TRANSLATION

TECHNOLOGY OF AVIATION INSTRUMENT CONSTRUCTION (TEKHNOLOGIYA AVIATSIONNOGO PRIBOROSTROENIYA)

STAT

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Table of Contents

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CHAPTER II

PRECISION IN MACHINING

1. General Statements

Precision in machining is understood to mean the degree of correspondence of the manufactured part to the theoretical dimensions, form, and mechanical and physical properties.

In cases of individual production, dimensional stability and precision of form is obtained by the trial-pass method, and in cases of series and mass production by the method of automatically obtaining measurements.

In machining a part by the trial-pass method, the worker adjusts the tool "to dimension" after each pass, and then proceeds to the machining of a small section of the part. The dimension obtained is checked, and after this the entire surface is machined. In precision work, the tool is adjusted "to dimension" after two or three trial passes. The trial-pass method is not very productive; highly skilled workmen are required for the machining of parts by this method which, for this reason, is used chiefly in cases of individual production.

In work done by the automatic method, the necessary dimensions of the part are obtained by a preliminary adjusting of the machine (preliminary tooling), or by the use of suitable tools and devices. As examples of the automatic obtainment of di-~~mensions we may cite machining on automatic machines, on turret lathes, on center-less grinding machines, etc. Work done by the method of automatically obtaining di-~~

mensions can be carried out by less skilled workmen. The use of the automatic method obliges the technologist to make a more careful analysis of the causes of errors in machining, and consequently to make a more careful calculation of the precision of the technological processes.

2. Sources of Production Errors in Machining

Discrepancies between the dimensions and form of the part under machining and its theoretical dimensions and form, which are due to production-technology causes, are referred to as production errors; all discrepancies between the actual technological process and the ideal technological process are referred to as primary errors.

Let us examine the basic primary errors.

Theoretical errors, due to the use of an approximate machining diagram. These errors occur as a result of the conscious use of an approximate machining diagram instead of an exact one, or as a result of the conscious use of a tool with an approximate profile. As an example of theoretical errors we may cite the cutting of thread on a screw-cutting lathe without the necessary change-gear wheels. As we know, in such a case these gear wheels are replaced by others which permit only the approximate obtainment of the set pitch on the part being threaded. As a second example we may use the cutting of teeth by the generating method. As a result of the finite number of cutting edges, the process of profile forming is interrupted, and for this reason, instead of an involute profile on the gear wheel which is being cut, we obtain a broken straight line which bends into an involute curve. The use of an approximate machining diagram may be justified only in cases where the technological process is simplified and the set precision is obtained.

Inaccuracies in equipment. Machines in actual use have a lower degree of precision in their work as a result of wear. However the degree of inaccuracy in the execution of the machine gives no indication of its influence on the accuracy of the

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machined part. To solve this problem, a special calculation must be made for each concrete case.

For example, in the cutting of thread on a thread-cutting machine, the inaccuracy of the machine results in a skew in the axis of the tap relative to the axis of the aperture being threaded, and this, as the analytical calculations by N.N.Ushakov (MAI) have shown, leads to oval threads.

Inaccuracies in the cutting tool and attachments. In working with a measuring or a profile tool, precision in machining is directly dependent upon the precision of the cutting instrument. Precision in the execution of a nonmeasuring tool (cylindrical milling cutters, pass cutters, etc.) has an indirect effect upon precision in machining. For example, when a milling cutter is ground incorrectly, its teeth will take off a chip of unequal thickness, and this will lead to a change in dimensions and a distortion of the form of the surface.

Errors in the execution of attachments also have an effect upon precision in machining. As an example we may use the error which occurs in boring as a result of inaccuracy in the design of the jig bearings, as a result of the distance between the axes of these bearings, and as a result of other causes.

Wear of the tool. In the process of working, a tool wears out. We may estimate roughly that the wear of a tool is in proportion to the length of the path traveled by the tool blade. Wear also depends upon the material and the geometry of the tool, upon the material under machining, etc.

Deformation of the elastic system machine Part-Tool*. Under the action of the force of cutting and other forces brought to bear on the machine-part-tool system, a deformation is produced in it; as a result of this, the form and dimensions obtained in the part are different from those which might have been obtained if the system were rigid.

* Rigidity as a technological factor is examined in detail in the paper by Prof. A.P.Sokolovskiy (Bibl.1).

STAT

The rigidity j of the elastic system is the usual name for the ratio of the component of the force of cutting P_y (this component being directed according to what is normal for the surface which is being machined) to the displacement y of the tool blade relative to the part, this displacement being reckoned in the same direction:

$$j = \frac{P_y}{y} \ \text{Kg/mm}. \qquad (2.1)$$

The rigidity of an elastic system depends upon the rigidity of all its links. The rigidity of the part under machining may in many cases be determined by calculations on the basis of the formulas for the material strength. For example, to determine the rigidity of a cylinder which is under center machining, Prof. A.P.Sokolovskiy recommends using the formula for the flexure of a beam freely supported at two ends.

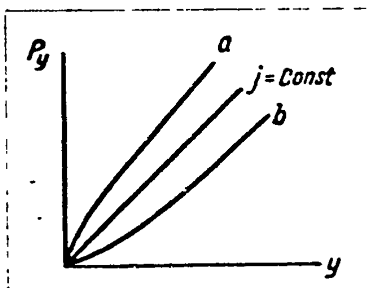

Fig.1 – Types of Load Curves

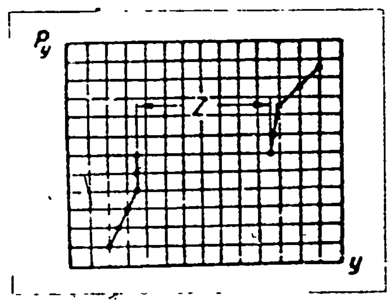

Fig.2

The rigidity of the joints of a machine is determined by experimenting. To do this, the joint of the machine is subjected to a definite force, corresponding in direction and point of application to the stress exerted under the normal operating conditions of the machine, and then the deformation of the joint in the direction normal for the surface being machined is measured. On the basis of the data obtained, the dependence P = f(y) is set up, where P is the load. The experiment shows that the rigidity characteristics may differ (Fig.1). In some cases, j = const and the characteristic is rectilinear; in other cases, the rigidity falls as the load is increased (see curve a); finally, in still other cases, the rigidity may increase with an increase in load (curve b). The total effect of the gaps is characterized by the "break of the characteristic", i. e., by the displacement z of the joint, determined at the smallest points of the diagram under a load equal to zero (Fig.2). The "rigidity of the joint" and the "break of the characteristic" are the basic values which determine the quality of the assembly of a joint.

Thermal stresses. In the process of working, the operating temperature of the machine-part-tool system changes. As a result of this it is difficult to determine by analytical means the effect of the deformation of a part, caused by the action of heat, upon precision in production. At the same time, temperature strains may have a substantial effect upon precision in machining. For this reason, in planning technological processes one must provide for conditions which will weaken the effect of temperature on precision in machining.

Internal strains. Internal strains may crop up as a result of cast shrinkage, uneven plastic deformation, heat treatment (hardening) and other causes.

The effect of internal strains may be considerably reduced by creating a rational design for the part, by perfecting methods of machining, and by introducing into the technological process special operations to remove internal strains (ageing, for example).

Other errors. In this last class belong errors which depend directly upon the worker, for example fluctuations in clamping pressure, unevenness of supply, etc., and also vibrations in cutting* errors connected with the action of the tool's cutting edge, etc.

3. Methods of Precision Analysis and Computation of the Technological Processes

STAT

For precision computation of the technological processes, two methods are used:

* Vibrations in the cutting process are reflected chiefly in the smoothness of the surface. This problem is examined in Chapter III. For a detailed analysis, see Bibl.2.

1) the calculatory-analytical and

2) the experimental-statistical.

In the calculatory-analytical method, the causes of production errors are exposed, and analytical relationships between the production errors and their causes are established.

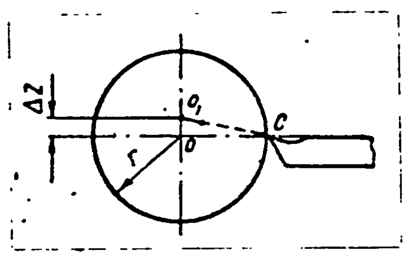

Fig.3 - Effect of Vertical Displacement of the Center upon the Precision of Diametrical Dimensions

The calculatory-analytical method is the progressive method, since it permits direct intervention in the technological processes.

However at the present time the problem of determining the total error can hardly be solved, in practice, on the basis of analytical calculations alone, since for the time being we still lack the exhaustive calculatory and experimental data which would permit us to determine the influence exerted by all primary errors upon the precision.

The calculatory-analytical method is used chiefly to analyze the technological process with a view toward establishing the effect of basic production-technology factors upon the production errors. To determine the total (resultant) error, the experimental-statistical method is used.

Let us examine some examples of the use of the experimental-statistical method*.

Example. To determine the effect upon the precision in machining caused by the displacement of the center of rotation of a part due to the action of the tangential component of the force of cut.

If the center of rotation O (Fig.3) of a part is displaced by Δz in a vertical direction and occupies position O_1, the error of the radius r will be

* The examples are borrowed from Bibl.3.

STAT

$$\Delta r = O'C - OC = \sqrt{r^2+\Delta z^2} - r = r\left(\sqrt{1+\frac{\Delta z^2}{r^2}} - 1\right) =$$

$$= r\left[\left(1+\frac{\Delta z^2}{r^2}\right)^{\frac{1}{2}} - 1\right].$$

The expression $\left(1 + \frac{\Delta z^2}{\Omega^2}\right)^{1/2}$ may be expanded into a series. If, in this expansion, we restrict ourselves to two terms we obtain

$$\left(1+\frac{\Delta z^2}{r^2}\right)^{\frac{1}{2}} = 1+\frac{\Delta z^2}{2r^2}.$$

Substituting this into the original equation we obtain

$$\Delta r = \frac{\Delta z^2}{2r} = \frac{\Delta z^2}{d}.$$

<u>Example</u>. To determine the effect of the form and dimensions of a blank upon the accuracy (precision) of machining the part on an automatic longitudinal lathe.

As a result of the action of the components P_z and P_y, the center of the rod is displaced from point O to point O' (Fig.4).

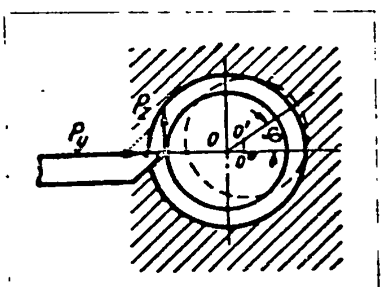

Fig.4

It is evident that OO' is equal to half the gap between the rod and the rest bearing.

Disregarding the vertical displacement, we can determine the increase in the radius of the part by the formula

$$\Delta r = OO'' = \frac{z}{2}\cos\varphi.$$

where z is the gap between the rod and the rest bearing.

If we take $P_y = 0.4P_z$, then $\tan\varphi = 2.5$ and $\varphi = 68^\circ$.

Consequently,

$$\Delta r = \frac{z}{2} \cos 68^\circ = 0{,}185z$$

or the diametral error is $\Delta d = 0.37z$.

The experimental-statistical method is based on the theses of the theory of probabilities. From the point of view of the theory of probabilities an error which occurs in machining is an accidental quantity which depends upon a large number of production-technology factors.

If we execute a number of parts under a practically unchanging technological process, all the measurements of the machined parts will differ. This phenomenon is called diffusion of measurements.

An error which has no constant numerical value may be characterized by a distribution curve (or by the corresponding Table). Determining the diffusion of errors with the help of distribution curves consists in the following: Let us assume that, in some established technological process, we have machined a number of parts, which we have measured with a universal measuring tool. As a result of the measuring, it is established that the error x is characterized by a certain combination of numerical values which represent its deviations from the nominal dimensions. Let us write the resultant deviations in a decreasing order of their absolute values. Then let us break down the series of deviations into intervals (the smaller these intervals, the more exact the construction of the curve) and count the number of parts in each interval. On the basis of the data obtained let us compile a Table according to the following form: In the first column, let us show the intervals of the deviations in millimeters (or in microns); in the second, the absolute frequency m, i. e., the num-

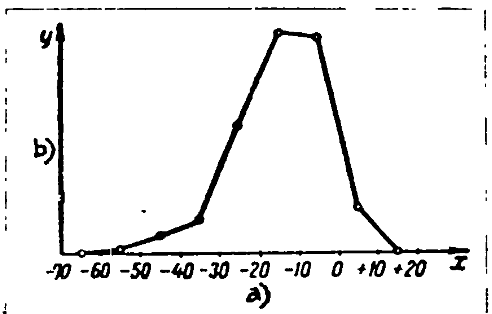

Fig.5 - Distribution Curve
a) Readings of the measuring instrument in microns; b) Frequency

ber of deviations in a given interval; and in the third, the relative frequency $\frac{m}{N}$, i. e., the relationship of the absolute frequency of a measurement to the overall number of measured parts (see Table 1).

On the basis of the data of Table 1, let us construct a distribution curve (Fig.5). To do this, let us lay off the values of the errors along the axis x, and the absolute or the relative frequency of a measurement along the axis y. The resultant broken line is transformed into a smooth curve when the number of intervals is increased limitlessly, and this is called the curve of distribution.

Table 1

a)		b)	c)
from	to	m	$\frac{m}{N}$
−60	−50	2	0,011
−50	−40	5	0,027
−40	−30	9	0,050
−30	−20	35	0,194
−20	−10	59	0,328
−10	0	57	0,318
0	+10	13	0,072
d)		180	1,000

a) Intervals in deviations in microns; b) Absolute frequency m; c) Relative frequency $\frac{m}{N}$; d) Total

The outstanding Russian mathematician A.M.Lyapunov (1857 – 1918) has demonstrated that, if an independent quantity is the sum of accidental independent quantities which are as numerous as one chooses, this quantity, as soon as certain additional conditions are satisfied, will follow the law of normal distribution as accurately as one chooses.

The factors which have an effect upon precision in machining on metal-cutting machines, and which are brought out in the works of N.A.Borodachev (Bibl.4), A.B. Yakhin (Bibl.5), and other authors, show that the basic condition of Lyapunov's theorem (multiplicity of factors in machining on metal-cutting machines) is satisfied.

In addition, a great deal of experimental research, whose results have been systematized in the above-mentioned papers by N.A.Borodachev, has established the fact that the distribution curves of errors (dimensions) in parts under machining, on machine tools, obey the law of normal distribution.

STAT

The equation for the curve of the normal distribution law has the form

$$y = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-x_{cp})^2}{2\sigma^2}}, \qquad (2.2)$$

where y is the deviation frequency, corresponding to the abscissa x;

e is the basis of natural logarithms (2.7181...);

π is a constant quantity (3.14...);

σ is the mean-square deviation

$$\sigma = \sqrt{\frac{\sum_{i=1}^{k} n_i (x_i - x_{cp})^2}{N}}, \qquad (2.3)$$

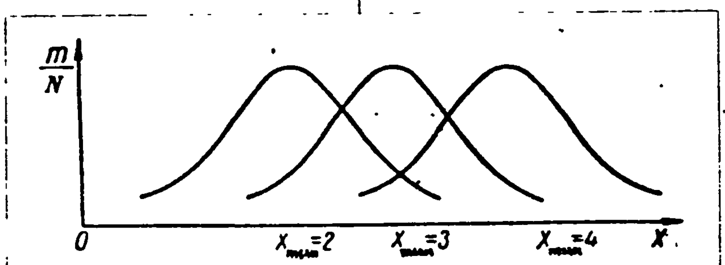

Fig.6 – The Effect of X upon the Position of the Distribution Curve

where N is the overall number of deviations;

n_i is the frequency in the i^{th} interval (i = 1, 2, 3,...k).

x_{mean} is the arithmetic mean of all quantities x, determined by the formula

$$x_{mean} = \frac{x_1 n_1 + x_2 n_2 + \ldots x_k n_k}{n_1 + n_2 + \ldots n_k} = \frac{\sum_{i=1}^{k} n_i k_i}{N}, \qquad (2.4)$$

A study of the equation of normal distribution shows that the curve is symmetric with respect to the axis passing through the point $x_i = x_{mean}$, in which the curve maximum is located. The inflection points are located at a distance of $\pm\sigma$ from the center. On both sides, the curve asymptotically approaches the axis X. The equation of the curve depends upon the two parameters x_{mean} and σ.

When x_{mean} is changed, the curve preserves its form but moves along the axis X (Fig.6). When σ is changed, the curve changes its form (Fig.7). The probability

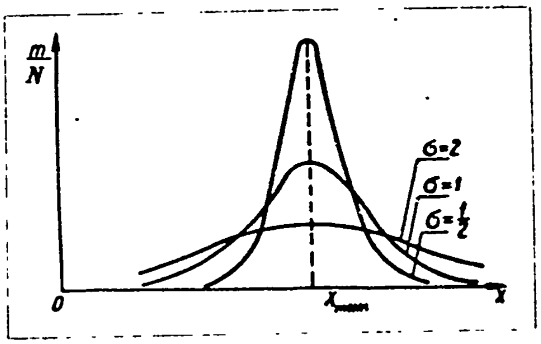

Fig.7 – Effect of σ upon the Slope of the Distribution Curve

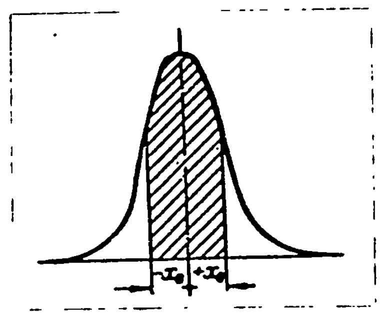

Fig.8 – Probability of Obtaining Parts with a Deviation of $\pm x_0$

that the errors will not differ from the mean value by more than $\pm x_0$ (Fig.8), is equal to

$$\frac{1}{\sigma\sqrt{2\pi}}\int_{-x_0}^{+x_0} e^{\frac{(x-x_{mean})^2}{2\sigma^2}}\,dx. \qquad (2.5)$$

The value of the adduced integral is denoted by $\Phi(z)$ and is determined by the relationship

$$z=\frac{x_0}{\sigma}.$$

In Appendix 3 we are giving the numerical values of the adduced integral, as a function of z. Using this Table, it is easy to determine $\Phi(z)$ and, consequently, to determine the maximum deviation from the mean value.

As an example, let us determine the maximum deviation x_0 with a probability of 90%, it being known that the distribution of errors obeys the law of normal distribution, and that $\sigma = 0.02$.

When $\Phi(z) = 0.90$, we find from the Tables (see Appendix 3) that

$$z = \frac{x_0}{\sigma} = 1{,}65; \quad x_0 = z\sigma$$

or $x_0 = 1.65 \times 0.02 = 0.033$ mm.

When $x_0 = \pm 3\sigma$, we have $z = 3$ and $\Phi(z) = 0.997$, i. e., the probability of obtaining parts with deviations from the mean value within the limits of $\pm 3\sigma$ is 99.73%. With a probability of practically 100%, we may assume that the maximum deviation of errors from the mean value is equal to $\pm 3\sigma$, under the normal law of distribution.

The full field (or base) of diffusion Δ_p will be

$$\Delta_p = 6\sigma. \qquad (2.6)$$

The experimental-statistical method is widely used for analyzing the technological process. When the technologist wishes to establish the degree of the effect of some factor upon the precision in machining, he makes as accurate a comparison as possible of the distribution curves constructed on the basis of measuring two groups of parts produced under conditions where the action of the factor of interest here was different in both cases, but the remaining conditions were the same. For instance, in a study of the effect of a given type of coolant upon the precision, we must produce two groups of parts on the same machine, under the same cutting conditions, with the same material, etc., changing only the type of coolant. To obtain a reliable distribution curve we recommend making approximately 100 to 200 measurings.

The number of parts, which must be measured in order to determine the mean-square deviation, depends upon the accuracy with which we want to determine this deviation.

However, in practice, sufficiently reliable results may be obtained when the number of measurings is equal to approximately 100.

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From mathematical statistics it is evident that the mean error in determining the mean-square deviation is equal to $\pm\frac{\sigma}{\sqrt{2(n-1)}}$, and in determining the mean arithmetic deviation, to $\pm\frac{\sigma}{m}$, where n is the number of measurings.

Thus, in order to obtain σ with an accuracy of ±5% we must measure the following number of parts:

$$0{,}05\sigma=\frac{\sigma}{\sqrt{2(n-1)}},$$

whence we obtain $n \approx 200$.

In order to obtain the mean-square deviation with an accuracy of ±10% we must measure 50 parts, etc.

In cases where the number of parts is less than 25, we must evaluate the degree of accuracy and reliability of x_{mean} and σ, obtained as a result of measuring these parts. The indicated problem is solved in courses of mathematical statistics in the following manner:

Let the arithmetic mean, obtained on the basis of the measuring of n parts, be equal to x_{mean}, and let the mean-square deviation be equal to σ. Further, let us define the accuracy ε with which we want to determine the arithmetic mean, and let us find the reliability α depending upon the number of measured parts n.

The reliability α is equal to the probability that the real arithmetic mean a is to be found within the limits of

$$x_{mean}-\varepsilon \text{ and } x_{mean}+\varepsilon.$$

The accuracy ε is determined in accordance with the following formula (see Bibl.6):

$$\varepsilon=\frac{t_1\sigma}{\sqrt{n}}.$$

Knowing n and ε, we can find t_1 and, using Table 2*, we can determine α.

* A more complete Table is given in Bibl.6.

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Table 2

t_1 \ $n-1$	1	2	3	4	5	6	7	8	9	10
0	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,5	0,705	0,667	0,651	0,643	0,638	0,635	0,632	0,631	0,629	0,628
1	0,500	0,423	0,391	0,374	0,363	0,356	0,351	0,347	0,343	0,341
1,5	0,374	0,272	0,231	0,208	0,194	0,184	0,177	0,172	0,168	0,165
2	0,295	0,184	0,139	0,116	0,102	0,092	0,086	0,081	0,077	0,073
2,5	0,242	0,130	0,088	0,067	0,054	0,047	0,041	0,037	0,034	0,031
2,9	0,211	0,101	0,063	0,044	0,034	0,027	0,023	0,020	0,018	0,016

Example. To determine with an accuracy of 0.5 σ the reliability of the value of x_{mean}, obtained on the basis of measuring four parts.

