other French works [2, 3, 4, 6, 8, 12, 15, 16, 18] present the dimensions chain method, either on fixed distances, i.e. between parts immobile between them, which poses no particular problem, either on distances configured in an unexplained way which does not allow to know what should be done on another mechanism.

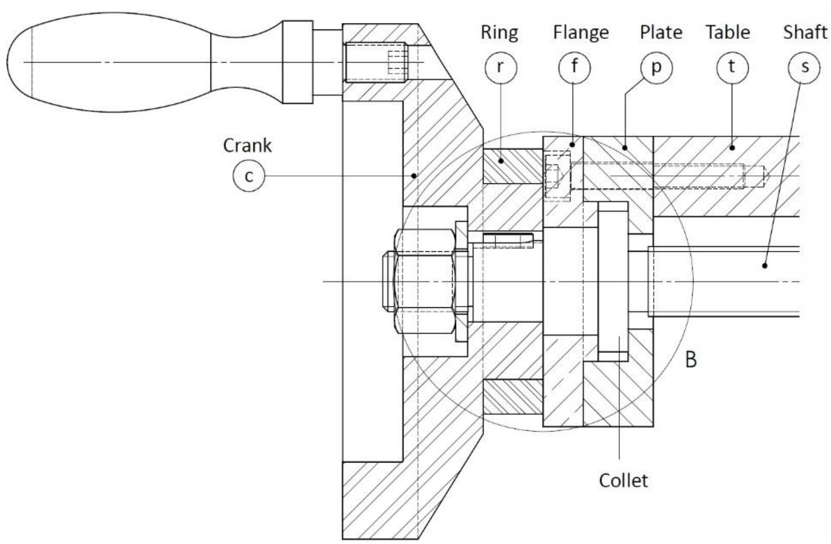

Figure 3 Drawing in nominal geometry of the operating mechanism of the table of a grinding machine

The English books [5, 9, 13, 23] which followed that of Wade [19] ignore this subject preferring to present the symbolic coding of standardized geometric tolerances. Only that of Henzold, in 2006 [9], presents a dimensions chain on a simple example that eludes the problem of the choice of the functional distance and the configuration of the parts.

On the side of scientific publications, few are those relating to the dimensions chain [17, 14, 20, 21, 22] and all present drawings with distances already identified without explaining how they were.

The coloured contact method, which we present in the following section, makes it possible to identify the functional distances even in complex mechanisms such as the one that will serve as an example in the following of this paper.

This is an operating mechanism of the table of a grinding machine represented by its initial design in nominal geometry i.e. without gap (clearance) or interference (clamping) between the parts (Figure 3). It consists in a crank (c) connected to screwed shaft (s) which, by screwing into a nut linked to the base and not shown in the Figure, makes it possible to translate all the parts represented and, particularly, the table (t) with its plate (p) and its flange (f). The graduated ring (r) can be secured to the crank by a pressure screw not shown.

The operating requirements are as follows:

- the rigid group formed by the crank and the shaft (and some clamping parts) must be able to freely rotate relative to the rigid group consisting of the table, the plate and the flange interconnected by clamping screws;
- the shaft is stopped axially by contact of its collet with either the plate (p) to the right, preventing the crank from coming into contact with the flange (f), or the flange to the left;
- the ring must not be able to be clamped between the flange and the crank when it is pushed towards the table.

2 Coloured contacts method

2.1 Starting point and objectives of the method

To determine the functional dimensions of the parts of a mechanism, i.e. those which are critical for its assembly and its running, the designer has only the nominal drawing of it, i.e. a drawing without gap nor interference between the parts in apparent contacts (Figure 3).

The coloured contacts method will allow him to locate the functional clearances in the mechanism; configure them; and to deduce the functional dimensions of the parts.

The method takes place in three main steps:

- Characterization of all apparent contacts between parts on the nominal drawing according to three types: forbidden, allowed or imposed. This step makes it possible to explain, directly on the drawing, the intention of the designer concerning the actual contacts desired between the parts;
- For each forbidden or allowed contact, not already crossed by a path of contacts, plot of its path of contacts;
- For each path, plot of the corresponding dimensions chain and writing the relationship between the distance and the dimensions of the pieces. This last step corresponds to the dimensions chain method. The first two steps could therefore be seen as missing links to the current dimensions chain method.