Let us find t_1:

$$t_1 = \frac{\varepsilon \sqrt{n}}{\sigma} = \frac{0,56\sqrt{4}}{\sigma} = 1.$$

According to Table 2 we find that the probability P of values of t_1 which are numerically not less than 1, is equal to 0.391 for n - 1 = 3. Consequently, the probability of the opposite inequality will be whatever must be added to the preceding inequality to make 1, i. e. will be equal to 1 - P:

$$\alpha = 1 - 0,391 = 0,609.$$

In evaluating the accuracy and reliability of σ, we must determine the probability of the fact that σ will be confined within the limits $\sigma - \varepsilon$ and $\sigma + \varepsilon$. This probability is equal to the difference $P_1 - P_2$, where P_1 and P_2 are the probabilities determined according to Table 3 and corresponding to the values

STAT

$$\chi_1^2 = \frac{(n-1)\,\sigma^2}{(\sigma+\varepsilon)^2} \text{ and } \chi_2^2 = \frac{(n-1)\,\sigma^2}{(\sigma-\varepsilon)^2}. \qquad (2.7)$$

Table 3

χ^2 \ $n-1$	1	2	3	4	5	6	7	8
1	0,3173	0,6065	0,8013	0,9098	0,9626	0,9856	0,9948	0,9982
2	0,1514	0,3679	0,5124	0,7358	0,8491	0,9197	0,9598	0,9810
4	0,0455	0,1353	0,2615	0,4060	0,5494	0,6767	0,7798	0,8571
6	0,0143	0,0498	0,1116	0,1991	0,3062	0,4232	0,5398	0,6472
8	0,0047	0,0183	0,0460	0,0916	0,1562	0,2381	0,3326	0,4335
10	0,0016	0,0067	0,0186	0,0404	0,0752	0,1247	0,1886	0,2650
12	0,0005	0,0025	0,0074	0,0174	0,0348	0,6620	0,1006	0,1512
14	0,0002	0,0009	0,0029	0,0073	0,0156	0,0296	0,0512	0,0818

Example. To determine with an accuracy of 0.5σ the reliability of the value of the mean-square deviation, obtained on the basis of measuring four parts:

$$\chi_1^2 = \frac{(4-1)\,\sigma^2}{(\sigma+0{,}5\sigma)^2} = 1{,}33; \qquad \chi_2^2 = \frac{(4-1)\,\sigma^2}{(\sigma-0{,}5\sigma)^2} = 12.$$

Further, according to Table 3, for n - 1 = 3 and for the values we have found for x^2, we calculate

$$P_1 = 0{,}7871 \text{ and } P_2 = 0{,}0074,$$
$$P = 0{,}7871 - 0{,}0074 = 0{,}797.$$

By using the stated method we can easily determine the accuracy and reliability of the basic statistical indexes x_{mean} and σ depending upon the number of measured parts.

Let us consider some examples of the use of the experimental-statistical method.

Example. To determine the amount of the total error occurring in the cutting

STAT

of M 1.4 × 0.3 thread on a screw-cutting machine.

As a result of measuring 180 parts, we have established the deviations from the greatest value of the mean diameter. These deviations are graphically represented in Fig.5 and Table 1.

Let us determine the value of the arithmetic mean in accordance with eq.(2.4)

$$x_{mean} = \frac{-55\cdot 2 - 45\cdot 5 - 35\cdot 9 - 25\cdot 35 - 15\cdot 59 - 5\cdot 57 + 5\cdot 13}{180} = -14{,}61.$$

In order to determine the mean-square deviation, let us draw up Table 4.

Table 4

Deviation in microns		n	$x_i - x_{mean}$	$(x_i - x_{mean})^2$	$n_i(x_i - x_{mean})^2$
from	to				
−60	−50	2	−40,39	1631,35	3262,70
−50	−40	5	−30,39	923,55	4617,76
−40	−30	9	−20,39	415,75	3741,77
−30	−20	35	−10,39	107,95	3778,25
−20	−10	59	−0,39	0,15	8,97
−10	0	57	+9,61	92,35	5263,95
0	+10	13	+19,61	384,55	4999,15

$$\sum n_i(x_i - x_{mean})^2 = 25672{,}55; \qquad \sigma = \sqrt{\frac{25672{,}55}{180}} = 11{,}95 \text{ microns.}$$

Consequently, the greatest deviation from the mean value is equal to $3\sigma = \pm 3 \times 11.95 = \pm 35.85$ microns. Assuming that the distribution obeys the law of normal distribution, we can reckon that the total error is equal to 6σ, i. e. 71.7 microns. Under these conditions, the probability of determining the zone of diffusion (i. e. 6σ) constitutes, as has been shown above, 0.9973, i. e. practically 100%.

Example. To determine the percentage of suitable parts in the machining of cylinders with a diameter of $20_{-0.1}$ mm (Fig.9).

On the basis of measuring it has been established that the curve of distribution obeys the law of normal distribution with a mean-square deviation of $\sigma = 0.025$ mm, the apex of the curve being displaced 0.03 mm from the center of the field of tolerance toward the go-side of the gage.

The probability of obtaining suitable parts is

$$W=\Phi(Z_A)+\Phi(Z_B),$$

where

$$Z_A=\frac{x_A}{\sigma}=\frac{0,05+0,03}{0,025}=3,2,$$
$$Z_B=\frac{x_B}{\sigma}=\frac{0,05-0,03}{0,025}=0,8.$$

According to the Table of adduced integrals (Appendix 3) we find that $\Phi(Z_A) = 0.499$, and $\Phi(Z_B) = 0.288$,

$$W=0,499+0,288=0,787\approx 79\%.$$

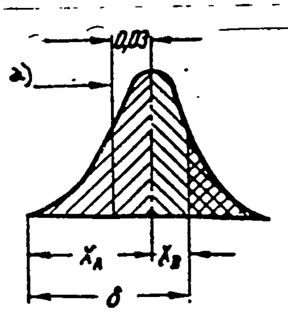

Fig.9 - Probability of Obtaining Suitable Parts
a) Center of the field of tolerance

The probability of obtaining dimensions greater than the measurement of the go-gage (corrected defect) is equal to

$$0,5-\Phi(Z_B)=0,5-0,288=0,212=21,2\%.$$

Example. To determine the correctness of a setup on the basis of measuring certain test parts.

It is evident that there will be no defects in machining if the arithmetic mean of the entire group of machined parts L_{mean} is to be found within the limits (Fig.10).

$$L_{min}+3\sigma < L_{mean} < L_{max}-3\sigma.$$

The problem, consequently, boils down to judging the position of L_{mean} on the basis of measuring a small number of parts.

In the example analyzed above we have shown that if x_{mean} is reckoned on the basis of the measuring of four parts, i. e. with a probability equal to 0.609, we may expect that x_{mean} will not differ from L_{mean} more than $\pm 0.5\sigma$.

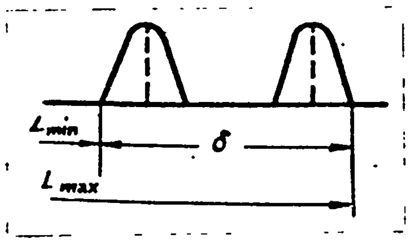

Fig.10 - Extreme Positions of the Curves of Distribution when $\delta > 12\sigma$

If the number of parts is increased to nine, the probability will rise to 0.83.

Thus, by increasing the number of measured parts, we raise the probability of obtaining x_{mean} with a given accuracy.

In conclusion we should note that in the statistical methods of analysis it is important to know with what degree of approximation the empirical curve of distribution, characterizing some technological process, may be taken for a curve of normal distribution. This problem is examined in detail in specialized literature.

4. Conditions and Probabilities of Obtaining Set Tolerances in the Production of Parts

Making use of the statements set forth above, let us examine the conditions and possibility of obtaining set tolerances in the production of parts*.

All the causes of the errors which are possible in machine operations conducted in accordance with the principle of the automatic obtainment of measurements, are divided into three groups:

1) those which depend upon the type of machining;
2) errors in the set-up;
3) errors in the basing.

To the first group belong errors which occur as a result of fluctuation in the

*-Here we set forth the method proposed by Prof.A.B.Yakhin.

mechanical properties of the material, in the chemical composition, in the amount of allowance, etc.

A notion of errors in set-up may be obtained from the following example.

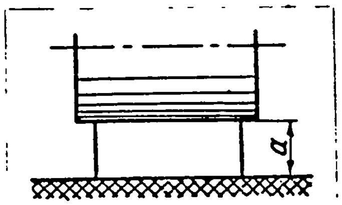

Fig.11 - Setting on a Plane without Error in Basing

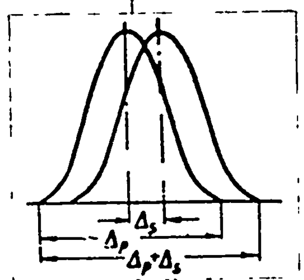

Fig.12 - Change of Position of the Curve of Distribution Depending upon the Set-up

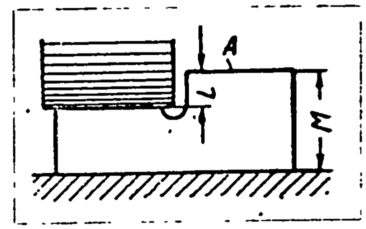

Fig.13 - Setting on a Plane which Causes an Error in Basing

Let us assume that we have machined a group of parts with a single milling cutter and without under-tooling the machine (Fig.11). Having measured the machined parts according to the measurement a, let us find the error, which depends upon the type of machining, and let us construct the curve of distribution (Fig.12). Then let us effect the set-up a second time, and execute a group of parts. It is evident that the curve of distribution of the measurements of the second group of parts will differ by Δ_H from the curve of distribution of the first group of parts (Fig.12), since it is impossible to accomplish a set-up with complete accuracy.

A conception of an error in the basing may be obtained from the following example (Fig.13).

In milling a ledge (Fig.13) we must keep a measurement L, reckoned from the plane A. It is evident that the accuracy obtained in the measurement L will depend upon the accuracy of measurement M.

Keeping the measurements of all the machined parts within the limits of tolerance is possible only on condition that

$$\Delta_p + \Delta_s + \Delta_y \leqslant \delta, \qquad (2.8)$$

where δ is the tolerance indicated in the blueprint of the part;

Δ_p is the base of diffusion depending upon the type of machining;

Δ_s is the error in the set-up and

Δ_y is the base of diffusion caused by the error in the basing.

Let us examine in greater detail each of the errors which enter into the inequation.

1) Causes which depend upon the type of machining.

In order to obtain data on the causes which depend upon the type of machining, we must establish a law of distribution of dimensions (of errors), i. e. machine a group of parts under unchanging production conditions and use an attachment scheme in which errors in the basing would equal zero.

As has already been shown, the law of distribution of errors in work done by the method of the automatic obtainment of dimensions obeys the law of normal distribution. In this case the basic parameter characterizing the diffusion of the dimensions is the mean-square deviation.

Keeping the dimensions of all the parts within the limits of tolerance is possible only on the condition that

$$\Delta_p < \delta. \qquad (2.9)$$

This condition is necessary, but still insufficient.

Under the law of normal distribution, we may, with a probability of 0.9973, as we know (2.6), take it that

$$\Delta_p = 6\sigma_0.$$

Consequently,

$$6\sigma_0 < \delta. \qquad (2.10)$$

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If this inequation is not observed, it is necessary to go over the technological process or to introduce additional machining of some of the parts*.

2) An Error in the Set-up is a constant quantity, and is caused by inaccuracy in the set-up of the machine, by inaccuracy in the cutting tool or attachment.

3) An Error in the Basing is not a constant quantity, and depends upon the position of the base of departure. The base of departure is our name for the element of a blank relative to which the dimension obtained in a given operation must be kept.

Base dimensions is our name for the dimensions of a blank upon which the position of the base of departure depends.

For the case shown in Fig.14, the dimension D is the base dimension, and the point A is the base of departure. Consequently, an error caused by fluctuations in the position of the base of departure may be called an error in the basing.

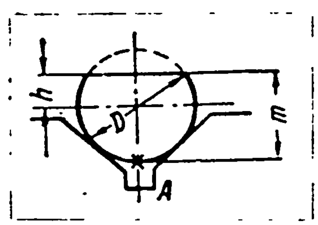

Fig.14 - Scheme of Setting on a Prism

In order to resolve the problem of the suitability of one or another basing scheme, we must determine the actual value of the error in basing and compare it with the permissible value.

Let us examine the usual method of determining the permissible amount of error in the basing.

If we hold that inaccuracies caused by the type of machining and setting are accidental, and that an error due to an inaccuracy in the set-up is a constant quantity, then on the basis of the law of the addition of accidental quantities we may write

$$\delta \geqslant \Delta_s + \sqrt{k_p^2\Delta_p^2 + k_y^2\Delta_y^2}, \qquad (2.11)$$

where k_p and k_y are coefficients which depend upon the laws of distribution.

Resolving the inequation in relation to Δ_y, we obtain

* The number of parts subject to additional machining is determined by the method stated above.

$$\Delta_y \leqslant \frac{\sqrt{(\delta - \Delta_s)^2 - k_p^2 \Delta_p^2}}{k_y}. \qquad (2.12)$$

The right member of this inequation determines the permissible amount of error in the basing, and the left member determines the actual amount of error in the basing.

Thus the accepted scheme of the setting of a part in an attachment may be permitted only if the actual amount of error in the basing is less than the permissible amount.

The values of the coefficients k_p and k_y which enter into the inequation depend upon the law of the distribution of errors, and were defined by N.A.Borodachev (Bibl.7). For the law of normal distribution $k_y = k_p = 1$. Consequently, in this case computation of the actual amount of errors in the basing may be made according to the following formula:

$$\Delta_y \leqslant \sqrt{(\delta - \Delta_s)^2 - \Delta_p^2}. \qquad (2.13)$$

An error in machining which occurs as a result of an inaccuracy in the execution of the attachment is a constant quantity and is taken into account by the term Δ_s which enters into the basic equation.

Taking $k_p = 1$ and substituting into formula (2.12) we obtain

$$\Delta_s \leqslant \delta - \sqrt{\Delta_p^2 + k_y^2 \Delta_y^2}. \qquad (2.14)$$

The attachment may be considered acceptable if the actual value of the adduced inaccuracy in the attachment is less than the permissible value.

The actual value of the adduced inaccuracy in the attachment, Δ_s, is determined according to the scheme of the attachment and by the base dimensions.

As an example of the computation of the actual amount of error in the basing let us examine the case of a setting along a cylindrical surface (see Fig.14).

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The dimension h must be kept.

As is clear from the drawing (Fig.15), the error in dimension h is equal to $c'c''$.

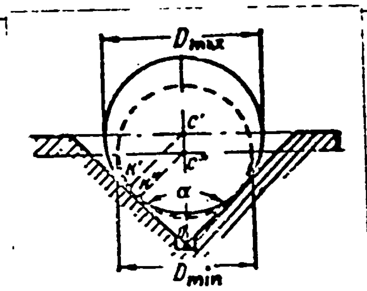

Fig.15 – Setting on a Prism Which Causes an Error in the Basing

From triangle $c'k'o$ we have

$$oc' = \frac{c'k'}{\sin\frac{\alpha}{2}} = \frac{D_{max}}{2\sin\frac{\alpha}{2}},$$

where α is the prism angle;

D_{max} is the diameter of the blank.

From triangle $c''k''o$ we have

$$oc'' = \frac{c''k''}{\sin\frac{\alpha}{2}} = \frac{D_{min}}{2\sin\frac{\alpha}{2}}$$

or

$$\Delta_y = oc' - oc'' = \frac{(D_{max} - D_{min})}{2\sin\frac{\alpha}{2}} = \frac{\delta_D}{2\sin\frac{\alpha}{2}},$$

where Δ_y is the actual amount of error in the basing.

Let us assume that

$$h = 20 \pm 0{,}08,\quad D = 60_{-0{,}2},\quad \alpha = 90^\circ,\quad \sigma_p = 0{,}01,\quad \Delta_s = 0{,}02.$$

$$\Delta_y = \frac{0{,}2}{2 \cdot 0{,}7071} \approx 0{,}14 \text{ mm}.$$

The permissible error is determined by inequation (2.13)

$$\Delta_y \leqslant \sqrt{(0{,}16 - 0{,}02)^2 - (6 \cdot 0{,}01)^2} \approx 0{,}12 \text{ mm}.$$

The inequation is not satisfied, and consequently such a scheme of setting is unsuitable.

The actual amount of error in the basing may be decreased by:

a) decreasing the tolerance in the diameter 60 to the extent determined by the equation

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$$0{,}12 = \frac{\delta_D}{2\sin 45^\circ}$$

and

$$\delta_D = 2\cdot 0{,}12\cdot 0{,}701 \approx 0{,}16 \text{ mm (instead of } 0{,}20);$$

b) changing the prism angle

$$0{,}12 = \frac{0{,}2}{2\sin\frac{\alpha}{2}}$$

or

$$\sin\frac{\alpha}{2} = \frac{0{,}2}{0{,}12\cdot 0{,}2} = 0{,}8 \text{ and } \frac{\alpha}{2} = 55^\circ;$$

c) changing the method of setting (Fig.16).

In this case $\Delta_y = 0$.

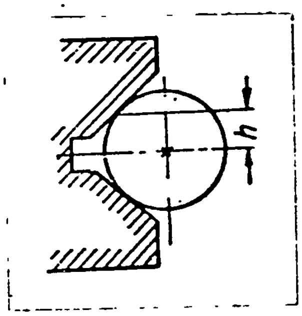

Fig.16 – Setting on a Prism without an Error in the Basing

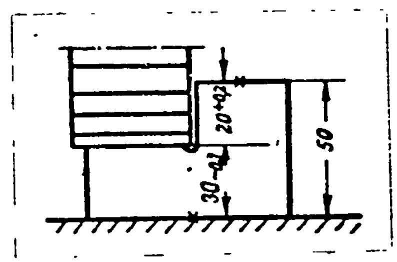

Fig.17

Examining a large number of examples is inexpedient, since in all cases the problem boils down to finding interdependences between the error in the basing and the deviations in the base dimensions.

Let us examine the method of computing the basis dimensions in the following example.

Let us assume that in a given operation the dimensions $30_{-0.1}$ and $20^{+0.2}$ must be kept (Fig.17).

STAT

104

In relation to the dimension 20, the base dimension is 50. Consequently the problem boils down to establishing such a tolerance for the dimension 50 that the dimension 20 will be obtained automatically. The dimension which is obtained immediately in a given operation will be referred to as the base dimension.

Let us express the produced dimension (20) as a function of the base dimension (30) and the base dimension (50):

$$20=50-30.$$

In composing the equation we must see to it that the produced dimension will be in the left-hand member.

In computing to maximum and minimum we obtain:

$$20_{max}=50_{max}-30_{min},$$
$$20_{min}=50_{min}-30_{max}.$$

Consequently,

$$50_{max}=20_{max}+30_{min}=20{,}2+29{,}9=50{,}1 \text{ mm},$$
$$50_{min}=20_{min}+30_{max}=20{,}0+30{,}0=50{,}0 \text{ " }.$$

Thus the base dimension will be equal to

$$50{,}05\pm0{,}05.$$

We have computed to maximum and minimum, i. e. without taking into account the dimensional scattering.

If the dimensional scattering obeys the law of normal distribution and the center of the field of tolerance coincides with the mean arithmetic value, we may write the following equations:

$$20_{mean}=50_{mean}-30_{mean},$$
$$50_{mean}=20_{mean}+30_{mean}=20{,}1+29{,}95=50{,}05 \text{ mm},$$
$$\delta_{50}=\sqrt{\delta_{20}^2-\delta_{30}^2}=0{,}17 \text{ mm}.$$

The base dimension will be equal to

$$50{,}05 \pm 0{,}085,$$

i. e. the mean value has remained the same as it was in computation to maximum and minimum, but the tolerance has been extended by 0.07 mm.

Computation of the base dimensions, while taking diffusion into account, may be accomplished only when a great number of parts are made. In doing this, it must be established that the laws of the distribution of the basic, the produced, and the base dimensions are close to the law of normal distribution. It must be remembered that in this method of computation the possibility of defect is not excluded, but the probability of such defect is slight.

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CHAPTER V

ALLOWANCES AND INTERMEDIATE DIMENSIONS

1. General Principles

An allowance for machining is a layer of material which is subject to removal in machining. A distinction must be made between general and intermediate allowances for machining.

A layer of material, which is the difference between the dimensions of a blank and the dimensions of a completely machined part, is called a general allowance for machining.

A layer of material which is taken off in the completion of one or another stage of the operation is called an intermediate machining allowance.

In instrument design, in the construction of small parts, the weight of the allowance is often greater than the weight of the finished part; in addition, the parts are made of nonferrous metals and their alloys, so that reduction of the allowances is a very important task. An increase in the allowance leads to an increase in the cutting forces and this, in the machining of parts which are not very rigid, may cause a considerable increase in the deformation of the parts and a reduction in the accuracy of their execution. On the other hand, a reduction in the allowance makes it impossible for us to obtain the required degree of accuracy and surface smoothness of the part.

Professor V.M.Kovan was the first to lay the scientific groundwork for a method for determining the amount of allowance. Further work in this direction was done by I.B.Plotkin (Bibl.1 and 2).

However characteristic this work may be for general machine construction, in aircraft instrument design it needs additional experimental checking and correcting, although the general method of calculating is preserved.

2. Method for Determining the Amount of Allowance

A blank obtained by casting or forging will still contain surface roughnesses in the form of casting skin or slag; in steel blanks, a decarbonized surface layer remains. It is evident that, in this case, the cutting tool must take off a layer of chip which must be of a greater thickness than the casting skin or slag, and which must be deeper than the irregularities; otherwise the resistance will be very low, even at moderate cutting speeds. In the process of machining, irregularities in the form of tiny ridges remain on the surface of the part being machined; in addition, the surface layer of the metal of the part being machined differs in structure from the structure of the remaining section.

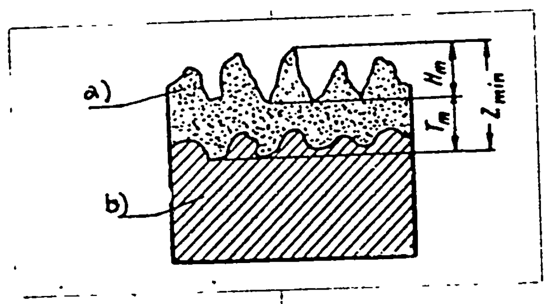

Fig.69

a) Defective surface layer; b) Normal structure of the material

To eliminate surface irregularities and the defective surface layer (the layer of different structure), in every subsequent stage (operation) the minimum intermediate machining allowance must not be less than an amount which is the sum of the greatest height of the irregularities (ridges) and the greatest depth of the defect-

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ive surface layer. The surface layer is schematically represented in Fig.69, where H_m is the greatest height of the surface irregularities (ridges), and T_m is the greatest depth of the defective surface layer.

The minimum intermediate machining allowance, when the allowance is arranged unilaterally, is

$$z_{min} \geqslant H_m + T_m. \qquad (5.1)$$

In the case of a symmetrical arrangement of allowances, for example in machining external cylindrical surfaces and apertures, the minimum intermediate allowance is equal to

$$z_{min} = 2z_{min} \geqslant 2(H_m + T_m). \qquad (5.2)$$

In determining the amount of machining allowance, we must set a tolerance δ for execution in accordance with the intermediate dimensions. The tolerance δ is the total error composed of dimensional scattering, error in setups, and possible errors of a systematic character, proper to a given method of machining.

Errors in form (ellipticity, conicity, nonparallelism, etc.) lie within the limits of the dimensional tolerance, which must be taken into account in establishing the machining allowance. However, any disturbance in the accuracy of the mutual arrangement of the elements of a part, eccentricity, nonperpendicularity, etc., as well as an error in the basing Δ_y - none of these are connected with the dimensional tolerance, and therefore must be considered separately in cases where such errors occur.

The maximum intermediate machining allowance, when the allowance is arranged unilaterally, will be equal to

$$z_{max} = \delta_p + z_{min} + \delta, \qquad (5.3)$$

where δ_p is the tolerance in the preceding operation (stage);

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Table 9

Type of Surface Being Machined	Stage of Machining	H_m	T_m	
		microns		
External cylindrical, conical, and profile turning surfaces	Lapping	0.05 - 0.5	3 - 5	4 - 11
	Fine turning	1 - 5	15 - 20	8 - 25
	Grinding	1.7 - 15	15 - 25	10 - 40
	Smooth turning	5 - 45	30 - 40	50 - 200
	Rough turning	15 - 100	40 - 60	100 - 400
	Cold-drawn steel	25 - 100	80 - 100	70 - 340
	Rolling	100 - 225	300	500 - 1600
	Drop-forging	100 - 225	500	400 - 1000
Cylindrical apertures	Lapping	0.05 - 0.5	3 - 5	4 - 13
	Fine boring	1 - 5	15 - 20	15 - 25
	Breaking with a ball	1 - 5	20 - 25	12 - 18
	Broaching	1.7 - 8.5	10 - 20	18 - 30
	Grinding	1.7 - 15	20 - 30	15 - 35
	Smooth boring	3 - 25	30 - 40	100 - 200
	Smooth reaming	15 - 45	10 - 20	20 - 80
	Rough reaming	25 - 100	25 - 30	40 - 150
	Rough boring	25 - 225	30 - 50	200 - 350
	Turning out	25 - 225	40 - 60	140 - 300
	Jig drilling	45 - 225	50 - 60	70 - 300
	Drilling without a jig	45 - 225	50 - 60	120 - 350
	Drop-forging	100 - 225	500	600 - 1000
Planes	Lapping	0.05 - 0.5	3 - 5	4 - 15
	Grinding	1.7 - 1.5	15 - 25	10 - 50
	Smooth milling	5 - 45	25 - 50	25 - 100
	Rough milling	15 - 100	40 - 60	70 - 200
	Planing	15 - 100	40 - 50	80 - 200
	Rolling	100 - 225	300	500 - 1600
	Drop-forging	100 - 225	500	300 - 1000

δ is the tolerance in the given operation (stage).

When the arrangement is bilateral, the allowance will be

$$z'_{max} = \delta_p + z'_{min} + \delta. \quad (5.4)$$

The values H_m, T_m, and δ depend upon the method of machining and are determined experimentally.

Table 9 gives the values of H_m, T_m, and δ for the methods of machining most often used in instrument making*.

3. Calculation of Intermediate Dimensions

In the working drawing of a part being machined, only the final dimensions are indicated. The technologist indicates the intermediate dimensions (or, as they are sometimes called, the inter-operational dimensions) in the operation drawing. These dimensions must take into account the intermediate allowances for subsequent machining.

Calculation of the intermediate dimensions must be made from the last operation, based on the dimensions and tolerances specified in the working drawing.

The intermediate dimensions in machining are determined from the following expressions:

for external cylindrical surfaces (Fig.70)

$$A^p_{max} = A_{max} + z'_{min} + \delta_p, \quad (5.5)$$

for cylindrical apertures (Fig.71)

$$A^p_{min} = A_{min} - z'_{min} - \delta_p, \quad (5.6)$$

for planes (Fig.72)

* For a more detailed treatment see Bibl.1.

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$$A^p_{max} = A_{max} + z_{min} + \delta_p, \quad (5.7)$$

where A^p is the dimension maintained in the preceding machining;

A is the dimension maintained in the given operation;

z' is the allowance for the given operation, based on H_m and T_m for the preceding operation (according to Table 9);

δ_p is the tolerance for the preceding operation.

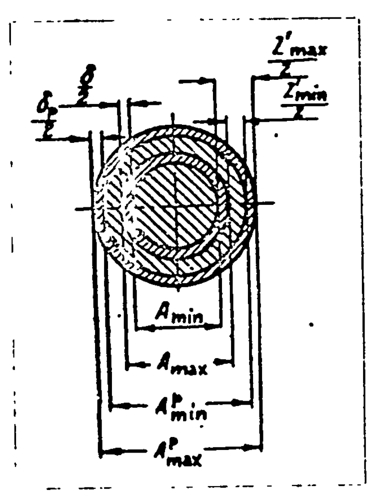

Fig.70 - Diagram of the Distribution of Dimensions and Tolerances in an External Cylindrical Surface

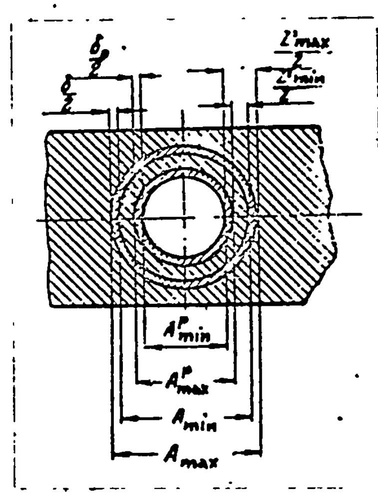

Fig.71 - Diagram of the Distribution of Dimensions and Tolerances in an Internal Cylindrical Surface

Let us cite some examples for the use of the above formulas in calculating the intermediate dimensions.

Example. To determine the allowance and intermediate dimensions in the machining of a shaft (Fig.73) from a cold-drawn steel bar.

The order of machining for a diameter of $9^{+0.034}_{+0.022}$ is as follows:

1) Smooth turning on a lathe with a clamp in the chuck;

2) Grinding on a centerless grinding machine;

3) Grinding on a base of cones, which may have an eccentricity of 0.01 mm rela-

tive to the diameter under machining, on a circular grinding machine.

We begin calculation of the intermediate dimensions with the last operation, i. e., grinding on a circular grinding machine (the preceding operation is centerless grinding).

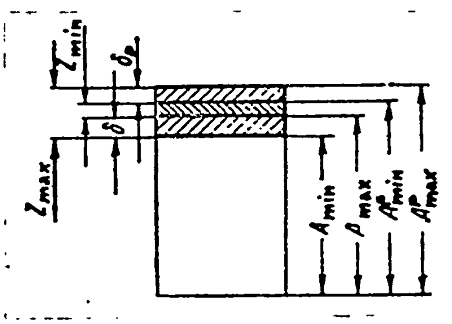

Fig.72 – Diagram of the Distribution of Dimensions and Tolerances in a Plane Surface

The minimum allowance for diameter machining in the final operation is

$$z'_{min} = 2\,(H_m + T_m).$$

Taking the mean values of H_m and T_m according to Table 9, where

$$H_m = 8 \text{ micr. and } T_m = 20 \text{ microns},$$

we will have

$$z'_{min} = 2\,(8+20) = 56 \text{ microns.}$$

The eccentricity of the cones in relation to the diameter under machining will cause an error in the basing of Δ_y = 10 microns, and for this reason the allowance must be increased by 10 microns

$$z''_{min} = z'_{min} + \Delta_y = 56 + 10 = 66 \text{ microns.}$$

The dimensions of the shaft, after centerless grinding, will be equal to

$$A^p_{max} = A_{max} + z''_{min} + \delta_p.$$

According to Table 9, the mean value of δ_p for grinding is 25 microns. Finally, we will have

$$A^p_{max} = 9{,}034 + 0{,}066 + 0{,}025 = 9{,}125.$$

Let us determine the intermediate dimensions of the shaft, obtained after smooth turning on the lathe.

The minimum allowance for diameter machining in grinding is

$$z'_{min} = 2(H_m + T_m).$$

Taking, in accordance with Table 9, the mean values

$$H_m = 25 \text{ micr. and } T_m = 35 \text{ microns,}$$

we will have $z_{min} = 2(25+35) = 120$ microns.

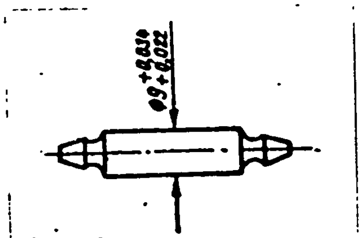

Fig.73

The dimensions of the shaft, after smooth turning, must be equal to

$$A^p_{max} = A_{max} + z'_{min} + \delta_p.$$

According to Table 9, the mean value of δ_p for smooth turning is 125 microns.

In the end, we will have

$$A^p_{max} = 9{,}125 + 0{,}120 + 0{,}125 = 9{,}37.$$

Now let us determine the dimensions of the blank, i. e., the diameter of the bar.

The minimum allowance for diameter machining in smooth turning on a lathe is

$$z'_{min} = 2(H_m + T_m).$$

Taking, in accordance with Table 9, the mean values for a blank of cold-drawn steel as

$$H_m = 60 \text{ micr. and } T_m = 90 \text{ microns,}$$

we will have

$$z'_{min} = 2(60+90) = 300 \text{ microns.}$$

The bar is fastened in the chuck, which may have a pulsation of 0.02 mm; this will cause a basing error of Δ_y = 0.01 mm, and for this reason the minimum allowance must be increased by 10 microns

$$z''_{min} = z'_{min} + \Delta_y = 300 + 10 = 310 \text{ microns.}$$

The dimensions of the shaft, after centerless grinding, will be equal to

$$A^{p}_{max} = A_{max} + z'_{min} + \delta_p.$$

The tolerance for OST 7128 cold-drawn steel bars is δ_p = 100 microns. In the end, we will have

$$A^{p}_{max} = 9{,}370 + 0{,}310 + 0{,}100 = 9{,}78.$$

In sorting, we take the next highest measurement $9.8_{-0.1}$.

Example. To determine the allowances and intermediate dimensions in the machining of an aperture with a diameter of $6^{+0.025}$ mm. The order of machining the aperture is as follows:

1) Drilling;
2) Smooth boring;
3) Reaming.

Let us determine the intermediate dimensions which the aperture should have after smooth boring.

The minimum allowance for reaming is

$$z'_{min} = 2(H_m + T_m).$$

Taking, in accordance with Table 9, the mean values of H_m and T_m,

$$H_m = 14 \text{ micr. and } T_m = 35 \text{ microns,}$$

we will have

STAT

$$z'_{min} = 2\,(14+35) = 98 \text{ microns.}$$

The dimensions of the aperture, after smooth boring, will be equal to

$$A^{p}_{min} = A_{min} - z'_{min} - \delta_p.$$

In accordance with Table 9, we take the value δ_p = 100 microns for smooth boring. In the end, we will have

$$A^{p}_{min} = 6 - 0,098 - 0,100 = 5,802 \approx 5,8.$$

Let us determine the intermediate dimensions which the aperture should have after drilling.

The minimum allowance for boring is

$$z'_{min} = 2\,(H_m + T_m).$$

Taking the mean values of H_m and T_m according to Table 9

$$H_m = 135 \text{ micr. and } T_m = 55 \text{ microns},$$

we will have

$$z'_{min} = 2\,(135+55) = 380 \text{ microns.}$$

The dimensions of the aperture after drilling will be equal to

$$A^{p}_{min} = A_{min} - z'_{min} - \delta_p.$$

According to Table 9, we take a value of δ_p = 120 microns for drilling.

$$\delta_p = 120 \text{ microns.}$$

In the end, we will have

$$A^{p}_{min} = 5,80 - 0,38 - 0,120 = 5,30.$$

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CHAPTER XI

PARTS OF TOOTH GEARINGS

1. General Principles

Designations

In instrument construction, four basic types of geared transmissions are used (Fig.180):

1) straight-toothed cylindrical gear wheels or spur gears (Fig.180a);

2) screw-toothed cylindrical wheels or helical gears (Fig.180b);

3) straight-toothed cone wheels or bevel gears (Fig.180c);

4) worm wheels or worm gears (Fig.180d).

Specifications for Parts of Tooth Gearings

The basic requirements applying to tooth gearings in instrument construction are as follows:

a) Smoothness in transmission;

b) Accuracy of center-to-center distance;

c) Low angular error;

d) Resistance to corrosion.

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Particularities of Tooth Gearings in Instrument Construction

Among the peculiarities of tooth gearings are:

The use of a transmission with high gear ratios (10 : 1, 20 : 1) in one pair. To realize such high gear ratios in instrument construction special parts are used.

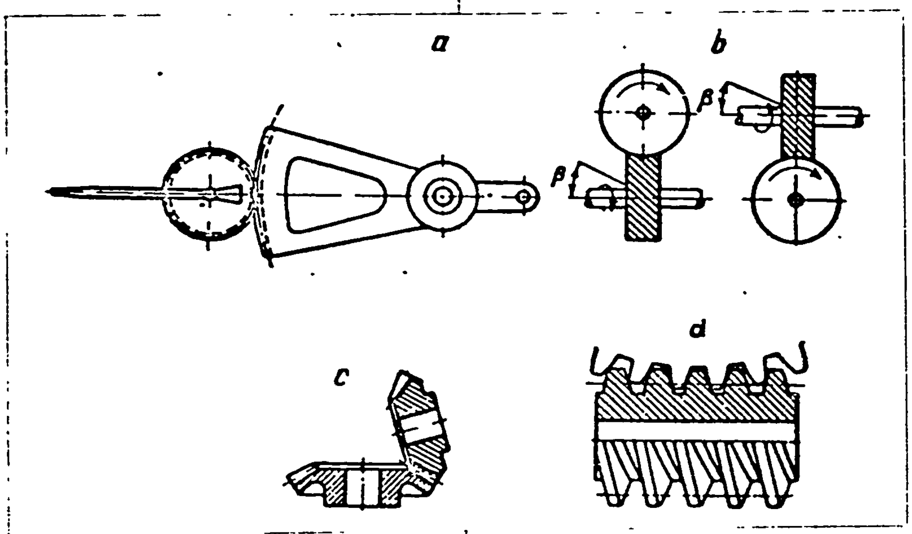

Fig.180 - Types of Gears

a - Spur gears; b - Helical gears; c - Bevel gears; d - Worm gears

One wheel (of a pair of wheels) with 10 to 12 teeth is executed integral with its axis and is known as the driving gear; the other wheel of the pair has 200 - 300 teeth and is called a sector; teeth are cut only into a definite part of its periphery. Placing such transmissions in an instrument of comparatively small bulk is made possible by the use of small modules (up to 0.5 mm).

Involute gearing with 20° angle. At one time, cycloidal gearing was used simultaneously with involute gearing in aircraft instrument construction. Cycloidal gearing permits a reduction in the number of teeth of the driving gear (the wheel) to six when the period of gearing is more than unity. When the profile is cycloidal, the wear of the teeth is not as great as when it is involute. One shortcoming of cycloidal gearing is the fact that it is impossible to cut the teeth by the rolling method. In addition, cycloidal gear wheels require a higher degree of accuracy in

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center-to-center distance (otherwise there will be irregularity in rotation).

At present, cycloidal gearing is practically out of use in aircraft instrument construction.

Involute gearing does not have the shortcomings of cycloidal gearing. The great advantage of involute gearing lies in the fact that it is possible to cut the teeth by the rolling method. In addition, wheels with involute gearing permit, in assembling, a variation in the center-to-center distances of the wheels, without disturbing the regularity of their rotation.

Methods of Machining Gear Wheels

The various methods of manufacturing gear wheels for aircraft instruments may be divided into two groups:

1. Making the gear wheels by chip-removing processes;
2. Making the gear wheels without chip removal (stamping, rolling, pressure casting, and drawing). Machining of gear wheels with chip removal is the most widely used method.

Stamping is used for making fine gear wheels, at $m > 0.5$ mm. In aircraft instrument construction, such a method finds very limited application. Rolling is used for gear wheels with a module of 0.3 - 1 mm. This method is still used in the acceptance stage. Pressure casting and drawing are also seldom used.

Materials.

In instrument construction, gear wheels are usually made of steel, brass, bronze, etc. Decisive factors in the choice of material are cost of machining, resistance to wear, and high corrosion resistance. To reduce wear different materials must be used, as far as possible, for a single pair of gear wheels, such as steel and brass, bronze of different types, and the like.

For low-speed gear transmissions, we generally use LS59 brass. This is pre-

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ferred over steel since brass is easily machined and subject to little corrosion. U8A steel and U10A steel are mostly used in making pinions and worms. Because of their small dimensions, these parts wear out sooner, and for this reason they must be subjected to heat treatment. Bronze of A10 and AMts9-2 types is used in making worm gears where high requirements as to resistance to wear are made. Textolite is also used as material for gear wheels.

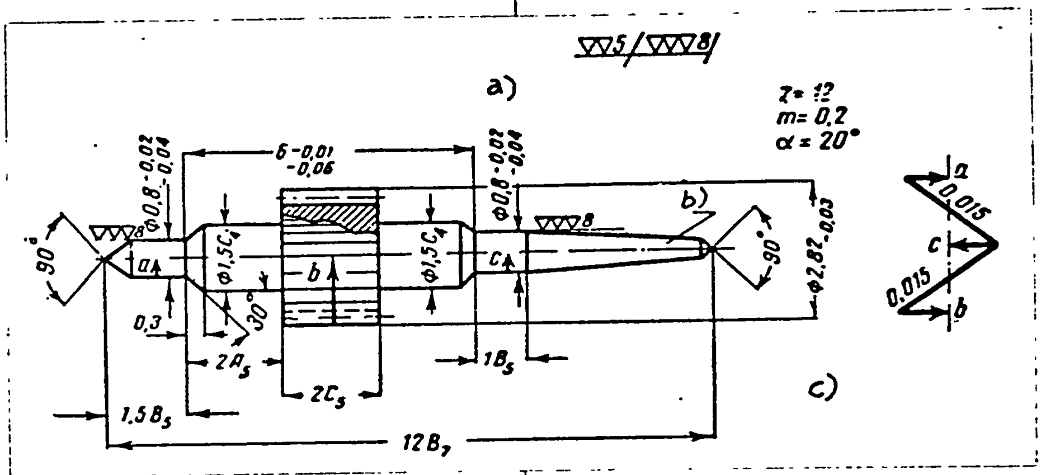

Fig.181 - Driving Gear or Pinion

a) Ellipticity of diameter $0.8^{-0.02}_{-0.04}$, not more than 0.12;

b) Taper 1:50; c) Material U7AV steel red-hot R_c 50 - 55

2. Technology of Executing Typical Parts of Tooth Gearings

A. Driving Gears

The technological process of machining driving gears consists of a series of operations: 1) preparatory operations; 2) teeth-cutting operations; 3) heat-treatment operations (these may be omitted); and 4) finishing operations.

Let us examine the standard technological process of machining a driving gear (Fig.181). The preliminary operations consist in preparing the bars (straightening and cutting) and turning. The turning is usually done on automatic longitudinal lathes or on turret lathes. In choosing a turret lathe or an automatic turret

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chucking machine, and in fixing the sequence of stages, the specifications given in the Chapter "Axles and Shafts", must be followed, since the blank for a driving gear must be treated as an axle.

Tooth-cutting is done by the duplicating method (since driving gears usually have less than 17 teeth).

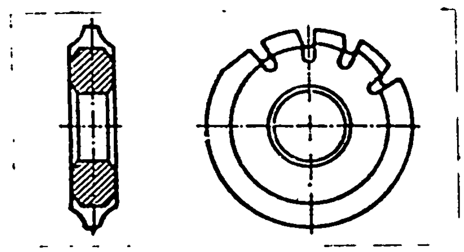

Fig.182 - Disk Gear Cutter

The disk gear cutter (Fig.182) is used as the cutting tool in gear-cutting. From the theory of meshing of gear wheels we know that, for every number of teeth, there is a special profile. Thus, in order to obtain the exact profile in cutting by the duplicating method, each number of teeth must have its own cutter. Special cutters are made only in cases of large-scale or mass production. Usually we use gangs of 3, 8, 15, or 26 cutters, each of which is designed to cut a gear wheel with a definite number of teeth (Table 28).

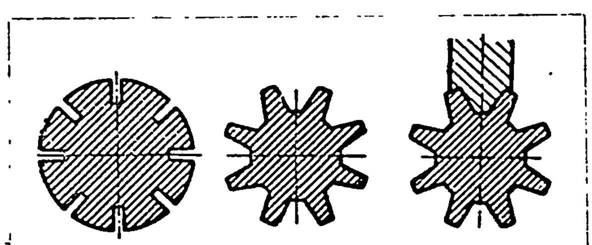

Fig.183 - Schematic Sketch of Milling of a Pinion Tooth in Three Passes

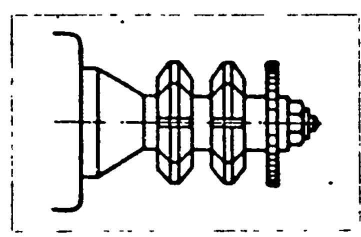

Fig.184 - Setting of Cutters on Arbor in Milling in Three Passes

In connection with the necessity of obtaining a high degree of accuracy and smoothness in the profile of a tooth, the machining must be done in several passes (in our case, three). Depending upon the type of machine, this may be done in either of the following ways:

1) Each pass is carried out by a separate cutter (Fig.183). In this method, three cutters are set on the arbor (Fig.184). The first is the usual splined cutter;

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the second is near the final profile in dimensions and form (allowance of 0.1 – 0.2 mm); the third has the final profile. In the beginning the first cutter goes into action. After it has cut all the teeth through, the cutter carriage is displaced, and the second cutter is set into working position (a worn cutter may be used for the second one).