2.2 First step: characterization of apparent contacts

This step consists in characterizing all apparent contacts between parts according to three types:

- A contact is imposed if the two parts are clamped against each other by clamping elements or because of the forces in the functional state of the mechanism considered. There is no distance between the two parts. For the operating mechanism, the imposed contacts are those between: the flange (f) and the plate (p); the plate (p) and the table (t); the crank (c) and the shaft (s); washer and crank (c); and finally, the nut and the washer. They are coloured in green on the nominal design of the mechanism (Figure 4).
- A contact is allowed if the parts can touch each other but must also be able to be separated to make appear a distance between them. For the operating mechanism, the allowed contacts are: those between the collet of the shaft and the plate or the flange; and between the ring and the crank or the flange. They are coloured in orange.
- Finally, a contact is forbidden if, even by bringing the two parts closer together thanks to the clearances, contact between the two parts must not be possible. In other words, a distance must remain between the two parts when they are brought closer to one another. For the operating mechanism, this is what is desired for the apparent contact between the crank and the flange which must not be in contact since the axial guidance of the shaft must be provided by its collet. It is coloured in red on the Figure 4.

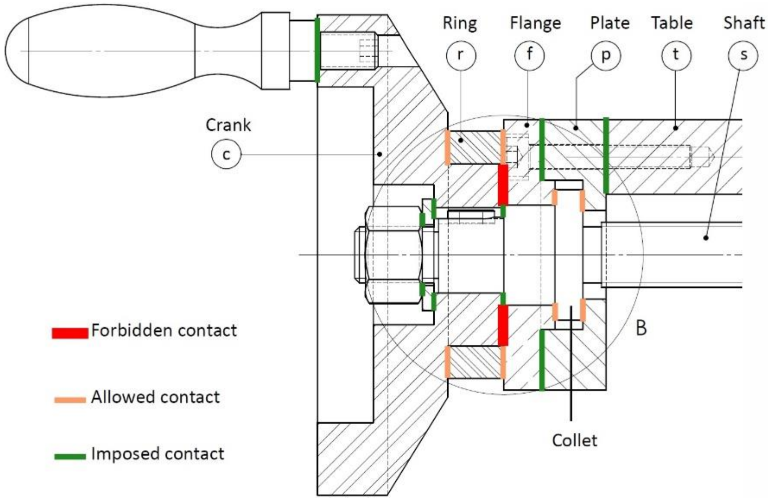

Figure 4 Characterization of apparent contacts between parts

The three colours used here are those of the tricolour light to make it easier to memorize their meanings: in green, it is imposed to pass; to orange, it's allowed; and red, it's forbidden. At this stage all apparent contacts have been reviewed, which guarantees the completeness of analysis of the mechanism by the method.

2.3 Second step: configuration of each allowed or forbidden contact, not crossed by a path of contacts, and its path of contacts

The red and orange lines on the drawing of the nominal mechanism (Figure 4) should be considered as gaps between parts for this second stage. We give a representation on Figure 5 to insist on this point, but this figure is not at all obligatory: the nominal drawing with the coloured apparent contacts is sufficient.

It is now a question of configuring each forbidden or allowed contact by decreasing or, respectively, by increasing, the distance between the two parts. Doing so, the both parts will rely on the other parts of the mechanism by their imposed or allowed contacts with them.

For example, by seeking to bring the crank (c) of the flange (f) to reduce the distance between them at the level of their forbidden contact, the crank will rest on the shaft that will rest on the plate (p) through at his collet. The plate is, itself, in imposed contact with the flange. This path of contacts is drawn on the nominal drawing (Figure 6.a). In addition, the configuration of the distance is represented by arrows at the ends of the path that shows here that the two parts are close together.

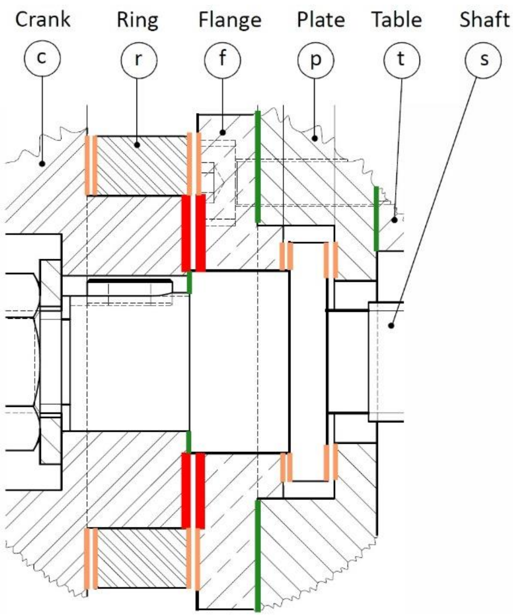

Figure 5 Illustration of gaps between parts at the level of allowed and forbidden contacts