After the carriage is shifted again, the third cutter is in operating position.

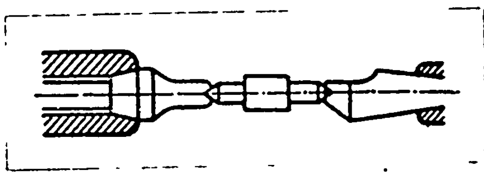

Fig.185 – Schematic Sketch of a Pinion Mounted Conically at the Driving Center

2) All the passes are done by a single cutter. In this method, one cutter is set on the arbor of the spindle; in the first pass it is not lowered to the full depth of the tooth, and only rough cutting is done. After all teeth are cut, the cutter is lowered farther into the part.

One shortcoming of the first method is the inaccuracy in the setting of the cutters relative to the axis of the part being machined; at the negligible allowances left for the smoothing passes, this may lead to the formation of bare spots.

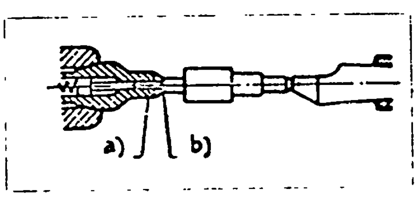

Fig.186 – Schematic Drawing of Mounting by the Driving Center, Set in the End of the Pinion

a) Journal; b) End

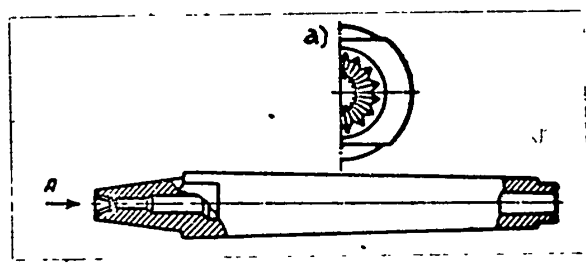

Fig.187 – Construction of the Driving Center

a) View from A

A shortcoming of the second method is the increased wear of the cutter.

In recent times, industrial plants have been using special devices to set the cutter accurately with respect to the center of the part being machined; as a result,

Table 28
Sets of Cutters and Number of Teeth Being Cut

a)		b)		c)		d)	
e)	f)	g)	f)	g)	f)	g)	f)
A	12—20	1	12—13	1	12	1	12
				1½	13	1½	13
		2	14—15	2	14	2	14
				2½	15—16	2½	15
						2¾	16
		3	17—20	3	17—18	3	17
						3¼	18
				3½	19—20	3½	19
						3¾	20
B	21—54	4	21—25	4	21—22	4	21
						4¼	22
				4½	23—25	4½	23
						4¾	24—25
		5	26—34	5	26—29	5	26—27
						5¼	28—29
				5½	30—34	5½	30—31
						5¾	32—34
		6	35—54	6	35—41	6	35—37
						6¼	38—41
				6½	42—54	6½	42—46
						6¾	47—54
C	55 and more	7	55—134	7	55—79	7	55—65
						7¼	66—79
				7½	80—134	7½	80—102
						7¾	103—134
		8	135 and more	8	135 and more	8	135 and more

a) Set of 3 cutters; b) Set of 8 cutters; c) Set of 15 cutters; d) Set of 26 cutters; e) Cutter; f) Number of teeth on wheel being cut; g) No. of cutter the first method must be considered superior, since it permits the cutter to operate for a longer period without being resharpened.

Setting and attaching the pinions being machined, is accomplished with the help of two stocks. If the journal of the pinion is sufficiently rigid, the fastening is done by the driving center, notched (Fig.185) and set in the headstock. If one of the journals is insufficiently rigid, the driving center is set in the end (Fig.186).

The construction of the driving center used on gear-cutting machines (of type OZPO) is shown in Fig.187. The driving center has a conical aperture with notching. The angle of the cone of the notched aperture is 30 – 50°. The number of teeth (of the notching) is usually 16.

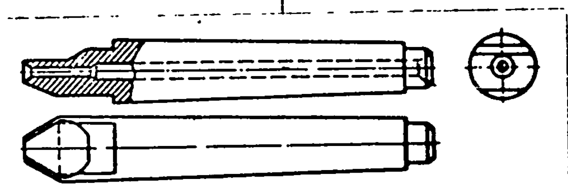

Fig.188 – Structure of the Center Inserted in the Indexing Head

The structure of the center for the tailstock is shown in Fig.188. After the teeth have been cut, steel pinions (in the majority of cases) are subjected to heat treatment. The heat treatment consists in hardening and subsequent tempering. Heating for the hardening is done in a special tube furnace, in a neutral medium. The neutral medium is prepared by dissociation of ammonia with partial liquefaction of hydrogen.

The usual composition for the neutral medium is:

$$H_2 — 75\% \text{ and } N_2 — 25\%.$$

Heating in a gaseous medium (neutral) for pinions of U8A and U10A steel is done at temperatures up to 780 – 800°C, with subsequent quenching in oil. After hardening, the parts are subjected to tempering by heating to 200 – 250°C, with subsequent quenching in oil (at 30 – 40°C). Pinions hardened in this manner have a smooth surface, and are outwardly indistinguishable from a surface obtained by chip-removing after machining.

To eliminate roughnesses resulting from tooth-cutting, additional finishing (polishing) is required, which is done on special tooth-polishing machines or on clock lathes rigged with special attachments.

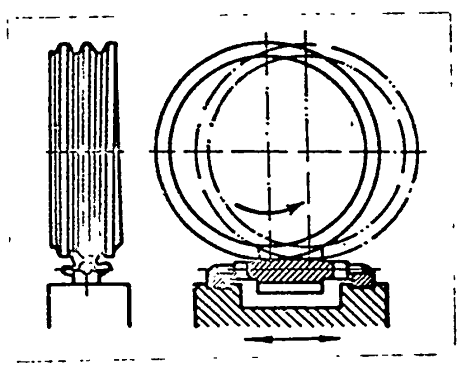

Fig.189 – Diagram of Polishing of Pinion Teeth

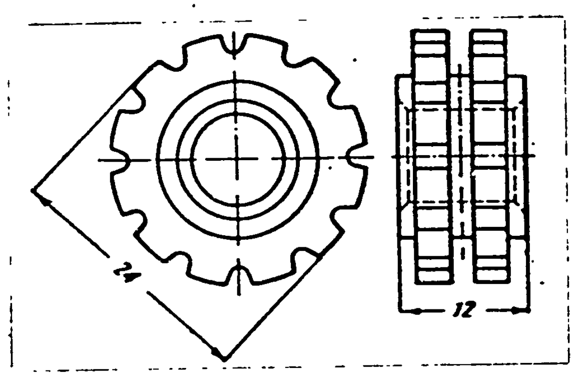

Fig.190 – Design of the Prop for the Pinion

The tool for polishing the teeth is a polisher made of wood (boxwood, palm, basswood) or of soft lead alloys, having a screw thread of the given module on a cylindrical surface. The disk revolves at a speed of 15 m/sec, entraining the pinion. In addition to rotation, the pinion performs a reciprocating motion at a speed of 180 – 200 strokes per minute (Fig.189). GOI paste is used as abrasive in polishing. In the process of polishing, the pinion is placed on a prop (Fig.190) which is a disk with several grooves cut into its periphery, for support. As the grooves wear out the disk is turned around. To polish the journals of the pinions, a sleeve of hard alloy is used (see Chapter X, "Axles and Shafts").

After cutting the tooth, the profile and pitch of the tooth are checked on a projector which enlarges 50 – 100 times. In checking, the pinion is set in the centers and is revolved by hand until the tooth profile coincides with the screen. In this way wobbling can also be checked. A special screen is used for this, on which a series of parallel lines is etched at a distance of 1 mm. The outer diameter of the pinion coincides with one of the lines on the screen. Wobbling can be determined by turning the pinion.

The outer diameter of the pinion is checked by special calipers (Fig.191). The no-go side of the gage d_{no} is distinguished from the go side d_{go} by a special cut-out. After the journals have been polished, they are checked for out-of-round with the help of an indicator with special jaws (Fig.192).

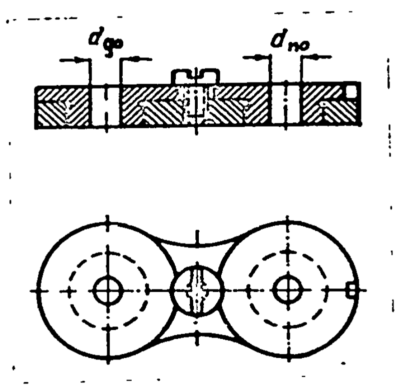

Fig.191 - Ring Gage for Checking the Outer Diameter of a Pinion

Out-of-round is determined in the following manner: By pushing the button (1), the moving bit (2) is pushed aside. The pinion journal is inserted in the gap formed between the moving bit (2) and the stationary bit (3). Then the button (1) is released, and the reading of the indicator is noted. By rotating the pinion, any deflection of the pointer, indicating out-of-round of the journal, will be noted.

Sectors

Let us examine the standard technological process for the production of a sector gear of the type shown in Fig.193. This technological process is characteristic not only of the production of sectors or racks but also of gear wheels made of sheet material. Notching the blank is done on eccentric presses with subsequent straightening. This is followed by trimming, countersinking the aperture, and turning the sector on the outer diameter (turning is not always done). Cutting the teeth is usually done by the rolling method on "Komsomolets" machines or by the indexing method on OZPO type machines.

Cutting the teeth by the rolling method has the following advantages:

1) Greater accuracy. This is explained by the fact that in the case of involute gearing the cutter has a rectilinear profile (the form of a trapezium with an angle of $\alpha = 20°$, Fig.194). A form such as this is easy to produce and easy to

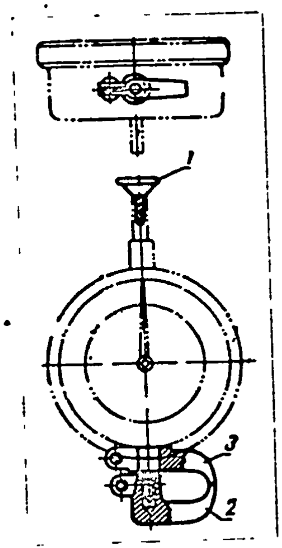

Fig.192 - Control Device for Checking Out-of-Round the Pinion Journal

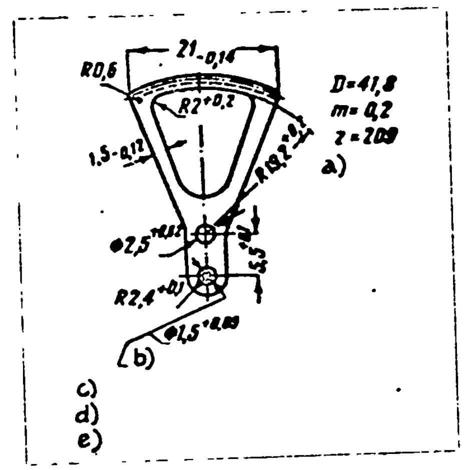

Fig.193 - Sector

a) Along entire circumference; b) Countersink to $\phi 2^{+0.25}$; c) Involute gearing $\alpha = 20°$; d) Eccentricity $\phi 2.5$ A_3; e) Relative to the center, not more than 0.01

check. In addition, when teeth are cut by the rolling method, errors in the indexing mechanism of the machine have no effect on the accuracy of the angle. On the basis of research done by S.V.Tarasov (of the MVTU imeni Bauman), it has been established that in cutting a tooth by the duplicating method, the thickness of the tooth may be maintained with a tolerance of 0.02 mm, and in cutting by the rolling method, with a tolerance of 0.01 mm.

2) Considerable increase in productivity. The machine time in working with the duplicating method is determined by the formula

$$T_м = \frac{Lz}{s_м k} + \frac{Lz}{s_{ox} k} + \tau_{z\,min} \frac{1}{k}, \qquad (11.1)$$

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where T_m is the time for machining one pass, in min;

L is the length of the cutter pass, equal to the length of a tooth plus the cut and the run (rated length), in mm;

z is the number of teeth of the sector (or wheel);

s_M is the feed per power stroke, in mm/min;

s_{ox} is the speed of backward motion of the table, in mm/min;

τ is the time needed for one turn of the sector (or wheel), in min;

k is the number of wheels (sectors) simultaneously set on the chucks (with the ends of the wheels touching).

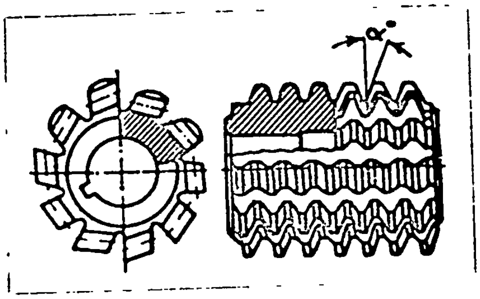

Fig.194 - Worm Cutter

The depth of cut is computed by the formula

$$y = \cos\varphi \sqrt{t(d-t)}, \qquad (11.2)$$

where y is the cut, in mm;

d is the diameter of the cutter, in mm;

t is the cutting depth, in mm;

φ is the angle of inclination of the tooth, in degrees.

In a case where a straight tooth is being cut, $\varphi = 0$.

Machining time when working with the rolling method is determined by the formula

$$T_m = \frac{Lz}{sni}, \qquad (11.3)$$

where T_m is the machine time for one pass, in min;

L is the length of the cutter pass, equal to the length of a tooth plus the cut and the run (rated length), in mm;

z is the number of teeth on the entire circumference;

s is the feed for one turn of the cutter, in mm;

n is the number of turns of the cutter, per minute;

i is the number of cutter settings.

The extent of the cut is computed by the formula

$$y=\cos\beta\sqrt{t(d-t)}+1{,}5\,\mathrm{tg}\,\beta(m\sqrt{z}+t), \qquad (11.4)$$

where t is the depth of milling, in mm;

d is the diameter of the cutter, in mm;

β is the angle of the cutter setting, in degrees;

m is the module of the wheel being cut, in mm;

z is the number of teeth of the wheel being cut.

In work done by the rolling method, greater productivity is reached, i. e., less time is spent on the return stroke and on turning the part in the process of cutting the teeth.

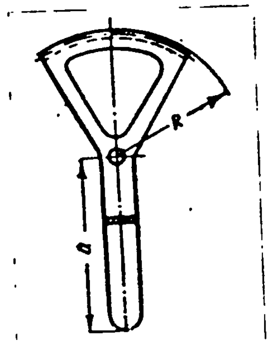

Fig. 195 - Design of a Sector Whose Teeth Cannot Be Cut by the Rolling Method

3) Less tools required. To cut a wheel of a definite module, only one worm cutter is required, regardless of the number of teeth of the wheel.

Despite the obvious advantages of the rolling method, the duplicating method must be employed in some cases of instrument construction, for example:

a) In cutting ratchet wheels;

b) In cutting sectors (rolling method may be uneconomical because of excessive idle motion);

c) In cutting teeth in special parts, where $a > R$ (Fig.195);

d) In cutting wheels with a small number of teeth.

Inspection of the sector after tooth cutting consists in checking the profile on a projector and measuring the outside radius of the segment by means of special gages (Fig.196).

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Cylindrical Gear Wheels

Let us examine the technological process for the production of the wheel depicted in Fig.197. Machining the blank on a lathe, preparatory to cutting of the teeth, is usually done on turret lathes or automatic lathes. The tooth cutting is done on machines operating on the rolling method. In tooth cutting, the blank of the wheel is set in the arbor and clamped by a nut or by the running center. To secure the necessary accuracy in the tooth cutting, the technological process must be so laid out that the preparatory operations, which precede the cutting, assure a sufficient degree of accuracy in the basing surfaces (in our case, the apertures and ends). As a rule the aperture must be machined to 2nd class accuracy. Arbors for gear-cutting machines are prepared on the go side of the operating gage, to assure seating of the blank with a minimum of clearance.

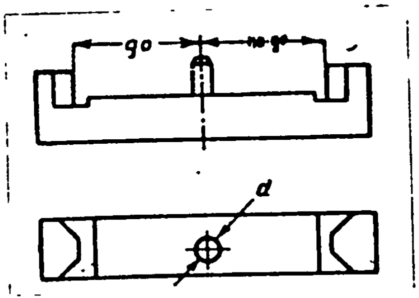

Fig.196 - Gage for Measuring the Outer Radius of a Sector

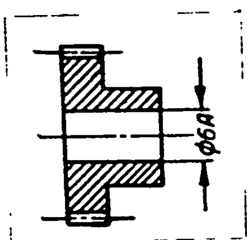

Fig.197

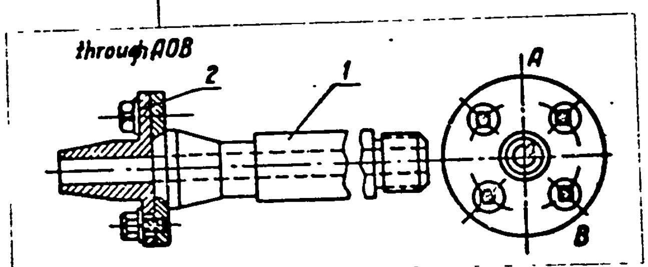

Fig.198 - Installation of (Adjustable) Arbor

In view of the high requirements for accuracy in the gear, a set of arbors is used. For example, if the gear wheel has a 6A aperture, three arbors are made, their working parts having the following dimensions;

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$$I — \phi\ 6_{-0.001};\ II — \phi\ 6{,}007_{-0.001};\ III — \phi\ 6{,}012_{-0.001}.$$

For this, the blanks into which teeth will be cut must be arranged into groups beforehand.

The accuracy of the gear cutting is also increased by the use of built-in arbors (Fig.198). The base of the arbor (1) is immovably fastened to the table of the machine. With the help of four bolts, the transition collar (2) is screwed to the base. The bolts pass through the apertures in the transition collar with a clearance, which permits the collar (2) to be displaced relative to the base (1). The collar position is checked with the help of the usual indicator gage.

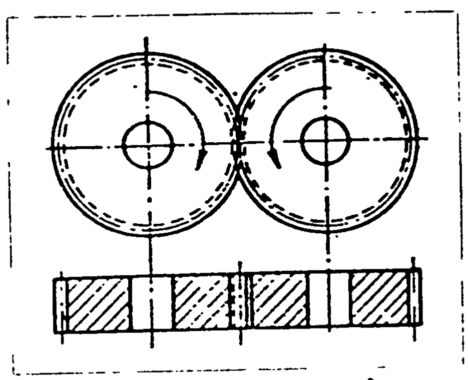

Fig.199 - Diagram of Running-in of Teeth

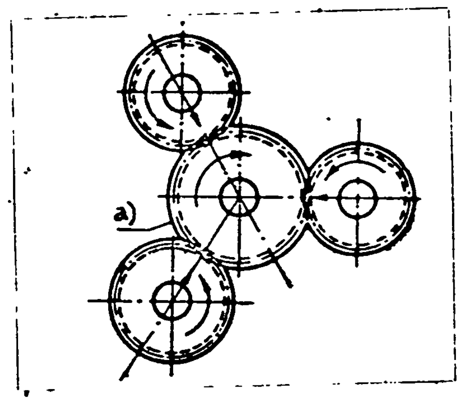

Fig.200 - Diagram of Generating of Teeth on the Blank with Three Standard Wheels

a) Blank

In cases where the above measures do not lead to the desired results, an additional operation is required, involving the machining of the aperture after the teeth have been cut. For this, we must provide a tolerance for machining the aperture, and must machine it in a special device.

The technology for machining of wheels with screw teeth differs little from that for machining of wheels with straight teeth. In cases where the teeth are cut with a disk gear cutter by the indexing method, the cutter is selected for a fictitious number of teeth in accordance with the formula

$$z_i = \frac{z}{\cos \alpha}, \qquad (11.5)$$

where z is the number of teeth of the wheel being cut;

z_i is the fictitious number of teeth;

α is the angle of inclination of the teeth.

If the teeth are being cut by the rolling method with a worm cutter, the angle of inclination of the cutter axis is defined as the algebraic sum of the angle of inclination of the cutter helix and the angle of inclination of a tooth relative to the axis of the gear wheel, i. e., when the direction of the helixes (on the wheel and on the cutter) is the same, the angles are added up; when it is different, the angle of inclination of the cutter helix is deducted from the angle of inclination of the wheel tooth.

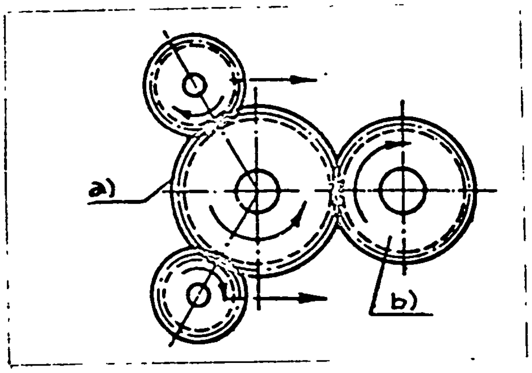

Fig.201 - Diagram of Generating of Teeth in the Blank with One Standard Wheel

a) Blank; b) Standard

In some cases, finishing operations are applied after cutting the teeth, in order to increase accuracy and smoothness.

Let us examine the basic finishing operations used in the execution of cylindrical toothed wheels.

Running-in. This method consists in placing two coupled gear wheels in a special device and making them revolve (Fig.199). With this method, no noticeable improvement in the quality of the tooth profile and smoothness is observed. This method does not provide for interchangeability of the parts of tooth gearings.

Generating. The generating method is distinguished from running-in by the fact

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that, in this case, the generating of the gear wheel which is being machined is done with three tempered standard wheels, executed with the greatest accuracy (Fig.200), or else with a standard wheel and two idler wheels which force the gear wheel against the standard (Fig.201). Under the influence of the pressure created between the standard and the blank (the gear wheel being machined), in the process of their rotation, the gear wheel is machined. This method is suitable only for non-dry gear wheels. The surface of the teeth after machining is noticeably improved.