The path of contacts for this distance cannot be that passing through the ring (r) and its permitted contacts with neighbouring parts, because it would mean that the ring can be clamped between these parts, which is not desired, as was announced in the functional requirements of the mechanism in the introduction. The proposed characterization of contacts is not able to explain this functional requirement. This is a limitation of the method. It is necessary to consider in addition, the verbal expression of this requirement which could nevertheless be postponed on the drawing and thus complete the expression by the colours of all the other functional requirements of assembly.

The allowed contact between the collet and the flange is now crossed by a path of contacts (Figure 6a). It is therefore unnecessary to configure it. However, three other allowed contacts are still not crossed by a path of contacts: they must be configured.

The configuration order of the allowed or forbidden contacts has no effect on the results. We can, for example, continue the configuration of the contacts by the allowed contact between the collet of the shaft and the flange (Figure 6b). An allowed contact means that it must be possible to move the two parts apart to reveal a distance between them. By removing the collet of the flange, it will rest on the plate (p) (Figure 6b). The path of contacts that also passes through the imposed contact between the plate and the flange is drawn with arrows showing the configuration of the distance between the shaft and the flange.

Pedagogically, it can be pointed out that a path of contacts can only pass through the imposed or allowed contacts. It cannot go through a forbidden contact.

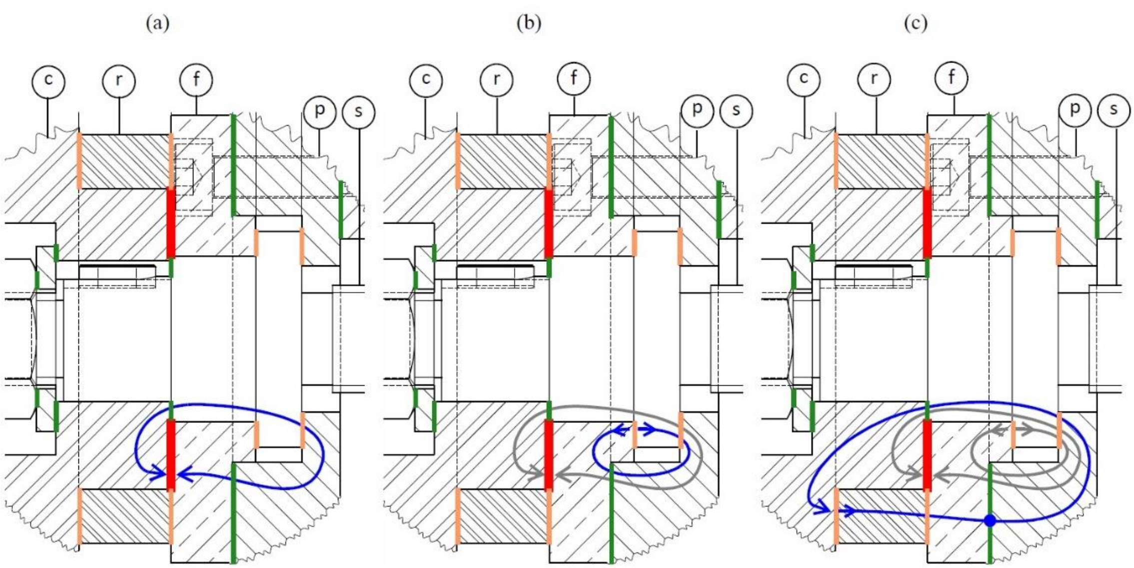

Figure 6 Plot of paths of contacts established by configured distances of forbidden and allowed contacts

There are still two allowed contacts: those of the ring with the crank and the flange. One of them could be configured by increasing the distance between the two parts but that would not guarantee the impossibility of tightening the ring between the crank and the flange. To do this, it is necessary to verify that by pushing the crank towards the flange, a distance remains in one of two contacts, for example that of the ring with the crank. The ring itself is pushed towards the flange to lean on it. The flange must be considered as fixed so that the crank and the ring can be pushed on it. This is represented by a point on the path of contacts (Figure 6c). The arrows at the ends of this path show the configuration of the distance between the crank and the ring.

The distance to be considered is not therefore the increased distance, as is normally the case for an allowed contact, but a distance obtained by pulling the face of the crank towards the space between it and the ring whose face must be pushed. We call this distance, a pull-thrust distance. This case is not explained by the colours of the contacts and it is a limit of the proposed method as already indicated. Nevertheless, on the one hand this case is quite rare and on the other hand it is more easily identified with the proposed method. It also shows that it is necessary to generalize the description of the distances in the mechanisms: for a forbidden contact, the distance to be studied is a pulled-pulled distance whereas for an allowed contact, it is, in most cases, pushed-pushed but it can sometimes be pulled-pushed or pushed-pulled (Figure 7).

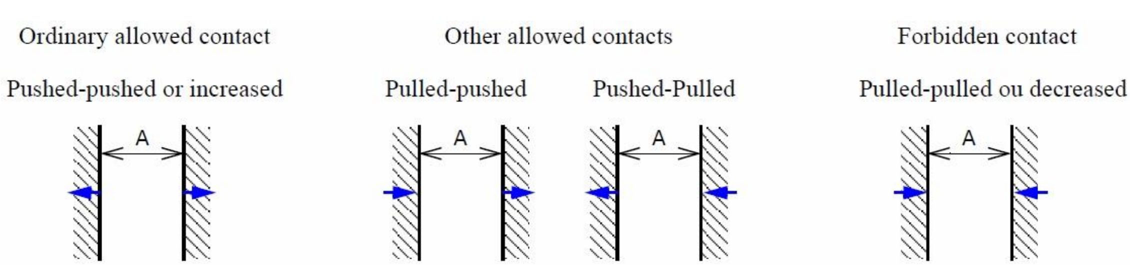

Figure 7 The four types of distance between parts

For the operating mechanism, all allowed and forbidden contacts are now in, at least, one path of contacts: the contact configuration process is therefore complete and there are only three functional distances for the assembly of this mechanism whereas at first glance, one would have thought that there would have been more.

2.4 Third step: drawing the dimensions chain of each functional distant

This step is much simpler than the previous one and corresponds to the current dimensions chain method. It consists in following each path of contacts, in one direction or the other, to determine the dimensions of the parts on which the distance that this path configures (Figure 8).

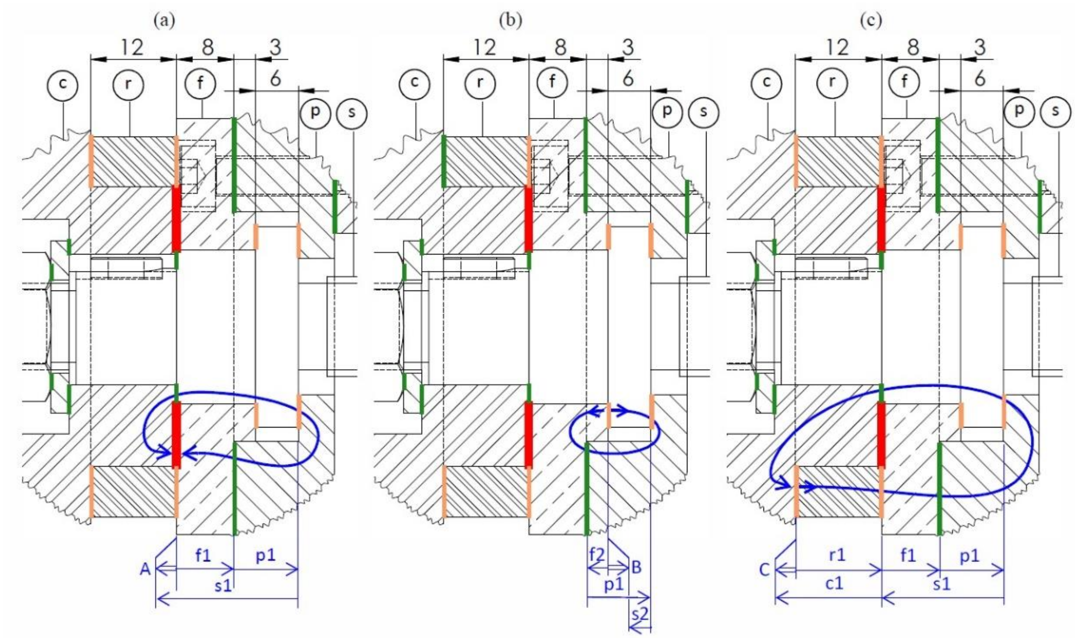

Figure 8 Plot of dimensions chains of each functional distance

The distance and the dimensions are represented as vectors so that the distance-vector, traditionally represented by a double straight lines arrow, is equal to the sum of the dimension-vectors, traditionally represented by a single straight-line arrow. Their projection then makes it possible to obtain the relations between them:

$$A = -f1 - p1 + s1 \quad (2)$$

$$B = -f2 + p1 - s2 \quad (3)$$

$$C = -r1 - f1 - p1 + s1 + c1 \quad (4)$$

These equations have the following general form:

$$Y = \sum_i \alpha_{xi} xi \quad (5)$$

where α_{xi} is the coefficient of influence of the dimension xi on Y (-1 or +1 for equations 2 to 4)