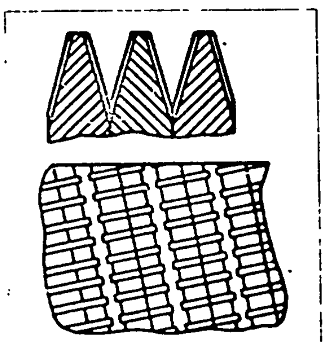

Fig.202 - Diagram of the Rack Shaver

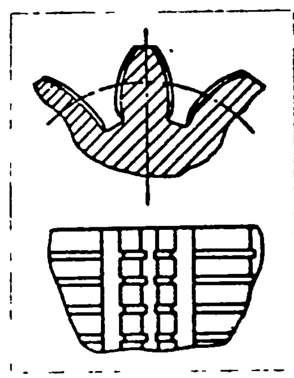

Fig.203 - Diagram of the Wheel Shaver

<u>Shaving</u>. To increase productivity and to obtain better quality in finishing the teeth, shaving is used.

The essence of finishing the teeth of non-dry gear wheels by shaving consists in scraping off a hair-thin chip from the side surface of the tooth with the help of a special tool (the shaver) which is designed in the form of a rack (Fig.202) or in the form of a toothed wheel (Fig.203). For finishing straight-toothed gear wheels, a rack with oblique teeth is used (Fig.204); for machining helical-toothed wheels, the teeth on the rack are straight. This is necessary to amplify the slipping motion of the teeth and to secure uniform wear of the teeth. The rack executes a reciprocating motion which revolves the wheel being machined, and the wheel is drawn onto the rack under some pressure. The wheel, during this process, is gradually shifted along its axis (for uniform wear of the rack). As a result of the intensified slipping motion of the coupled teeth, the cutting notches of the tool will scrape thin chips off the tooth surface being machined. The basic drawback of shaving is the complex design of the tool (the shaver).

The "Komsomolets" factory produces machines in which the cutting tool is a shaver representing a toothed wheel with transverse notches. In this case, the axes of the wheel being machined and of the shaver intersect (Fig.205). The process of cutting is analogous to that described above. The shaver revolves, while the wheel being machined moves horizontally (axial motion) and vertically to to insure its being drawn toward the shaver. As practice has shown, shaving done by this method can assure good surface finish and can provide the necessary accuracy: 8 microns in the profile, 8 microns in the pitch, 5 microns in the eccentricity.

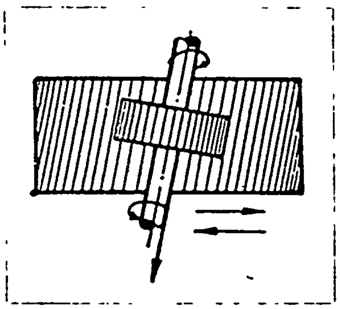

Fig.204 - Diagram of Operation of the Rack Shaver

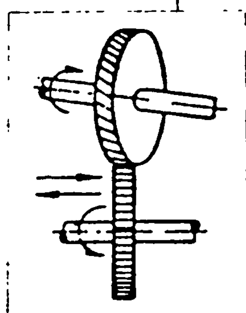

Fig.205 - Diagram of Operation of the Wheel Shaver

For shaving fine-module wheels, a special machine design is in existence, in which the axis of the round shaver and the axis of the wheel being machined are placed parallel to each other in a horizontal plane. The ZSh-1 machine (of NII MSP and MATI design) belongs to this type (see Bibl.1).

Lapping. The lapping method consists of machining the gear wheels by means of artificial intensified wear of the teeth, with the help of a lap (usually made of fine-grain cast iron) and an abrasive.

On "Komsomolets" machines (model 573) lapping is done in the following manner (Fig.206). The two laps (1) and (2) have helical teeth which, in touching the straight teeth of the wheel being machined (4), created a worm-type transmission which is conducive to uniform wear, profile-wise, of the teeth. The wheel revolves in engagement with three laps; the axes of the first two laps intersect in space with the axis of the wheel, while the axis of the third lap (3) is parallel to it. The wheel being machined, in addition to rotating, has a reciprocating motion. The laps are entrained toward the wheel under some pressure.

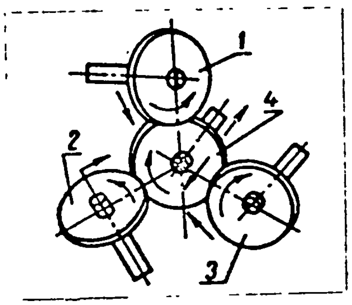

Fig.206 - Diagram of Tooth Lapping on a "Komsomolets"-type Machine

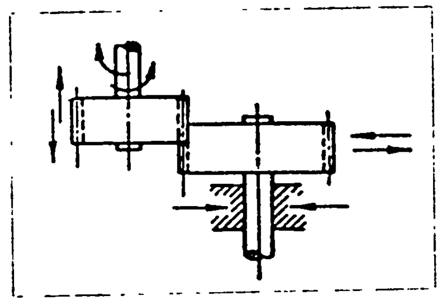

Fig.207 - Diagram of Tooth Lapping

In other machines (Fig.207), slow revolution of the lap and of the toothed wheel and rapid reciprocating motion of the lap (up and down) and of the wheel in a radial direction are used.

According to the data of experiments conducted in the ENIMS, lapping assures the following accuracy:

in wobbling . . . . 0.01 - 0.03 mm

in pitch . . . . 0.01 mm

in profile . . . . 0.005 - 0.010 mm

After lapping, the side surface is highly polished, with a mirror-like sheen; its quality is much superior to that of a ground surface. One drawback of lapping is the presence of abrasive grains on the surface of the teeth, which cannot be removed by washing and which cause premature wear of the teeth.

Grinding. The tooth-grinding method, in spite of many advantages (formation of a theoretically correct profile with great accuracy, high-quality surface finish), is not used in aircraft instrument construction in view of the fact that a great number of parts of aircraft instruments are made of nonferrous metals. In addition, because of the small modules and the small bulk of the gear wheels, this method is relatively unproductive.

Rolling of gear wheels. Recently, we have started using a new method for producing cylindrical gear wheels, namely a rolling process (Fig.208).

The blanks of the wheels being machined (1) are placed on the arbor a few at a time, and the arbor is mounted to the centers of a moving chuck (2). The index plate (3) is set on the same arbor. When the chuck is moved horizontally, the index plate engages the operating shafts (4), which, on further travel of the chuck, come into contact with the blank and perform the rolling process. The operating shafts are gear wheels with a corrected tooth profile and are equipped with a tapered intake at one end.

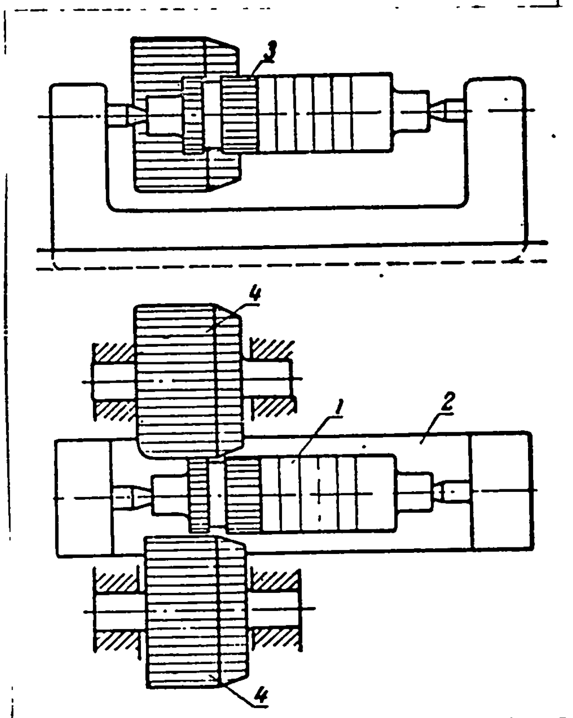

Fig.208 - Diagram for Tooth Production by the Rolling Method

The shafts are forced to rotate in one and the same direction and are spaced at a definite distance, corresponding to the dimensions of the wheel being machined.

The tooth-rolling method can be used in producing gear wheels with a module of 0.3 - 1 mm, including gear wheels of brass, bronze, hard aluminum, and steel. In the latter case, the blanks must be heated to t = 600 - 700°C.

The tooth-rolling method assures high productivity.

Bevel Gears

The production of blanks for cutting of teeth is analogous to the production of blanks for cylindrical gear wheels. Gear cutting is done on gear planers by the rolling method. On a machine of such type, gear planing is done by two cutters (Fig.209), simultaneously on both sides. The wheel being cut is constantly engaged with an imaginary flat wheel and, executing a rotary motion about the axis of the flat wheel, simultaneously rotates about its own axis. In this way, for each double swing of the "swing bolster", the tooth is machined on both sides (Fig.210). The time for machining the wheel is equal to the number of teeth of the wheel, multiplied by the time for one double swing of the "swing bolster" of the machine.

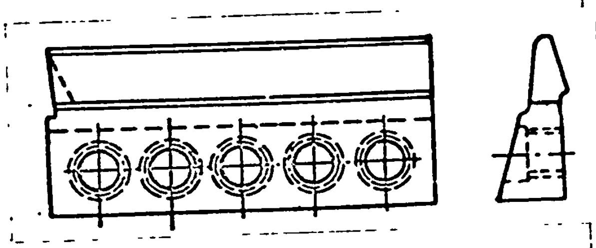

Fig.209 - Cutter for Cutting Teeth on a Bevel Wheel

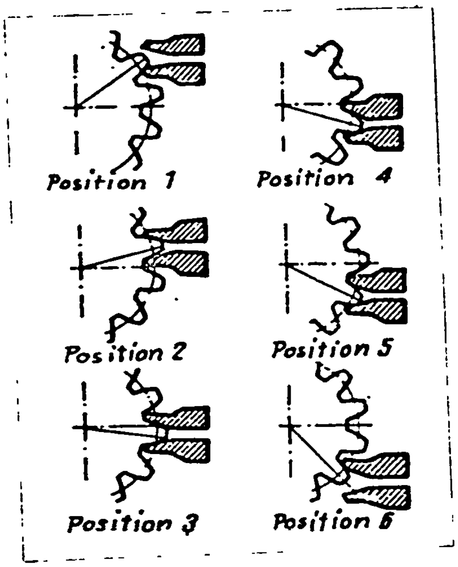

Fig.210 - Diagram of Machining of a Bevel Wheel on a Gear Planer

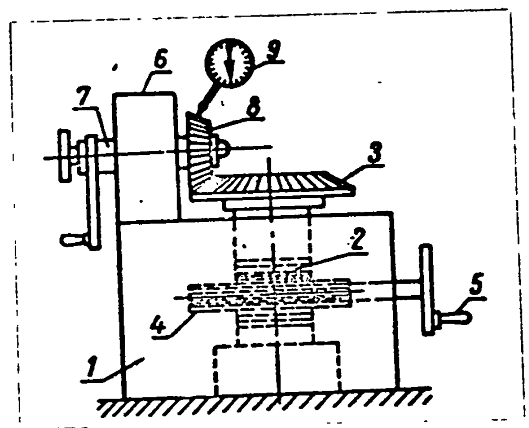

Fig.211 - Device for Checking Bevel Wheels

On the average, we can assume that the time for machining one tooth of a small-module wheel is 2 - 10 sec.

In bevel wheels, as in gear wheels, the chief elements determining the quality of the gearing are pitch, profile, and concentricity of the teeth.

In large-scale production, checking the gear wheel, meshing with standard wheels, is done on a special device (Fig.211). The arbor (2) whose center is provided with teeth forming a rack, is set in the body of the device (1). The rack meshes with a gear wheel (4) which, through the rotation of the flywheel (5) raises or lowers the arbor (2) and the standard gear wheel (3). The gear wheel (8) which is being checked is mounted on the shaft (7) in the stand (6). Holding the wheel (3) with one hand, we turn the wheel (8). The difference in the readings of the indicator dial (9) shows the amount of play in the side.

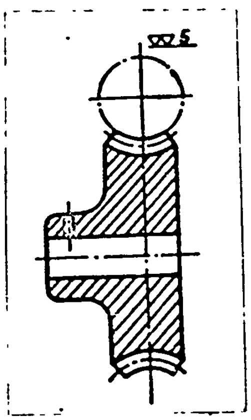

Fig.212

There are several other instruments in existence for checking bevel wheels (Bibl.2).

Worm Gears (Fig.212)

Blanks for tooth cutting are usually prepared on turret or turning lathes.

Gear cutting is done on gear-cutting machines which operate on the rolling principle.

Unlike the hobbing cutters used for cutting cylindrical gears, the profile of the hobbing cutter used for cutting worm gears must accurately correspond to the profile and dimensions of the worm, which must be coupled with the worm gear with allowance for additional play at the top of the thread. For this reason the outside diameter of the hobbing cutter is 0.32 module larger than the outside diameter of the worm. In this way, the overall height of the cutter tooth will be equal to 2.16 module. When the tooth has this height, the cutter will also remove a chip from the tops of the worm wheel teeth. This is done to keep the periphery of the worm wheel strictly concentric with its original circumference. This method is also often used for the parts discussed above (pinions, sectors, gears).

The machine time in cutting worm gears is computed in accordance with the formula

$$T_m = \frac{3mz}{sni}, \qquad (11.6)$$

where T_m is the machine time, in min;

m is the module of the wheel being cut;

z is the number of teeth of the wheel being cut;

s is the radial transmission, in mm, for one revolution of the wheel;

n is the rpm of the cutter;

i is the number of settings.

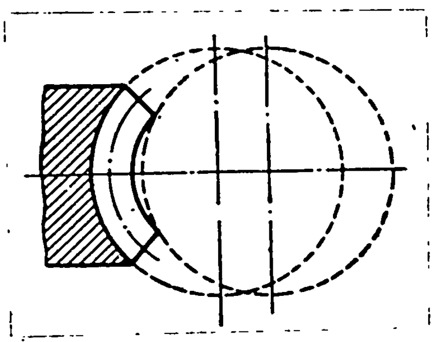

Fig.213 - Diagram of the Notching by a Hobbing Cutter

The cutter path during the machining of a worm gear is determined from the following data: The normal height of a tooth is equal to 2.166 m; the amount of notching done by the cutter, which in this case depends on the different curvature in the radii of the outside and inside diameters of the hobbing cutter (Fig.213), makes up 25% of the height of the tooth. Consequently, the length of the cutter path, counting the notching, is equal to 2.7 m. In addition, after the cutter has penetrated to the rated depth, when the radial transmission is disconnected, the worm gear being machined must be rotated through one or two full turns; then, the cutter path can be assumed as equal to ~3 m.

After gear cutting, the worm gears are checked for wobble and meshing. The accuracy of meshing is checked on special devices, by coupling the gear with a model worm.

Noncircular Gear Wheels

Noncircular (cylindrical) gear wheels are used for transmitting rotary motion between parallel axes with variable gear ratio. Until recently, no sufficiently reliable and simple methods for cutting teeth into noncircular wheels were available, which greatly interfered with their widespread use in instrument construction. By now, several methods for cutting noncircular gear wheels have been worked out (Bibl.3). Let us examine the method of cutting noncircular wheels on the "Linotype" machine (Fig.214). This method is used for producing wheels with a small module and short tooth lengths. The ring cutter (5), rotated by an electric motor, is used as the tool. The noncircular former (1) and the plane former (2) are linked by a steel band. By means of the handle (7), the noncircular former can rotate about its axis O_2O_2 and, together with the cleat (8), about the axis OO.

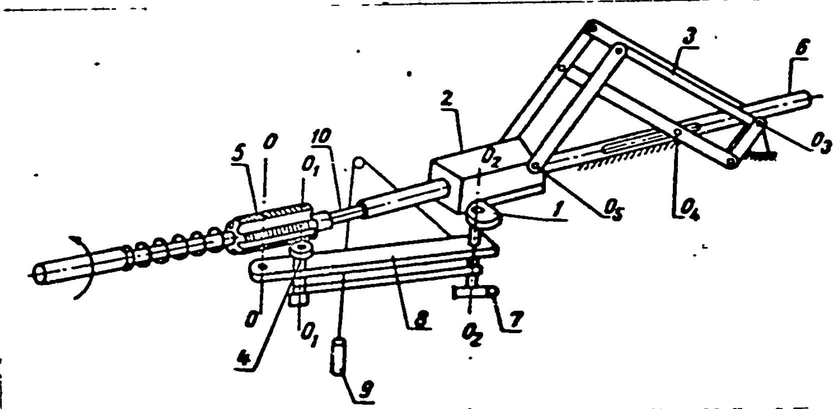

Fig.214 - Diagram of Machine for Cutting Teeth into Noncircular Gear Wheels

When the former (1) rotates, the steel tape unwinds, and the plane former (2) moves in the direction of the axis of the ring cutter (5). The counterpoise (9) ensures continuous contact of the formers (1) and (2). When the plane former (2) is moving, it entrains the axis O_5 of the pantograph (3). The stationary axis O_3 of the pantograph is mounted to the hollow shaft (6).

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When the former (2) is moving, by means of the axis O_4 of the pantograph, the axial displacements are transmitted to the shaft (10) of the ring cutter. The rate of displacement of this shaft to that of the plane former (2) is at the same ratio as the rates of displacement of the pantograph's arms O_3O_4 and O_3O_5. The former (1) is designed in accordance with the curve transformed according to the ratio of the wheel to the centroid (4). The transformed curve is obtained from the centroid, on multiplying the radii by the constant quantity M. The axes of the blank (4) and the former (2) are linked by a band and disks of different diameters. Consequently, when the former (1) rotates about the axis O_2, the blank (4) rotates about the axis O_1 with the same angular velocity. At the same time, the blank (4) rotates about the axis O, together with the cleat (8), so that

$$\frac{OO_2}{OO_1} = M.$$

The relative motion of the former (1) consists in rolling along the plane of the former (2). The relative motion of the wheel being cut must be a rolling motion, due to its centroid, along the genetrix of the dividing cylinder of the ring cutter.

3. Analysis for Accuracy in the Production of Toothed Gearings

Let us examine the basic errors in the production of toothed gearings.

Eccentricity in the Teeth

The error of eccentricity causes the gear wheel to rotate, in production, about one center while the mechanism works about another center whose distance from the first one is the amount of eccentricity. In addition to angular error, eccentricity in the wheel causes a pulsating noise with periodically decreasing and increasing intensity. This phenomenon is most typical of high-speed gear transmissions (for example, gear transmission of a tachometer).

Eccentricity in gear is caused by the following technological factors:

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a) Wobble in the arbor or the driving centers on which the gear wheel (pinion) is being cut;

b) Play between the fitting diameter of the arbor and the aperture in the wheel;

c) Deformation of the machine - part - tool flexible system, etc.

Example. In cutting a gear wheel on an arbor, determine the maximum possible amount of eccentricity produced by the presence of play between the fitting diameter of the arbor and the aperture in the wheel.

Given:

$$d_{arb}=2,8_{-0,004};\qquad d_{k}=2,8^{+0,01}.$$

It is quite obvious that the maximum amount of eccentricity is equal to one half the play:

$$e_{max}=\frac{s_{max}}{2},$$

where e is the eccentricity;

s_{max} is the maximum amount of play;

$$e_{max}=\frac{2,810-2,796}{2}=0,007.$$

It is evident from the example that the amount of eccentricity in the teeth can be diminished by:

a) More rigid tolerance along the inside diameter of the wheel blank;

b) Using a set of arbors;

c) More rigid tolerance for the production of arbors.

End Wobble

The error of end wobble of teeth results from the fact that the axis of the aperture at whose base the teeth are cut is not perpendicular to the support face of the arbor. This skewing may be the result of inaccuracies in the production of the wheel and arbor blanks.

Profile Error

In addition to angular error in the wheel, a profile error in the cutter teeth causes rapid wear and rough transmission. The basic technological causes of profile error are:

a) Theoretical errors inherent in the tooth cutting method;

b) Inaccuracy in execution of the cutter profile;

c) Wobble in the cutter;

d) Nonradial front face, etc.

Let us examine some of these errors in more detail.

In cutting with a module cutter, an error in profile may be caused by the fact that the cutter number does not correspond to the number of teeth on the wheel being cut. This error may be classified as theoretical, since it is the result of the intentional use of an approximated scheme of machining.

For calculating the maximum tooth-profile error when a set of cutters is used, it is convenient to use the data worked out by Cand. of Tech. Sci. V.A.Shishkov (Bibl.4).

Since, as a rule, only pinions with up to 20 or 22 teeth are cut by the duplicating method, we have given the values of coefficients up to that number.

z	12	13	14	15	16	17	18	19	20	21	22
Δ^r	0	18	35	55	70	84	97	110	122	133	142

The greatest profile error Δ^r (in microns) is determined according to the formula

$$\Delta^r = m(\Delta^r_{z_1} - \Delta^r_{z_2}), \tag{11.7}$$

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where m is the wheel module, in mm;

$\Delta^r_{z_1}$ is the tabular coefficient corresponding to the number of teeth of the wheel being cut;

$\Delta^r_{z_2}$ is the tabular coefficient corresponding to the number of teeth for which the cutter is accurately profiled.

An error due to inaccuracy in the module cutter profile is copied in full (with a reversed sign) on the teeth of the wheel being cut.

In first approximation, we can estimate that the probable total error Δ_r in the profile will be equal to

$$\Delta_\Sigma = \sqrt{(\Delta^r)^2 + (\delta f_i)^2}, \qquad (11.8)$$

where δ_{fi} is the tolerance for the profile of the cutter teeth.

We must note that irradiality in the front face will cause an additional error in the involute section of the tooth profile.

In cutting teeth with a hobbing cutter, theoretical errors result from the fact that the cutter-profiling process is interrupted. As a result, the profile of the tooth, in the end face, represents a broken line which osculates the theoretical involute curve.

The number of straight-line sections is equal to (Bibl.5)

$$\frac{\varepsilon k}{z_i},$$

where ε is the duration of meshing;

k is the number of cutter teeth;

z_i is the number of cutter settings.

The length of these sections (Fig.215) is equal to $\rho\psi$, where ρ is the radius of curvature at a given point of the ideal profile.