These relationships are necessary for calculating tolerance intervals for distances and dimensions in the next section. This next step is not a part of the coloured contact method but is its logical continuation and allows, in addition, to verify its efficiency.

3 Calculation of tolerance intervals of distances and dimensions

Whether the distance is of the type pulled-pulled, pushed-pushed or pulled-pushed, a minimum clearance must be guaranteed in a forbidden contact or in an allowed contact. It is therefore enough to choose a minimum positive value for each functional distance identified by the coloured contact method. These values can be chosen independently of each other.

For the operating mechanism, we have chosen relatively large minimum values so that they are visible on the median geometry presented in Figure 11, but they could have been smaller or even zero (equations 6 to 8. The unit of these lengths may be the millimetre or the inch of the imperial system):

$$Min_A = 0.300 \quad (6)$$

$$Min_B = 0.100 \quad (7)$$

$$Min_C = 0.300 \quad (8)$$

In mechanical design, the maximum values of the distances are more difficult to choose because they give the maximum clearances between the parts that one wishes always the weakest possible. Furthermore, by setting these maximum values, in addition to the minimum values, their tolerance intervals are fixed, and the calculations become more complicated and can especially lead to intolerable tolerances in manufacture. Yet it is often the way that the dimensions chain method is taught.

Table 1 Crossed table of tolerance intervals (known or chosen values in black and calculated in blue)

					$Nomi_{xi}$:	17,0	6,0	8,0	3,0	12,0	12,0	9,0
					$(t_{xi}/2)$:	0,014	0,009	0,018	0,013	0,014	0,035	0,013
					$Median_{xi}$:	17,345	5,865	8,000	3,000	11,951	12,000	9,000
Y	$(t_Y/2)$	Min_Y	$Median_Y$	Max_Y	xi :	s1	s2	f1	f2	r1	c1	p1
A	0,045	0,300	0,345	0,390	α_{xi} :	1		-1				-1
B	0,035	0,100	0,135	0,170	α_{xi} :		-1		-1			1
C	0,094	0,300	0,394	0,488	α_{xi} :	1		-1		-1	1	-1

It seems to us simpler and more pragmatic to first fix the tolerances of the functional dimensions considering the manufacturing processes of the parts or, if they are not known, by choosing standard ISO quality levels [10] and then deduce the maximum values of the distances.

To carry out these calculations, we use here a crossed table relatively well known in companies but oddly absent from the publications on dimensioning and tolerancing (Table 1).

The dimension chains are presented, in rows, by the influence coefficients of the several functional dimensions. For instance, the dimensions chain of the distance A, depends, respectively on the coefficients 1, -1 and -1, on the dimensions s1, f1 and p1.

The minimum values of the distances have been reported in the Min_y column. The nominal values of the dimensions, resulting from the nominal geometry of the mechanism, have been reported in the $Nomi_{xi}$ row and the half-tolerances in the (t_{xi} / 2) row. These half-tolerances were chosen based on the following ISO standard qualities [10]:

- IT8 for the shaft (s) and the ring (r), which give ±0.014 and ±0.009 for the dimensions s1 et s2, of the shaft and ±0,014 for the dimension r1 of the ring (line (t_{xi}/2) of the columns s1, s2 et r1) ;
- IT9 for the flange (f) and the plate (p), which give ±0.018 et ±0.013 for the dimensions f1 et f2 of the flange (f) and ±0.013 for the dimension p1 of the plate (p) (line e (t_{xi}/2) of the columns f1, f2 et p1) ;
- IT10 for the crank which give ±0.035 for the dimension c1 (line (t_{xi}/2) of the column c1).