The limiting value is determined (Fig.216) as follows:

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$$y=\frac{\rho}{\cos\frac{\psi}{2}}-\rho,$$

where

$$\rho=r_0\,\mathrm{tg}\,\alpha_x.$$

Here it is assumed that, within the limits of the angle ψ, the curvature of the involute curve remains constant, i. e., ρ = const. This assumption results in a negligible error.

Expanding the value $\cos\frac{\psi}{2}$ into a series, and restricting the calculation to the zero and first members of the series, we will obtain

$$\cos\frac{\psi}{2}=1-\frac{\left(\frac{\psi}{2}\right)^2}{2}=1-\frac{\psi^2}{2}.$$

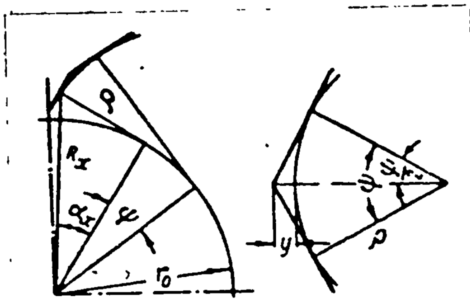

Fig.215

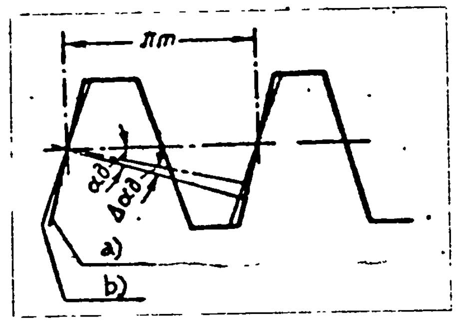

Fig.216

a) Theoretical profile; b) Actual profile

Substituting the value of the cosine into the formula for the height of the ridge, we will obtain

$$y=\frac{\rho}{1-\frac{\psi^2}{8}}-\rho=\frac{\psi^2}{8-\psi^2}\rho.$$

With an accuracy to within 0.02% we may assume that

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$$\frac{\psi^2}{8-\psi^2} \approx \frac{\psi^2}{8},$$

Then,

$$y = \frac{\psi^2 \rho}{8} = \frac{\pi^2 z_i^2}{2z^2 k^2}\rho. \qquad (11.9)$$

The maximum error will be along the circumference of the protusions. The value is

$$\rho_e = r_0 \operatorname{tg} \alpha_e = \frac{mz}{2} \cos \alpha_d \operatorname{tg} \alpha_e,$$

where the subscript e is the point of the profile lying on the circumference of the protusions.

Consequently,

$$y_e = \frac{\pi^2 z_i^2 m}{4zk^2} \cos \alpha_d \operatorname{tg} \alpha_e. \qquad (11.10)$$

In turn,

$$\cos \alpha_e = \frac{r_0}{R_e} = \frac{z \cos \alpha_d}{z+2}.$$

In the above equations, z is the number of teeth of the wheel being milled; α is the profile angle of the initial contour.

Wobble in the module and hobbing cutter also leads to distortion in the profile of the gear.

In the rolling method, as a result of wobble, the axis of rotation of the hobbing cutter will intersect the axis of its base cylinder. In this case, if there are no other inaccuracies in the tool, the cutting faces will be displaced from their correct position on the gearing line. Depending on the angle of rotation of the cutter, these displacements vary in accordance with the sine law. The extent of displacement (Δf) is determined by the formula

$$\Delta f = \Delta l_i \sin \alpha_d \sin \varphi_i,$$

where Δl_i is the parallel displacement of the axis of the base cylinder relative to the axis of rotation of the cutter;

φ_i is the angle of rotation of the cutter.

The displacement of the cutter varies within the limits

$$\Delta f_{max} = + \Delta l_i \sin \alpha_d \text{ and } \Delta f_{min} = - \Delta l_i \sin \alpha_d.$$

Consequently, the error in profile is equal to the algebraic difference

$$\delta f = \Delta f_{max} - \Delta f_{min} = 2 \Delta l_i \sin \alpha_d. \quad (11.11)$$

An error in the forming of teeth is caused by incorrect setting of the cutter and by end wobble of the cutter.

The correct setting of the cutter depends to a large extent on the experience of the adjuster. End wobble of the cutter depends chiefly on the accuracy of the cutter construction. For first-class hobbing cutters, the end wobble must not exceed 0.005 mm.

Pitch Error

Pitch error is mostly caused by kinematic inaccuracies in the machine. The accuracy of a machine working on the duplicating principle is determined by the accuracy of execution of the angular pitch of a dividing disk, by the concentricity of its fit on the spindle, and also by the wobble of the front drive center.

The accuracy in manufacturing the dividing disk should be such that the total error in the wheel being cut will be within the limits of 5 min on the full revolution of the wheel, and that the error in the individual pitch lies within the limits of 1 - 2 min.

In machines which operate on the rolling principle, the greatest inaccuracies

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are of the kinematic type which cause a disruption in the correlation of the magnitude of motion, or rate of motion, of the component links of a machine, i. e., a lack of coordination of the reciprocal movements of the parts of a machine. In the rolling method, the angular inaccuracy is 30 – 50".

Inaccuracies which depend on the rigidity of the machine have large magnitudes. Special research (e. g., see Bibl.5) has been devoted to establishing analytical dependences which express the effect of inaccuracy in individual parts of a machine on the accuracy of execution of the wheels being cut. We must note that, in the rolling method, any inaccuracy in the cutter profile causes a quite definite error in the pitch of the wheel being cut.

From Fig.216 it follows that the error in pitch of the wheel being cut will be equal to

$$\Delta t_e = \pi m [\cos \alpha_d - \cos(\alpha_d + \Delta\alpha_d)] \approx +\pi m \Delta\alpha_d \sin \alpha_d. \qquad (11.12)$$

In conclusion, let us note that in this Section only some basic technological causes of production error in machining were discussed. In addition, the technological process of assembly causes several other, no less important errors. These problems are examined below*.

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* See Chapter XVII, Technology of the Production of Special Parts, and Assembly of Instruments with Flexible Pickup Elements.

CHAPTER XVIII

TECHNOLOGY FOR THE PRODUCTION OF SPECIAL PARTS AND ASSEMBLY OF GYROSCOPIC INSTRUMENTS

1. General Principles

The most widespread gyroscopic aircraft instruments include the gyro turn indicator, the gyro horizon, the directional gyro and the gyromagnetic compass.

Gyroscopic instruments operate under difficult conditions; vibrations reach 80 cycles, with an amplitude of up to 0.15 mm; when the aircraft is landing, the instruments are subject to considerable impacts and jars; the temperature range at which an instrument must operate extends from +50 to -60°C.

The following requirements apply to gyroscopic instruments:

a) Accuracy of readings in rectilinear flight;

b) Stability in maneuvers of the aircraft;

c) Reliability in constant use.

2. Characteristics of Some Gyroscopic Instruments

The basic part of all gyroscopic instruments is a rapidly rotating rotor mounted on gimbals. Rotation of the rotor is accomplished pneumatically or electrically.

Pneumatic gyro instruments operate at a pressure variation of 40 – 50 mm Hg (gyro-turn-indicator) and 80 – 90 mm Hg (gyro horizon, gyromagnetic compass, automatic pilot). Depending upon what instrument is being used, the air consumption varies within considerably wide limits. For example, in some series-produced instruments the air consumption is 18 – 20 ltr/min for the gyro turn indicator, 40 – 60 ltr/min for the gyromagnetic compass, and 60 – 65 ltr/min for the gyro horizon.

The moment of inertia of the gyro rotor for each of these instruments is as follows: J = 0.6 gm-cm-sec^2 for the gyro turn indicator; J = 0.7 gm-cm-sec^2 for the directional gyro; J = 0.9 gm-cm-sec^2 for the gyro horizon, and J = 1 gm-cm-sec^2 for the gyromagnetic compass.

The rate of rotation of the gyro rotor is n = 6000 – 8000 rpm for the gyro turn indicator; n = 10,000 – 12,000 rpm for the directional gyro and the gyromagnetic compass; and n = 10,000 – 15,000 rpm for the gyro horizon. In electric gyroscopic instruments the rotor speed is as high as 23,000 or 23,500 rpm.

There are high requirements as to quality of the bearings of gyroscopic instruments. The moment of friction in the bearings of the gimbals of a gyro horizon must not exceed 0.3 – 0.5 gm-cm; in the directional gyro it must not exceed 0.2 – 0.3 gm-cm.

The dead angle in the instruments (gyro turn indicator, gyro horizon and gyromagnetic compass) must not exceed ±1°.

The rotor of gyroscopic instruments must be statically and dynamically well balanced.

The axes of the gimbal assembly must intersect in one point at a 90° angle.

The individual units of gyroscopic instruments must be balanced in relation to the axes of rotation of the instruments.

The housings and air ducts must be airtight.

In the case of electric gyroscopic instruments, special attention is given to the insulation resistance and to the reliability of current feed.

Accuracy of operation of gyroscopic instruments is largely determined by the quality of production of the gimbal assembly (coaxiality of the gimbal parts, minimum friction in the supports, and balance of units and parts relative to the axis of rotation). In the following, we will examine the technological processes for making the basic parts and units and for assembling the gyroscopic instruments.

3. Axles and Cups of Bearings

Accuracy of instrument readings and mechanical strength of the instrument depend to a large extent on the quality of manufacture axles and cups of the bearings. At overloads, the forces of inertia are absorbed directly by the instrument axles and ball bearings; for this reason, higher requirements as to resistance apply to these parts.

Tables 44 and 45 show several types of axles and cups for bearings of gyroscopic instruments as well as the corresponding requirements.

The basic indexes of the quality of axles and cups are:

1) Accuracy of dimensions;
2) Correctness of geometric form;
3) Smoothness of working and fitting surfaces;
4) Mechanical strength;
5) Basic structure of the material.

Brand ShKh15 steel is used as material for axles and cups.

The basic structure of ShKh15 steel must be fine-grain pearlite, with evenly distributed fine carbides. The structure must be uniform. When the structure is irregular, the mechanical strength of the working surface after heat-treatment will vary, resulting in rapid wear of the axles and cups. The permissible content of nonmetal elements and carbide liquations is indicated in the technological specifications. Carbide particles possess great hardness and brittleness (800 Brinell units). In the process of machining, the carbides may bloom to the working surface; like nonmetal elements, carbides stain easily, and like them, create centers of destruction in the working surface and increase friction. At uniform structure, the

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Table 44

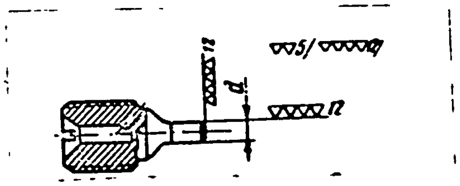
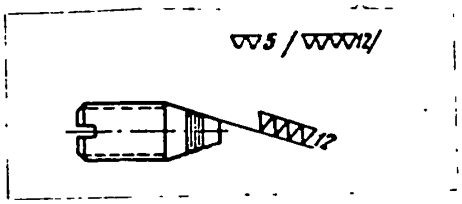
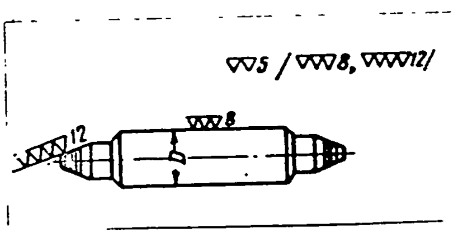
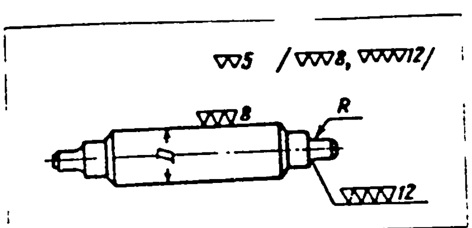
Axle	Basic Requirements
 Ground thread	1. Wobble in the thread relative to the surface d not more than 0.05 mm 2. Out-of-round of d, not more than 0.004 mm 3. End wobble, not more than 0.01 mm
 Ground thread	1. Wobble in the cone relative to the thread, not more than 0.05 2. Out-of-true of the cone, not more than 0.02 3. Tight thread
	1. Cone wobble relative to D, not more than 0.01 mm 2. Out-of-true of cone, not more than 0.003 mm
	1. Wobble of the ball race R relative to D, not more than 0.02 mm 2. Out-of-round of the profile of the ball race, not more than 0.003 mm

Table 44

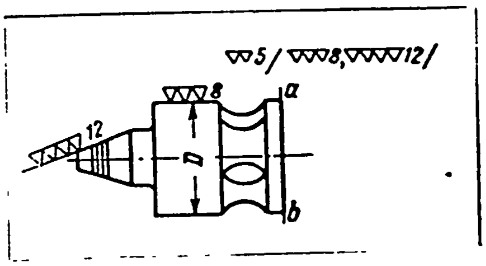
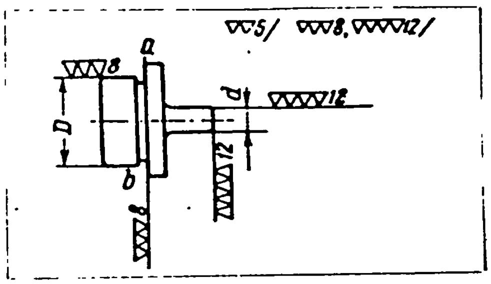
Axle	Basic Requirements
	1. End wobble ab relative to D, not more than 0.015 mm 2. Cone wobble relative to D, not more than 0.02 3. Out-of-true of the cone, not more than 0.02 mm
	1. Wobble of the surface d relative to the surface D, not more than 0.0012 mm 2. End wobble ab relative to d, not more than 0.01 mm

Table 45

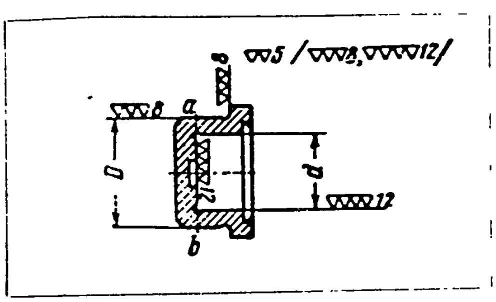
Cup	Basic Requirements
	1. Wobble of the surface d relative to the surface D, not more than 0.03 mm 2. Out-of-round of surface d, not more than 0.06 mm 3. End wobble ab relative to the axis of the part, not more than 0.015 mm

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Table 45

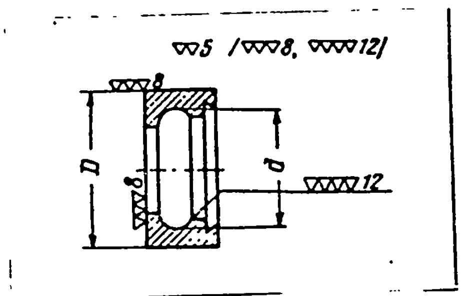
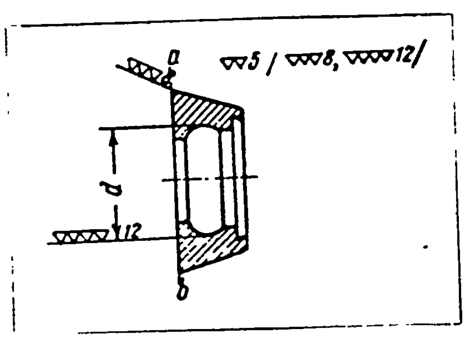
Cup	Basic Requirements
	1. Wobble of the surface d relative to D, not more than 0.006 mm 2. Out-of-round of the surface d, not more than 0.003 mm 3. Outer end wobble relative to D, not more than 0.01 mm 4. Side wobble of the surface d, not more than 0.025 mm 5. Taper of the surface D, not more than 0.003 mm
	1. Wobble of the surface d relative to the cone, not more than 0.015 mm 2. Out-of-round of the surface d, not more than 0.005 mm 3. End wobble ab relative to the cone, not more than 0.02 mm 4. Side wobble of the surface d, not more than 0.01 mm

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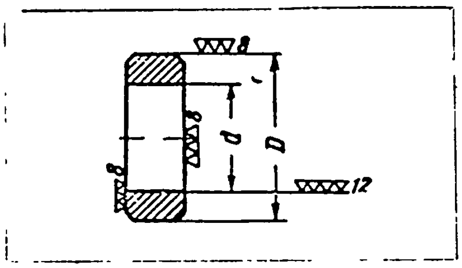
Table 45

Cup	Basic Requirements
	1. Wobble of the surface d relative to D, not more than 0.01 mm 2. Out-of-round of d, not more than 0.06 mm 3. End wobble relative to D, not more than 0.01 mm

hardness of the axles and cups should be 62 - 65 R_c.

The temperature of heating for hardening of ShKh 15 steel is 825 - 840°C, and quenching is done in oil. After hardening, the steel must be tempered to eliminate internal stresses. The best procedure for tempering is heating to 150°C with aging for 2 - 4 hrs.

To obtain stable dimensions and to eliminate waste due to deformation of axles and cups, artificial aging at a temperature of 125 - 130°C, with holding for 10 hrs is used.

In electric gyro instruments, bearings with inner races are used; for this reason axles for these instruments differ somewhat from axles for pneumatic instruments.

Table 46 lists several types of axles for electric gyroscopic instruments. The basic distinction between these axles and the axles examined above (see Table 44) lies in the fact that they do not touch the bearing balls but are joined to its internal ring. This group of axles is made from EZh4 steel and is not subjected to heat treatment. In electric gyroscopic instruments, the frames have thin walls, due to the absence of air ducts; for this reason, fixation of the axles, except for the diameter, is done also by the ends. In this connection, the base ends of the

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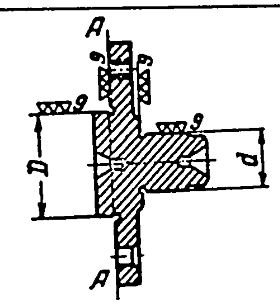
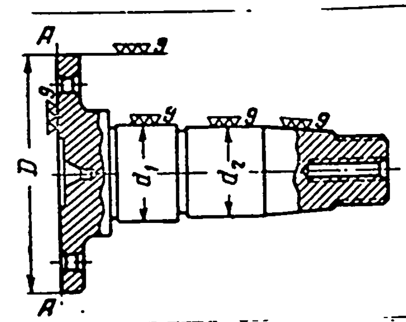
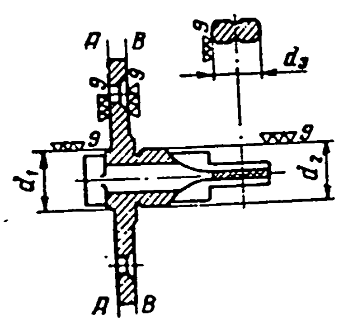
Table 46

Axles of Electric Instruments	Basic Requirements
	1. Wobble of the surface D relative to d, not more than 0.005 mm 2. End wobble AA relative to the axle, not more than 0.01 mm
	1. Wobble of the surface D relative to d_1, not more than 0.005 mm 2. Wobble of d_2 relative to d_1, not more than 0.1 mm 3. Wobble of the cone relative to d_1, not more than 0.01 mm 4. End wobble AA relative to the axle, not more than 0.01 mm
	1. Wobble of the surface d_1 relative to d_2, not more than 0.02 mm 2. Wobble of d_3 relative to d_2, not more than 0.04 mm 3. End wobble AA and BB relative to the axle, not more than 0.02 mm 4. Part surfaces in contact with wires must be coated with a layer of BF-4 adhesive

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axles must be strictly perpendicular to the geometric axis of the part. Since the working surfaces of these axles do not form raceways for the balls, somewhat lower requirements for smoothness in machining apply to them. Some axles have apertures for current leads. In this case, the axle surfaces in contact with the current leads, are coated with a layer of BF-4 adhesive, for better insulation.

Machining the Axle of the Gyro Rotor for Pneumatic Gyro Instruments

The axle of a gyro rotor is turned on turret lathes or on automatic horizontal lathes. After turning, the rotor is subjected to heat-treatment and then to grinding. The grinding must be done with special care; rough grain, burns, ellipticity, and conicity are not permissible.

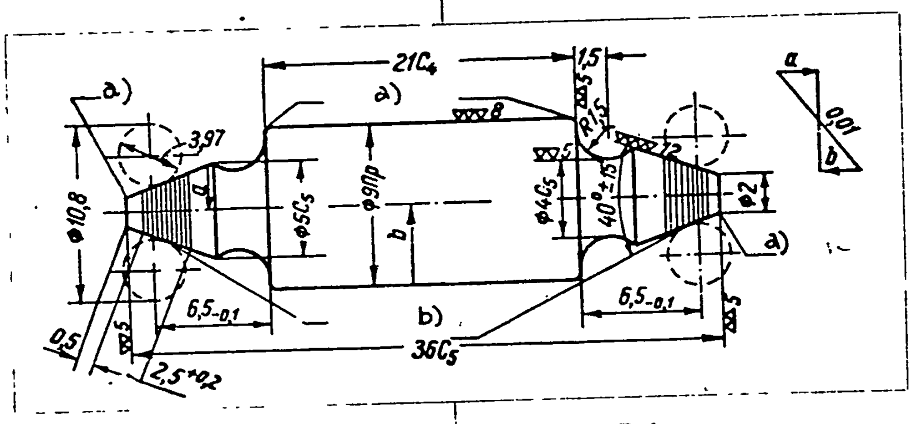

Fig.347 - Axle of the Gyro Rotor

a) Dull to RO.2; b) Finish to a glasslike surface

In grinding the cylindrical surface of an axle on a base of honed cones, the center of the back face must not touch the part at points of the raceway, which might result in damage to the parts.

Grinding the ends may be done on a circular grinding machine, or on a surface grinding machine. In the latter case, the process is considerably more productive, and no special devices are required.

To obtain the required surface smoothness of an axle cone, polishing is used. Polishing does not eliminate the inaccuracies in geometric form which had occurred in the previous machining process but only improves the smoothness of the surface. Polishing the axles is done on a drilling machine, with a special lap (Fig.348). The lap is made of brass; the working surfaces of the lap are clad with a layer of tin.