All these values are written in black in the table while the values calculated from them are in blue. Tolerances of the dimensions make it possible to calculate those of the distances in the column (t_Y /2), either at the most probable statistically or at worst-case as it is done here thanks to the Equation 9, itself deduced from the general Equation 5.

$$t_Y = \sum_i |\alpha_{xi}| t_{xi} \quad (9)$$

where t_{xi} is the tolerance of the dimension xi, i.e. $(Max_{xi} - Min_{xi})$ and t_Y that of Y

Knowing Min_Y and t_Y /2, the median and maximum distance values can be calculated in the $Median_Y$ and Max_Y columns using the following equations

$$Median_Y = Min_Y + t_Y/2 \quad (10)$$

$$Max_Y = Median_Y + t_Y/2 \quad (11)$$

It remains to fix the median values of the functional dimensions so that they lead to the median values of the distances according to the following Equation 12 itself also deduced from the general Equation 5,

$$Median_Y = \sum_i \alpha_{xi} Median_{xi} \quad (12)$$

The solution domain defined by the three equations on the seven median values is quite small and it is not easy to find a solution manually. Mathematical methods exist. A manual technique consists in, first, choosing the median values of the common dimensions of several distances while leaving at least one unknown in each equation. f1, f2 and p1 are fixed to their nominal values (values in black in the $Median_{xi}$ line). c1 is also fixed to its nominal value. From then on, the median values c of the other three dimensions can be calculated; first s1, then s2 and finally r1 (values in blue in the $Median_{xi}$ line).

4 Geometrical specification of the parts

The dimensions of the parts in nominal geometry are often outside the tolerance intervals previously calculated. For example, the dimension s1 has a value of 17 on the nominal geometry while its tolerance interval is 17.345±0.014 and therefore does not contain the nominal value.

In addition, the dimensions used to create the nominal parts do not necessarily correspond to the functional dimensions determined previously from the functional distances and, although it is possible to create part drawings with dimensions different from those of their 3D CAD models, we think it is better to modify the CAD models to use the functional dimensions and their median values. This is also mandatory the CAM process. Thus, their drawings can be made by projection of their CAD models and their dimensions. For the shaft, the two functional dimensions were created in its CAD model in median geometry and were displayed on its drawing enclosed in a frame: 17.345 and 5.865 (Figure 9).

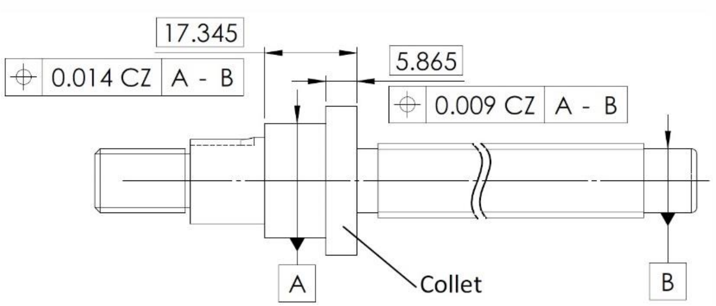

Figure 9 Drawing of (partial) definition of the shaft with these toleranced functional dimensions

These two dimensions cannot be directly toleranced by a dimensional tolerance interval because, for the dimension of 17.345, this would have no standardized meaning, and for the dimension of 5.865, this would not completely constrain the right flat face of the collet.

On the contrary, the standardized geometrical tolerancing makes it possible to completely constrain all the functional faces. Several solutions are nevertheless possible. The most direct is to specify the tolerance interval of each functional dimension as a gauge of two tolerance zones of width equal to half tolerance and distant from the median value of the dimension. For the dimension 17.345, this gives the virtual gauge given in Figure 10. Both manufactured faces must be lie inside those two zones.

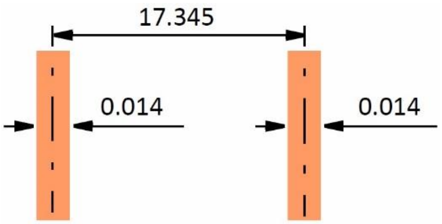

Figure 10 Tolerance interval of s1, specified as a gauge of two tolerance zones

By taking inspiration from examples of indication of ISO standards, we can encode this gauge in the form of a location tolerance of a "collection of zones". This is indicated by the letters CZ in the tolerance frame (Figure 9) in accordance with ISO1101 of 2017 [11].

With a different tolerance value, the tolerance interval on dimension 5.865 is coded in the same way In addition, these toleranced faces must be as perpendicular as possible to the two cylindrical surfaces which first position the shaft in the mechanism. These two cylindrical surfaces have therefore been taken as a common reference for the two location tolerances. This is specified in the frames by the indication A-B (Figure 9). Similar tolerancing must be done for the other parts of the mechanism.

On the other hand, the CAD assembly of the parts in median geometry reveals gaps between the parts that can be measured and displayed on the mechanism drawing. For the operating mechanism, the three functional distances are correctly configured when the right face of the collet is resting on the plate as we saw in section 2.3. It is thus that the CAD assembly of the median parts has been realized (Figure 11) and the measured distances on this CAD assembly correspond to the calculated median values in Table 1, which confirms the good determination of the functional dimensions allowed by the coloured contact method, the correct calculation of the tolerance intervals and finally the good creation of the median geometries of the parts.

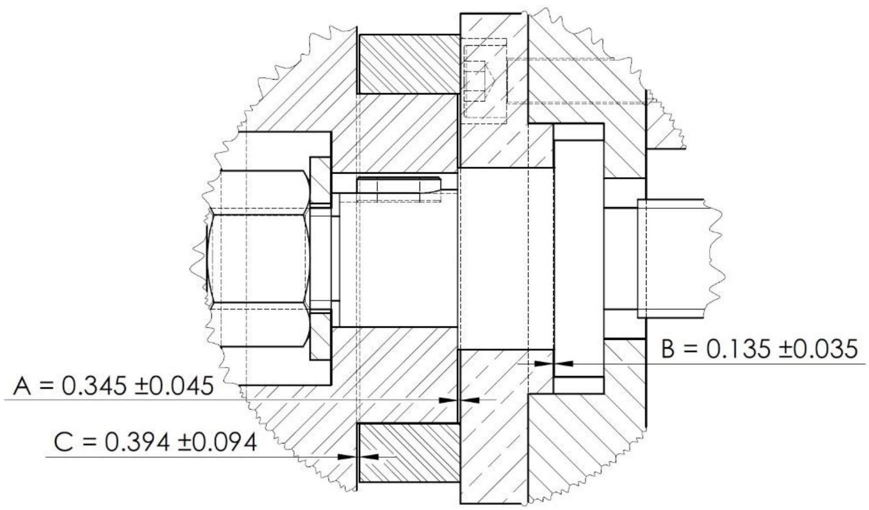

Figure 11 Median geometry of the mechanism showing functional distances in median value

The 3D CAD modelling of the mechanisms enables also the generation of the maximum geometries of the mechanism, i.e. the geometries giving the minimum value at one or more functional distances. This suffices to give the minimum value to each dimension having a positive influence on the distance, and the maximum value if its influence is negative. For instance, the minimum value of the distance A is obtained by the minimum value of the dimension s1 and the maximum values of the dimensions f1 and p1 (Table 1).

However, one dimension can have a positive influence on one distance and a negative on another. This is the case of the dimension p1, which has a negative influence on B and positive on the two others (Table 1). It is possible for this example to generate a first maximum geometry for A and C and a second for B. The same goes for the minimum geometries. These extreme geometries make it possible to observe the efficiency of the coloured contact method.

5 Nominal, median, minimum and maximum geometry

With 3D CAD it is easy to generate different geometries by changing dimension values. Among all these possible geometries, we have already defined the nominal and median geometries of a mechanism:

- the nominal geometry is that having neither gap (clearance) nor interference (clamping) between the parts of the CAD mechanism. This is usually the first created by the designer since it precedes the determination of distances and functional dimensions;
- the median geometry is that obtained by giving to the functional dimensions of the parts, the median value of their tolerance intervals and by correctly configuring as many functional distances as possible in the mechanism. Indeed, as we have shown, the functional distances are often configured distances, that is to say, to consider when the faces that they connect are either pushed or pulled, which configures the position of the parts of the mechanism (section 2.3). However, it is quite rare for all distances to be correctly configured by a single configuration of parts, unlike the case of the mechanism used as an example. There are

therefore often several possible configurations of the mechanism in median geometry that lead to the median values on certain distances and not the others.

It is the same for the maximum and minimum geometries we now define

We call, maximum geometry, the geometry giving the most material to the parts (in most cases) and leading to the minimum values of the correctly configured functional distances, i.e. the minimum clearances and the maximum clampings.

Conversely, the minimum geometry is that giving the least material to the parts (in most cases) and which leads to the maximum values of the correctly configured functional distances, i.e. the maximum clearances and the minimum clampings.

The creation of these extreme geometries can ensure clearances and clampings in the worst cases. It must be kept in mind that these worst cases are nevertheless very few statistically probable.