In polishing an axle, wobbling of the machine spindle must be avoided; the machine table must be perpendicular to the spindle. A reciprocating motion, within the limits of elasticity of the split end, is transmitted to the lap; at this, the rotational speed of the spindle is equal to 1400 - 1600 rpm. The polishing is done with GOI paste. After polishing, the surface should correspond to ∇∇∇∇ 12. Checking the surface is done on a Linnick microinterferometer. With it, the following defects can be discovered:

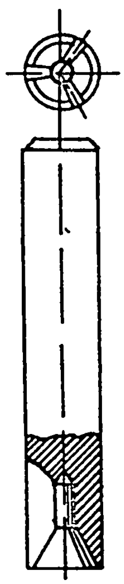

Fig.348 - Lap for the Gyro Rotor Axle

a) Scratches produced by dirt dropping into the paste;

b) Nonuniform width of polishing in the raceway, caused by noncoaxiality and skew of the lap;

c) Excessive undulation as a result of using a burnt, hardened abrasive.

After the final machining the parts should be lubricated with nonacid oil to protect them from corrosion.

Machining the Bearing Cup

Bearing cups are rolled (Fig.349) on turning or automatic turret lathes. Grinding the ends may be done on a lapping machine or on surface-grinding machines. For grinding along the outside diameter, centerless grinding machines are used, while internal grinding of the raceway is done on a special spherical grinding machine.

In grinding the raceway, the bearing cup is clamped in a special diaphragm chuck, shown in Fig.350.

The flange of the chuck body (1) carries the diaphragm (2) with three soldered bosses (3), to which three clamping cams (5) are fastened with the screws (4). By means of the rod (6) passing through the hollow spindle of the stock, the diaphragm can be bent; in this position, the cams will separate (see the lower projection in Fig.350), and the part to be machined can be easily inserted into the chuck. When the rod is pulled back, the diaphragm straightens, the cams make contact and clamp the cup being machined. The working surfaces of the cams of this chuck are ground after the chuck is placed on the machine, which results in concentricity of the race-way with respect to the outside diameter.

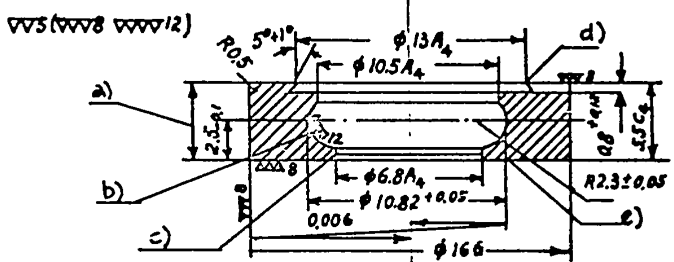

Fig.349 - The Bearing Cup

a) Polish; b) Finish to a glasslike surface; c) Facet 0.2 × 45°;

d) Dull to R = $0.1_{-0.02}$; e)Maximum end wobble relative to ϕ 16G

must be 0.01

The raceways in a bearing cup are polished on a lathe with the special lap illustrated in Fig.351. A tinned lap and 60' - 120' emery powder are used for preliminary polishing; machine oil is used as the lubricating fluid.

A palm lap and GOI paste are used for burnishing, with kerosene as lubricant. The profile of the raceway is checked from an impression, taken by pouring a fusible alloy into the raceway; the checking is done on a projector which enlarges 100 times.

4. Rotors

The rotor is one of the basic parts of gyroscopic instruments. In producing the rotor, extra care is required, since even insignificant imperfection in its balance generates an auxiliary centrifugal force which places a heavy load on the bearings.

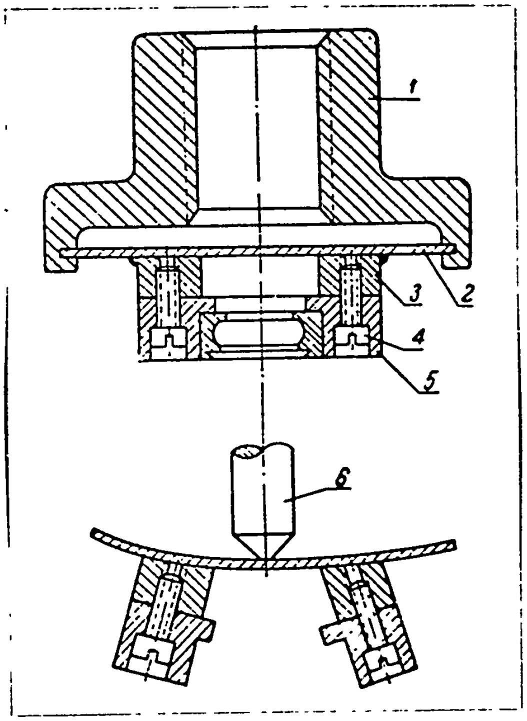

Fig.350 - Diaphragm Chuck for the Bearing Cup

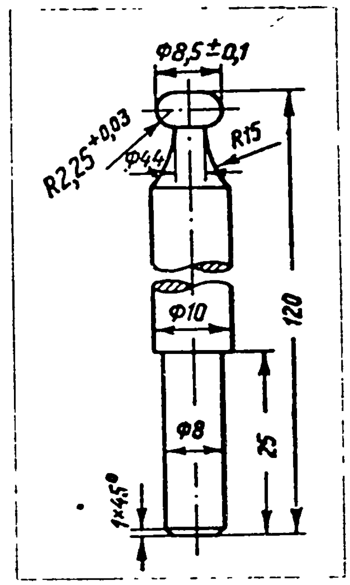

Fig.351 - Lap for Polishing the Bearing Cup

The material for the rotor must be uniform, without blowholes (a condition necessary for good balance), sufficiently tough to withstand the considerable centrifugal forces which develop at high rotational speeds, and resistant to corrosion; it must have a rather high specific gravity, to obtain a high moment of inertia despite small dimensions.

Rotors are usually made of LS59-1 brass, aluminium-nickel bronze, and stainless steel (the latter is rarely used, since it is difficult to machine).

Technological Process for Rotor Manufacture

LS59-1 steel is used in manufacturing rotors (Fig.352). The blank for the rotor is obtained by drop-forging.

To eliminate internal stresses which may subsequently cause warping of the rotor and lead to destruction of its balance, the forged blank is subjected to annealing, and then to etching and washing.

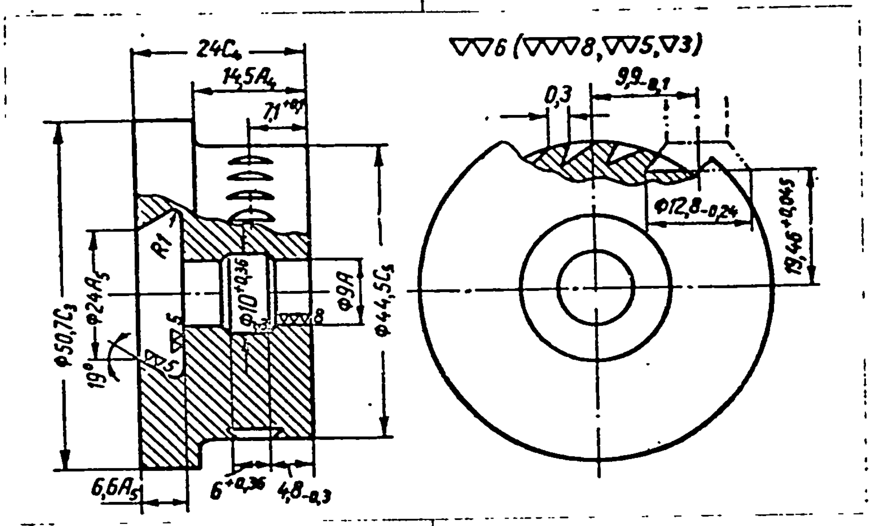

Fig.352 - The Rotor Viewed from the Axle

Machining the rotor on a lathe consists of three stages and is done to obtain minimum wobble of the outside diameter with respect to the inside diameter. In the first stage, the basic allowance is removed, and the aperture is drilled. In machining, the rotor blank is clamped in the usual three-cam chuck. In the second stage of machining, in order to obtain high concentricity, the part is clamped in special cams which are fastened on the usual cams of the chuck and are bored in situ. Clamping in such cams does not deform the part to be machined. The aperture is bored simultaneously with the external rolling, which ensures its concentricity.

To obtain the necessary accuracy and optimum surface smoothness of the aperture, the aperture is reamed. To prevent the reamer from breaking the aperture, the reamer is fastened in the chuck of the machine, while the rotor is held by hand and fed to the reamer. After this, the minimum allowance is ground off the external surface. The rolling is done on a precision lathe. In this case, the rotor is machined in one operation. The rotor is mounted to a smooth arbor. To prevent wobble of the arbor, it must be bored on the spot. Concentricity in the design of the rotor is checked in the centers with an indicator gage. After the final lathing, the holes are milled on a vertical milling machine, with a special cutter. In mounting the rotor to the arbor, the same base is used as in lathing, which process ensures concentricity in the distribution of the holes. The holes must have the same dimensions in depth and pitch, in order to avoid vibrations of the rotor when it is operating in the instrument. To obtain holes of the same dimensions, the cutter must rotate for three to five seconds without feed after the feed has stopped. In milling the holes, burrs are formed which are removed by rolling on the same machine and in the same arbor as in the final lathing.

After this, the remaining negligible burrs of the holes are removed with a scraper. This completes the machining of the rotor.

In transporting rotors, extreme care is required since even small scratches are difficult to smoothen, due to the fact that the allowances removed in the last lathing operation are negligible. For this reason, special packings with a separate compartment for each part should be provided for storing and transporting rotors.

After press-fitting the axle, the rotor may be nonconcentric relative to the working taper of the axle. For this reason, the rotor is again bored along the entire surface, after press-fitting of the axle.

Technology of the Rotor Construction

The above-described rotor is being replaced at present by a more perfect design in which the rotor is integral with its axle (Fig.353). The ends of this axle have cut-outs into which, during assembly, a ball is inserted which replaces the taper ends and raceway of the steel axle in the design of the first variant.

Such a rotor design results in great accuracy of balance and has several technological advantages: Assembly is simplified, since a spherical support is less sensitive to skews; repair is simplified, since all that is required is exchange of the ball; in machining, expensive operations for machining the taper ends of the rotor axle are eliminated. Thus, this kind of rotor is more economical to produce.

The technological process of manufacturing a rotor of the second variant does not differ in principle from manufacturing a rotor of the first variant; it is just that machining an aperture for the steel axle is replaced by machining the cone flanges. The basing in the final lathing is also simplified, since instead of a specially prepared arbor for each part, the machining is done in the centers. Producing a rotor of the second variant is more economical, since there is no need for a steel axle, for assembling it with the axle, or for boring the rotor after it has been shrink-fitted to the axle.

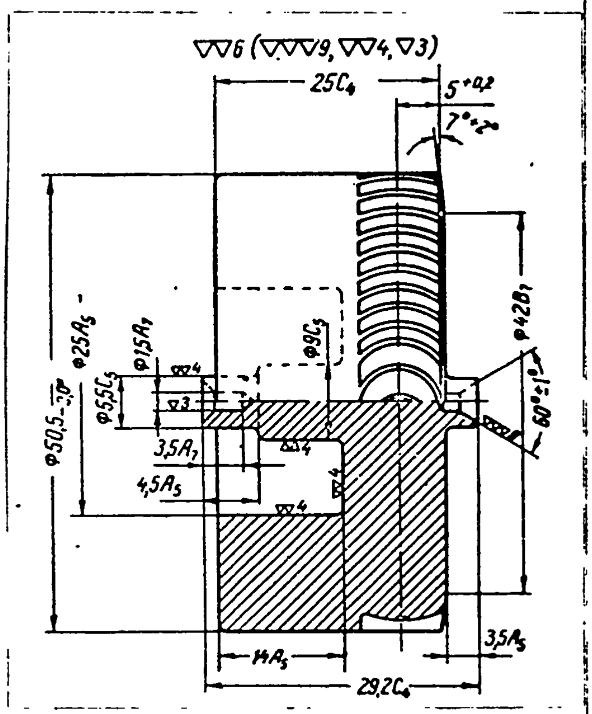

Fig.353 - The Rotor with Axle

To increase the rotor efficiency, the number of holes in the second variant is increased from 24 to 42, and their form is changed. The new form of the holes requires the use of special index heads (Fig.354). The index plate (2) with 42 divisions, and the worm wheel (3) with 42 teeth are mounted to the spindle (1) of the head. The housing (4) is mounted to the spindle by the index pin (5). The index pin (5) is moved away from the index plate (2) by the lever (6) and the handle (7). When the lever (6) rotates, the sliding bar (8) and the pawl (9) start moving; as soon as the index pin (5) is no longer engaged with the index plate, the worm wheel turns the spindle one division. When pressure is released from the handle, the spring (10) returns the sliding bar (8) and the pawl to their original position and at the same time, through the lever (6), acts on the index pin (5), forcing it against the index plate. During this, the housing (4) of the index pin rests on the stop (11).

The feed in this device is supplied by lifting the handle (7). This causes the housing (4) of the index pin, together with the spindle (since this is connected with it through the pin) to move away from the stop (11) and drop by the required angle, until the adjustable stop screw (12) rests against the stop (13).

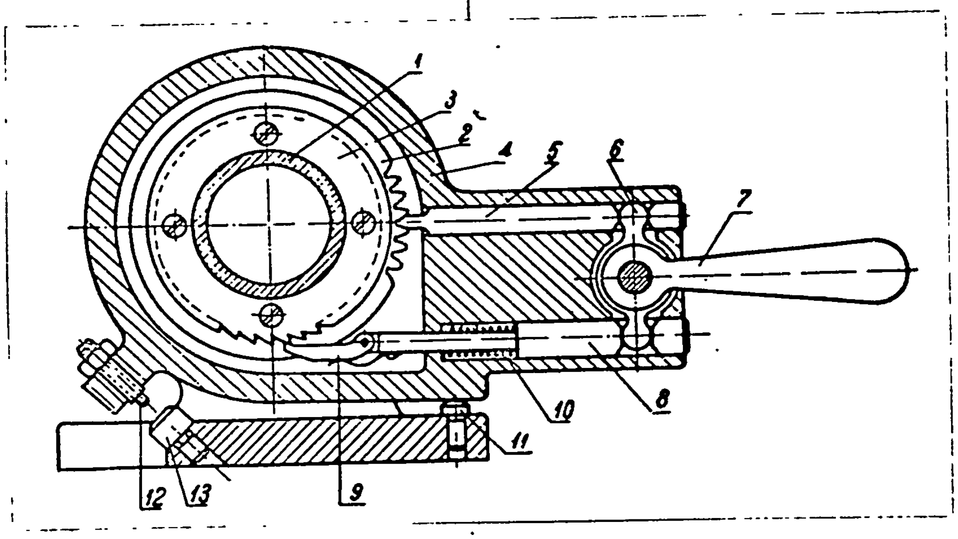

Fig.354 – Index Head for Milling the Holes of a Rotor

5. The Frames of the Gimbals

The frames of gyroscopic instruments must satisfy rigid requirements with respect to accuracy in the execution of the bores and in their distribution. Check tests must be made, after the frame has been machined, to determine whether

a) the two opposite bores are coaxial;

b) the two intersecting axes are located in one plane;

c) the two axes intersect at an angle of 90°;

d) the base ends are perpendicular to the basic axes of the frame (especially in the case of electric gyroscopic instruments).

In machining the frames of pneumatic instruments, we must provide for hermetic

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sealing of the internal air ducts, and there must be no blowholes or brittle spots in the material. This is obtained by preparing the blank of the frames by chill-casting or pressure-casting. (The frames of electric gyroscopic instruments need not satisfy any requirements as to hermetic seal.)

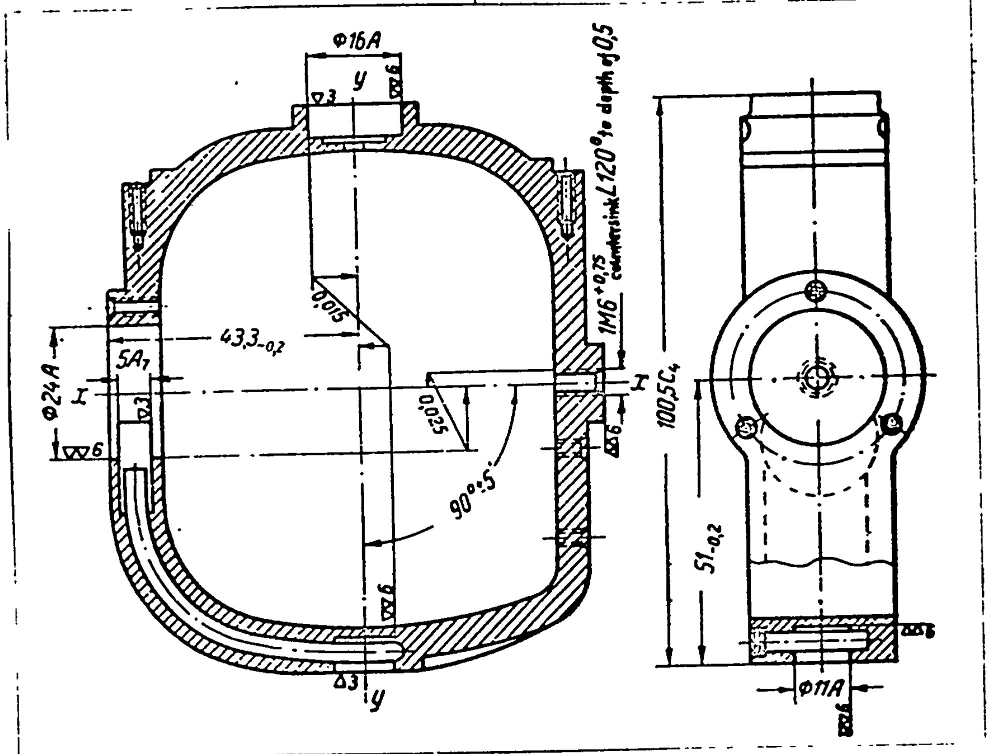

Fig.355 – Frame

Aluminium alloy is used in the production of the frames. AL6 and AL08 alloys are used for chill-casting; brand AL3 alloy is used for pressure-casting. Let us study the typical example of a technological process for producing the frames of the gyro horizon (Fig.355).

The blank of the frame is chill-cast, after which the cast gates are cut off. Aging is used to eliminate internal stresses. Internal stresses may cause warping of the frame and loss of the accuracy attained in machining.

After aging, the bores are subjected to preliminary drilling, which allows boring with a smaller set of instruments. Subsequent operations are: sandblasting, washing in gasoline, drying, and sealing the air duct with special gaskets. The gaskets are set in methanolic adhesive. This is followed by caulking the duct bead, and drying for 24 hrs. After completion, the frames are checked for hermetic seal under a pressure of 200 mm Hg.

One of the basic stages in machining a frame is the preparation of the base plane, in reference to which the holes will be bored. In machining the base plane, the frame clamped in the device must not undergo elastic deformations, since it may later straighten on removal of the clamping force, resulting in warping of the correctly machined base plane. Fixation and clamping to an uneven plane will cause the same phenomena in the boring of holes.

After preparing the base plane, the basic bores of the frame are made at a 90° angle. If the frame is subjected to elastic deformation under clamping, then even in accurately executed bores the accuracy will be canceled as a result of warping of the part after it is taken from the device.

Let us show on a typical example the inaccuracies which may occur when the frame is clamped incorrectly. In a device for milling a frame, the supporting surfaces AA of the frame and the direction of action of the clamping force P are shown schematically in Fig.356.

If we consider the frame as a beam supported freely at two points, the angle of rotation of the walls, in which the apertures are bored under the action of the applied load, may be determined from the formula

$$\varphi = \frac{PL^2}{16EI} \text{ radians},$$

where P is the clamping force;

L is the distance between the supports;

E is the modulus of elasticity;

I is the moment of inertia of the section.

The numerical value of this error may be judged from the following example:

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For simplicity of calculation, let us assume that the cross sections of the flexible walls of the frame are rectangular: b_1 = 6 mm and h = 25 mm in each wall, making in all, b = 12 mm and h = 25 mm. The clamping force is P = 200 kg; the distance between the supports is L = 100 mm. The modulus of elasticity for aluminum is taken as equal to $E = 72 \times 10^4$ kg/cm^2. Under these conditions,

$$I = \frac{bh^3}{12} = \frac{1{,}2 \cdot 2{,}5^3}{12} = 1{,}56 \ cm^4;$$

$$\varphi = \frac{PL^2}{16EI} = \frac{200 \cdot 10^2}{16 \cdot 72 \cdot 10^4 \cdot 1{,}56} = 0{,}001 \text{ radians},$$

which corresponds to 0.001 × 3438 = 3.438 ≈ 3.4 min.

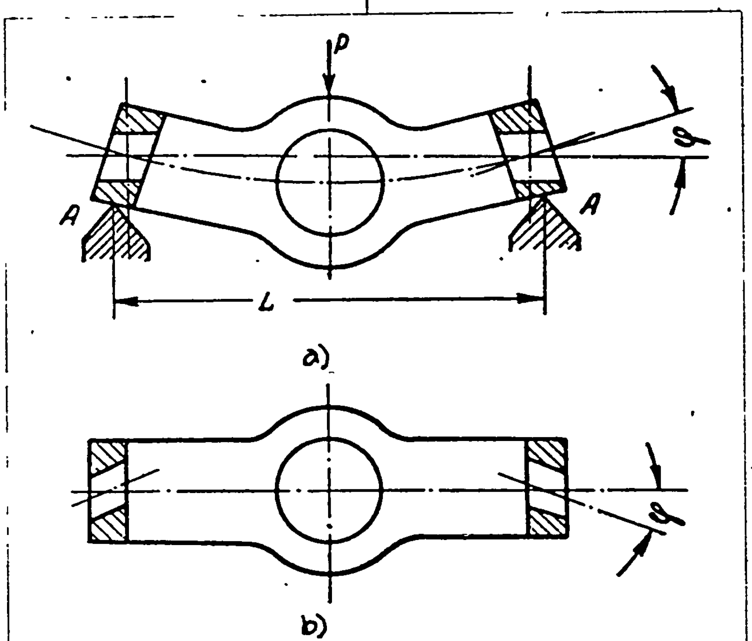

Fig. 356

a) Frame clamped on the device; b) Frame taken off the device

A skew of 3.4 min in a length of 50 mm will be 0.05 mm, while the permissible skew is 0.03 mm in a length of 50 mm.