As an example, we give in Figure 12 the maximum geometry for A and C. It is not for B, even if this distance is correctly configured, because the dimension p1 has opposite influences on these distances (Table 1). The measurement of these distances on this geometry again confirms the correct calculation of tolerance intervals on good dimensions since A and C are indeed at the initially chosen minimum values. B takes a higher value in its tolerance interval [0.100; 0.170].

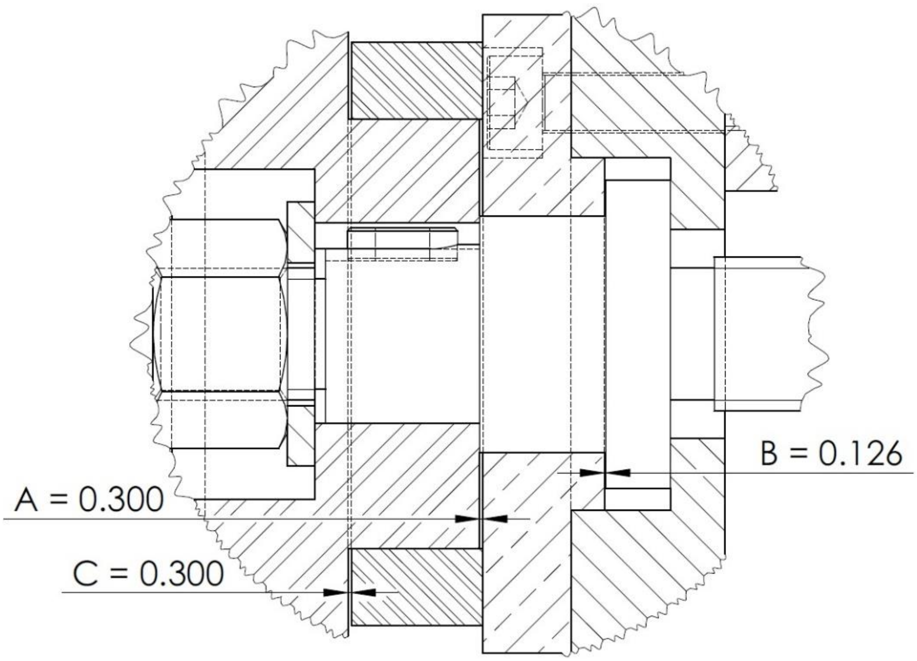

Figure 12 Maximum geometry of the mechanism for distance A and C (but not for B which is not at its minimum value)

These definitions are original as is the coloured contacts method from which they derive. The ISO standards on the geometrical specification have not yet defined these geometries. In fact, some use the word "nominal geometry" but without defining it. In companies, the median geometry is well known. It is usually called the medium geometry.

6 Conclusion

The coloured contacts method makes it possible to identify exhaustively the distances between parts, critical for the assembly and the functioning of the mechanisms. To our knowledge, this is the first time such a method is proposed.

These distances configure the contacts between parts as they are either pulled-pulled, pushed-pushed, pulled-pushed or pushed-pulled distances. The plots of the paths of contacts that they establish make it possible to identify the dimensions of the parts on which they depend. These two concepts greatly improve the today dimensions chain method.

The coloured contacts method is therefore a major advance for the functional dimensioning of the mechanisms. Its computerization is possible: the designer would only have to specify the nature of the apparent contacts between parts in the nominal CAD model of the mechanism so that distances and functional dimensions could be automatically determined. This remains to be developed.

We have also presented a method for calculating tolerance intervals of distances and functional dimensions, based on a cross-table well known in the industry but curiously missing in the literature on functional dimensioning. This table also makes it possible to determine the values of the dimensions giving the maximum or the minimum geometry for one or more distances.

These two methods were tested on a similar mechanism to the one used in this paper and whose parts were made by three-dimensional printing with a rapid prototyping machine. The printing of the parts in nominal geometry led to an impossible assembly while those in the median geometry led to fully assembling and functioning parts. To do this, it has been necessary to consider the random dispersion of each type of dimension produced by the prototyping machine as well as the systematic deviations that it creates on each of them.

We have also shown that even if the dimension chain is based on a geometric model whose only defects are the dimensional deviations in one direction, it is quite possible to specify the tolerance intervals in the form tolerance zones limiting all geometric deviations in accordance with standardized tolerancing.

Finally, we have defined four particular geometries of parts and mechanisms that must be distinguished in order to geometrically specify the products: the nominal, minimum, median and maximum geometries.

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