Such an error in machining the bores in frames cannot be allowed; consequently, in devices for preparing the base plane and boring the apertures, moments of flexure from the clamping forces must be prevented from acting on the frame. This can be avoided if the action of the clamping force is directed against the supports.

Boring the holes in the frame is done on a universal milling machine or on an aggregate machine. In machining on a milling machine, the frame is attached to the table, and the replacement tools are inserted in the spindle of the machine. For undercutting the ends, a special arbor with knives is used. For boring the apertures we use a special chuck inserted in the spindle of the machine and carrying the boring cutter. This chuck provides for movement of the cutter in a radial direction, with the help of a micrometer screw. For preliminary machining of blind holes we use special end mills which, unlike drills, do not lead off the aperture; this is important to obtain an even allowance for final boring.

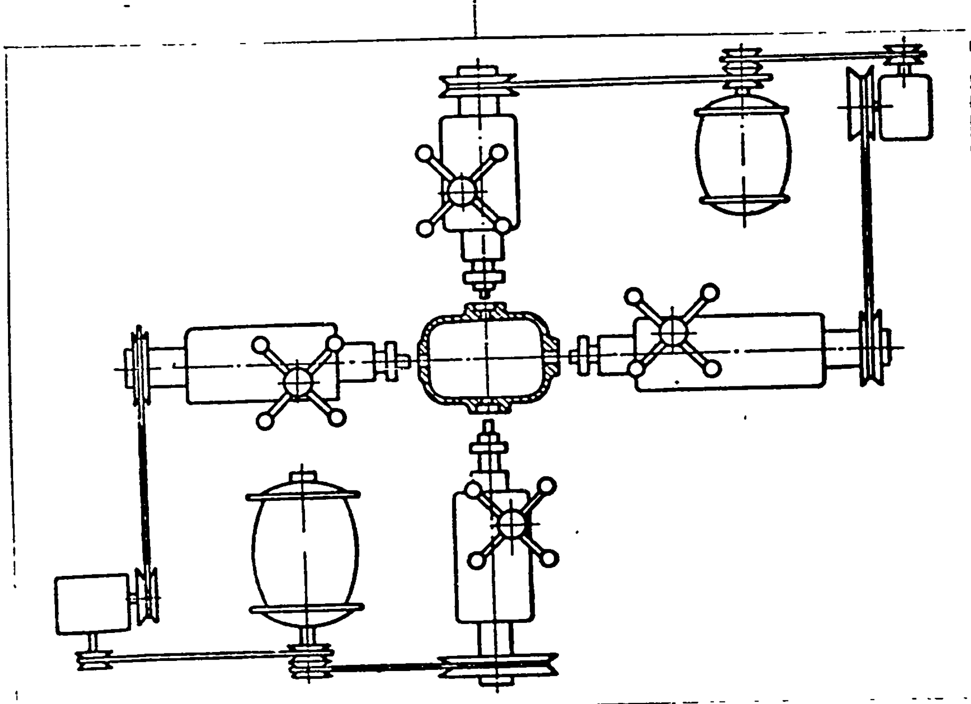

Fig.357 - Diagram of an Aggregate Machine for Boring Apertures in a Frame

Machining apertures in the frame of the gimbals on an aggregate machine is more productive than on a milling machine. A diagram of such a machine is shown in Fig.357. The machining is done in two operations from two settings. Advance of the

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tool is produced by each spindle in turn, since this operation is done by hand by a single worker.

Fixation of the frame in the second setting is done in accordance with the pre-bored apertures. Apertures in the frame of the gimbals may also be bored on semi-automatic machine groups, in this case feed for the power heads is supplied automatically. Correct distribution of the apertures is checked on special devices. The device simplest in design is the following: A special large frame with accurately placed apertures is prepared; the frame to be checked is placed inside this frame; through four pairs of apertures in both frames, plugs are inserted; if the apertures of these frames coincide these plugs should drop in readily. If a plug does not pass through a certain pair of apertures, the frame is rejected. A device of this type cannot check the distribution of the apertures within any definite tolerances, since this will be affected by the tolerances of the apertures themselves, by inaccuracy in the distribution of the apertures, and by elasticity of the frame. This method is not objective, since the plugs may be inserted with varying degrees of effort. The most perfect method of checking the distribution of apertures in the frame is with an indicator gage. To do this, we insert into the apertures of the frame special plugs with center apertures which are strictly concentric with the fitting diameters. There is a set of such plugs, down to 0.005 mm, for every aperture, which simplifies selection of the plugs according to the diameter of the aperture, which may vary within the limits of the tolerance. The selected plugs are inserted into the apertures in a tight fit. The coaxiality of two opposite apertures is checked by setting the frame, with the inserted plugs, on the centers (Fig.358).

Checking the perpendicularity of the axle apertures is done on vertical centers (Fig.359).

Correct distribution of axle apertures in one plane is checked in the following manner: Four plugs with the same size necks are inserted into the frame. The generatrixes of the necks of these plugs should lie in one plane; this is checked on a special plate, with which the necks of the plugs, with their generatrixes, should coincide.

The correct distribution of apertures in a frame should be checked with great care, but should be checked only once. When repeated measurements are taken, the plugs must be reinserted into the apertures. Measuring two or three times may bring the dimensions outside the limits of the tolerance, since the frame material is plastic so that the size of the aperture may easily enlarge.

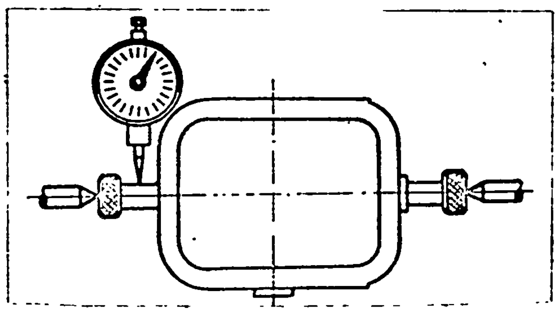

Fig.358 - Diagram for Checking the Coaxiality of Frames on Horizontal Centers

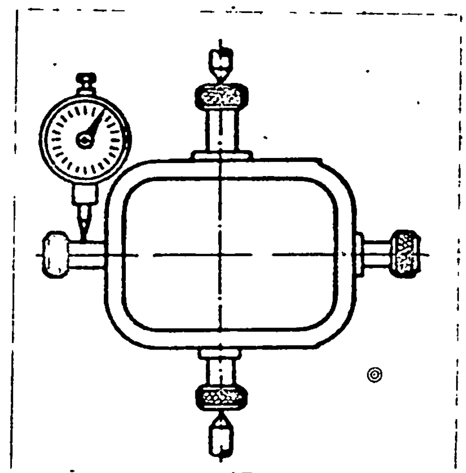

Fig.359 - Diagram for Checking the Perpendicularity of Axial Frames on Vertical Centers

Subsequent operations are: turning the bead to scale, which is done on the base of the bored apertures; drilling the apertures; threading; and milling the recess in the air duct from the bored aperture end. Threading for a center screw is done by hand, with a special tap having a guide which moves through a collar inserted in the opposite aperture.

After the final machining, the frame should be carefully cleaned of chip and washed in kerosene. No trace of chip or dirt must remain in the air ducts of the frames. In the process of operating an instrument, a chip may fall out of a duct and drop into the bearings, which will disrupt normal operation, cause additional

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friction, and early failure.

In the process of machining and in storing the frames prior to assembly, they should be kept in special packings to protect them from scratches and dust.

6. Assembly of the Bearing Unit

The ball bearings of gyroscopic instruments operate under difficult conditions; they are subject to vibration and impacts; the rotor rotates at a high rotational speed (up to 23,500 rpm); the temperature varies from +50 to -60°C. For these reasons, the bearings must meet rigid requirements as to accuracy of geometric dimensions, surface finish, hardness, minimum friction, failure-free operation over a guaranteed period, resistance to corrosion, and smooth running at high rotational speeds.

Two types of bearings are distinguished in gyroscopic instruments.

Bearings which provide for free rotation of the rotor relative to the principal axis of the gyroscope are called principal supports, while those which provide for free rotation of the gimbal suspension are called suspension supports. The rotor axle, resting on the principal supports, rotates at an angular velocity which is many times greater than the rotational speed of the outer and inner frames of the suspension.

This constitutes the basic difference between the principal supports and the suspension supports.

In setting the bearings in the instrument, proper clearance must be maintained. A large clearance in the bearings leads to a shift in the center of gravity, which causes precession. A small clearance causes an increase in friction. The moment of friction in the principal bearings has an effect only on the power consumed in rotating the rotor, while the moments of friction in the suspension bearings of a gyroscope cause precession of its axis.

Let us examine the effect on the stability of a gyroscope having a weight P and

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a horizontal axis, by a shift of its center of gravity along each axis of coordinate. A shift of the center of gravity along the vertical axis produces no moment. Conversely, a shift of the center of gravity along the horizontal axis, perpendicular to the principal axis of the gyroscope, generates a moment relative to the principal axis – a moment which will be absorbed by the outer ring of the gyroscope. In displacing the center of gravity along the principal axis of the gyroscope, directed horizontally, a moment equal to $\pm P_c$ and corresponding to the axial clearance $\pm c$ in the principal supports is produced; this causes a precession with an angular velocity of

$$\omega = \pm \frac{Pc}{I\Omega}. \qquad (18.1)$$

From this we may conclude that an axial clearance in the suspension supports of a gyroscope with a horizontal axis of rotation, from this point of view, is impermissible. However, for proper assembly such a clearance is necessary; therefore, it should be reduced to the minimum possible size, which is determined chiefly by the correlation between the temperature coefficients of linear expansion of the rotor body and axle. The principal supports of a gyroscope should have maximum accuracy, since the rotor rotates at high speed. When the shape of the principal bearings is distorted (skew, ellipticity, etc.), even an ideally balanced rotor will cause dynamic forces which may lead to failure of the instrument.

Thus the following requirements apply to the supports of a gyroscope:

a) Principal supports:

1) accuracy in execution;

2) minimum permissible axial clearance.

b) Suspension supports:

1) accuracy in execution;

2) minimum friction.

Ball bearings used in gyroscopic instruments are divided into three types according to their design:

1) Radial (built-in) bearings with a metal separator;

2) Magnetic (dismountable) bearings with a metal or a textolite separator;

3) "Thrust" bearings without inner ring and separator (the tapered axle which enters the bearing, or the ball which replaces this axle, directly touch the balls of the bearing itself).

Radial and magnetic ball bearings are widely used in electric gyroscopic instruments since, despite the fact that they have the same bulk as "thrust" bearings, they have a considerably larger inside diameter. This permits their use on hollow shafts of comparatively large diameter – axles or shafts accomodating current feeds.

Magnetic ball bearings may be taken apart and washed before final assembly of the instrument, and in the process of use; this is their advantage over radial ball bearings. For the principal supports we use ball bearings with a textolite separator, which ensures best lubrication; this is very important under conditions of high-speed rotation. For the gimbal supports, where it is important that friction be kept to a minimum, bearings with a metal separator are used.

The technology for producing the individual parts of a "step" bearing (axles and bearing cups) was examined above.

Balls for "thrust" ball bearings are obtained ready-made from the factories. ShKh 6 steel (OST 3426) serves as the material for the balls.

The dimensions and out-of-round of the balls are checked on a vertical telescope caliper. The surface smoothness is checked expediently on a microinterferometer. Pits, scratches, burrs, protuberances, blowholes, and traces of corrosion cannot be allowed.

The balls should have no uneven tempering or burnt spots. The hardness of the balls should be within the limits of 61 – 65 R_c. The quality of the balls is largely responsible for the service life. In storage, the balls should be lubricated with acid-free grease after preliminary washing, and should be packed in boxes lined

STAT

with oiled paper.

Balls which do not satisfy the specific requirements and which have an allowance are subjected to additional machining - honing on a lapping machine.

Smooth Running

The assembled bearing should provide smooth and even running, without jerks and starts, for the rotor and the gimbal rings. The bearings should cause no vibration of the gyro assembly and should not set up much noise in operation. The smooth running of the bearings is checked separately as well as in the gyro assembly. The bearing is calibrated with a standard gage inserted in a special frame together with the rotor. In the bearings the rotor should rotate smoothly and noiselessly. Poor quality of the bearing balls is determined by a characteristic sound caused by uneven running; when this is discovered the balls must be replaced.

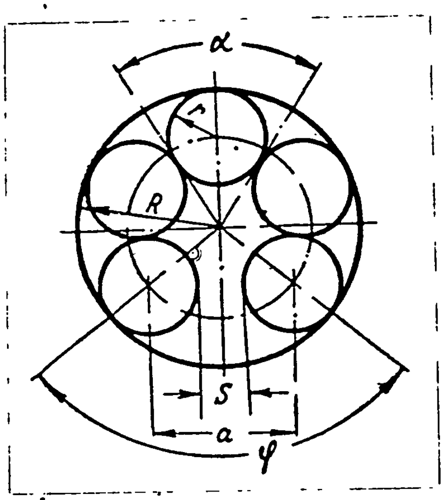

Fig.360

Minimum Friction

The moment of friction causes precession or sets up a zone of stagnation. For the suspension supports of pneumatic instruments, the moment of friction should not exceed 0.3 - 0.5 gm-cm; for the suspension supports of electric gyroscopic instruments, 0.5 - 0.7 gm-cm; and for principal supports, 0.6 - 0.9 gm-cm.

For normal operation of a "thrust" ball bearing there should be clearances along the raceway between the balls of the bearing. In these bearings, the sum of the intervals between the balls, when the latter are in contact with the raceway, is called the total clearance.

The total clearance may be determined from the geometric dimensions of the

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bearing. The schematic distribution of the balls is shown in Fig.360. We must find the interrelation of the values:

S, the total clearance between the balls in the bearing;

R, the radius of the bearing-cup raceway;

r, the radius of a ball;

n, the number of balls.

From Fig.360 it follows that

$$\sin\frac{\alpha}{2}=\frac{r}{R-r} \quad \text{or} \quad \alpha=2\arcsin\frac{r}{R-r};$$

$$(n-1)\alpha=2(n-1)\arcsin\frac{r}{R-r}.$$

Since

$$\varphi=2\pi-(n-1)\alpha,$$

then

$$\varphi=2\pi-2(n-1)\arcsin\frac{r}{R-r}$$

or

$$\frac{\varphi}{2}=\pi-(n-1)\arcsin\frac{r}{R-r}.$$

$$\frac{a}{2}=(R-r)\sin\frac{\varphi}{2}=(R-r)\sin\left[\pi-(n-1)\arcsin\frac{r}{R-r}\right]=$$

$$=(R-r)\sin\left[(n-1)\arcsin\frac{r}{R-r}\right].$$

Since

$$a=S+2r,$$

then

$$S=2(R-r)\sin\left[(n-1)\arcsin\frac{r}{R-r}\right]-2r$$

or (18.2)

$$S=2\left\{(R-r)\sin\left[(n-1)\arcsin\frac{r}{R-r}\right]-r\right\}.$$

By this formula we may also, in selective assembly, determine the dimensions of the balls for a given radius of the bearing-cup raceway or, on the other hand, determine the radius of the raceway for a given dimension of the balls, when the values of S are also given.

The amount of clearance is measured with a clearance gage.

The total clearance between the balls depends upon the dimensions of the balls and the diameter of the bearing-cup raceway. When the dimension chain is computed we may find that full interchangeability cannot be obtained in assembly. To provide for the required clearances, selective assembly should be used.

Before being set in the bearing, the balls are sorted into groups. The balls in a single bearing should be of the same size, with permissible deviations of 0.002 mm.

As research has shown, the moment of friction in bearings increases during a period of 25 - 50 hrs after the instrument starts to operate. If, after this period, the bearing is taken apart and washed, the moment of friction returns to its original value and does not increase during the subsequent operation of the instrument. This is explained by the fact that the balls run-in to the raceway, during which process a thin chip is removed; this fouls the bearing. For this reason, the bearings should be subjected to running-in before they are set in the instrument.

Checking the Moment of Friction in Ball Bearings

The moment of friction in "thrust" bearings is checked on the setup depicted in Fig.361*, by a method of checking the moment of displacement, i. e., the moment necessary to displace the lever which is set on the bearing.

The setup consists of a pedestal (1) on which the bearing (2) which is being checked is set. In the bearing is set an axle (3), to which is attached a lever (4). On one end, the lever carries a cup (5) which is acted upon by a stream of air; on the other end is a counterpoise (6), to maintain equilibrium. The stream of air is released from the mains by gradually opening the valve (7), until the pressure of

~~* The setup was proposed by Eng. S.A.Kondratyuk.~~

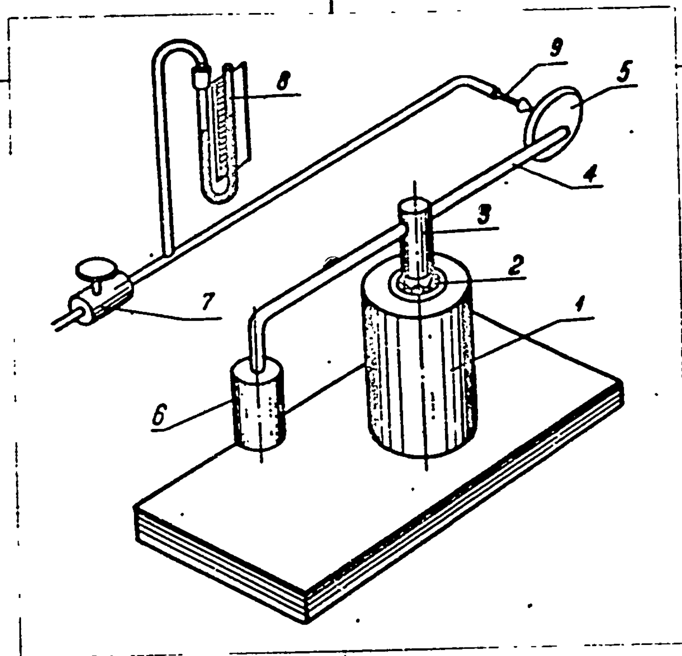

Fig.361 - Schematic Drawing of the Setup for Checking the Moment of Friction in Thrust Bearings. Constructed by Eng. S.A.Kondratyuk

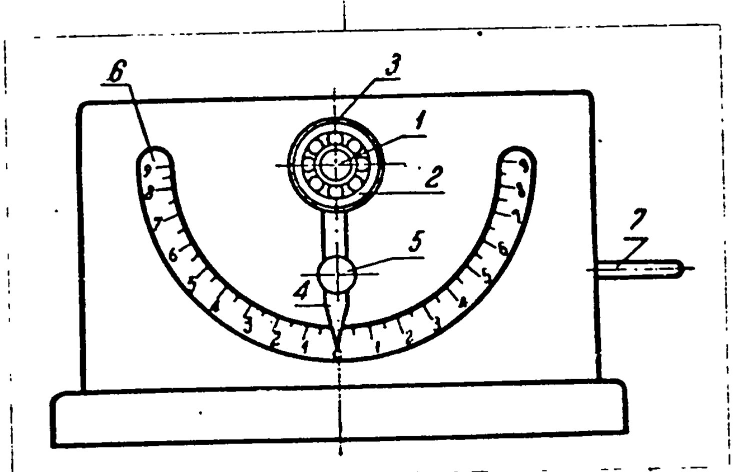

Fig.362 - Setup for Checking the Moment of Friction in Bearings

the air issuing from the nozzle (9) overcomes the moment of friction and makes the lever (4) rotate. At that moment, a computation is made from a water gage (8), which is calibrated directly in units of the moment of friction.

The moment of friction in built-in bearings is checked on the setup depicted in Fig.362. This method of checking has been adopted in ball-bearing factories and is called checking by the angle of deviation.

The setup consists of an electric motor with reduction gear, which rotates the spindle (1) at a speed of 20 rpm. By means of a change-over mandrel, the bearing (2) is fitted tightly onto the spindle by means of the internal ring. By means of the spring-filled lathe dog (3), the pointer (4) with the weight (5) is fitted to the outer ring of the ball bearing. The pointer moves across the scale (6) which is divided into degrees. As the spindle is made to rotate, the pointer and weight are entrained by the outer ring of the bearing until the moment of friction in the bearing balances the moment set up by the weight. The rotation of the spindle may be reversed by means of the lever (7), which permits checking the moment of friction in both directions.

If we know the magnitude of the weight G, the radius r at which it is placed, and the angle of deviation α calculated from the pointer position on the scale, it is easy to determine the moment of friction

$$M_{fr} = Gr \sin \alpha. \qquad (18.3)$$

Lubrication of the Bearings

When the rotor bearings are insufficiently lubricated, its operating surfaces wear rapidly, and when operating in a humid medium, corrosion takes place. When the lubrication is excessive, the number of revolutions of the gyrowheel is reduced whenever the instrument operates at low temperatures (freezing weather), due to a sharp rise in the viscosity of the oil (the lubricant thickens and increases the

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friction).

Special types of oil are used for lubricating the bearings. The specific gravity of the oil is 0.868 – 0.875. The pour point is -57°C. When t = 50°C, the viscosity is equal to 1.5° Engler.

The oil should be clean and transparent. Two or three drops of oil from a small eye-dropper are put on each bearing.

The felt stuffing boxes, installed into the bearings are soaked to saturation with oil.

As research has shown, lubrication of ball bearings in the supports of the gimbal suspension increases the friction, especially at low temperatures. For this reason, the use of lubricants for the supports of the gimbals is justified only by the necessity of protecting the supports from corrosion.

A ball bearing installed in an instrument should be demagnetized, since magnetic forces will increase the friction.

Ball bearings which have been lubricated with oil should be kept in closed jars. Before assembly, all parts of the bearing are washed in gasoline and re-lubricated.

The service life of the bearings of gyroscopic instruments is about 320 – 350 hrs.

7. Assembly of the Gyroscope Unit

Let us discuss the assembly of the gyroscope unit, using the assembly of a gyro horizon as example (Fig.363).

The process of assembly starts with assembling the housing of the rotor (1) with plugs which close off the apertures in the external wall, apertures which are necessary for the nozzle cut-outs.

The plugs are set into nitrocellulose adhesive; the adhesive must be prevented from flowing into the nozzle apertures. A check is made by measuring the air consumption; the amount of air, according to technical specifications, is between 49 and

55 ltr/min on the unit when there is a pressure variation of 90 mm Hg. In checking, the housing is clamped endwise to a rubber gasket. The plugs are sawed on the out-

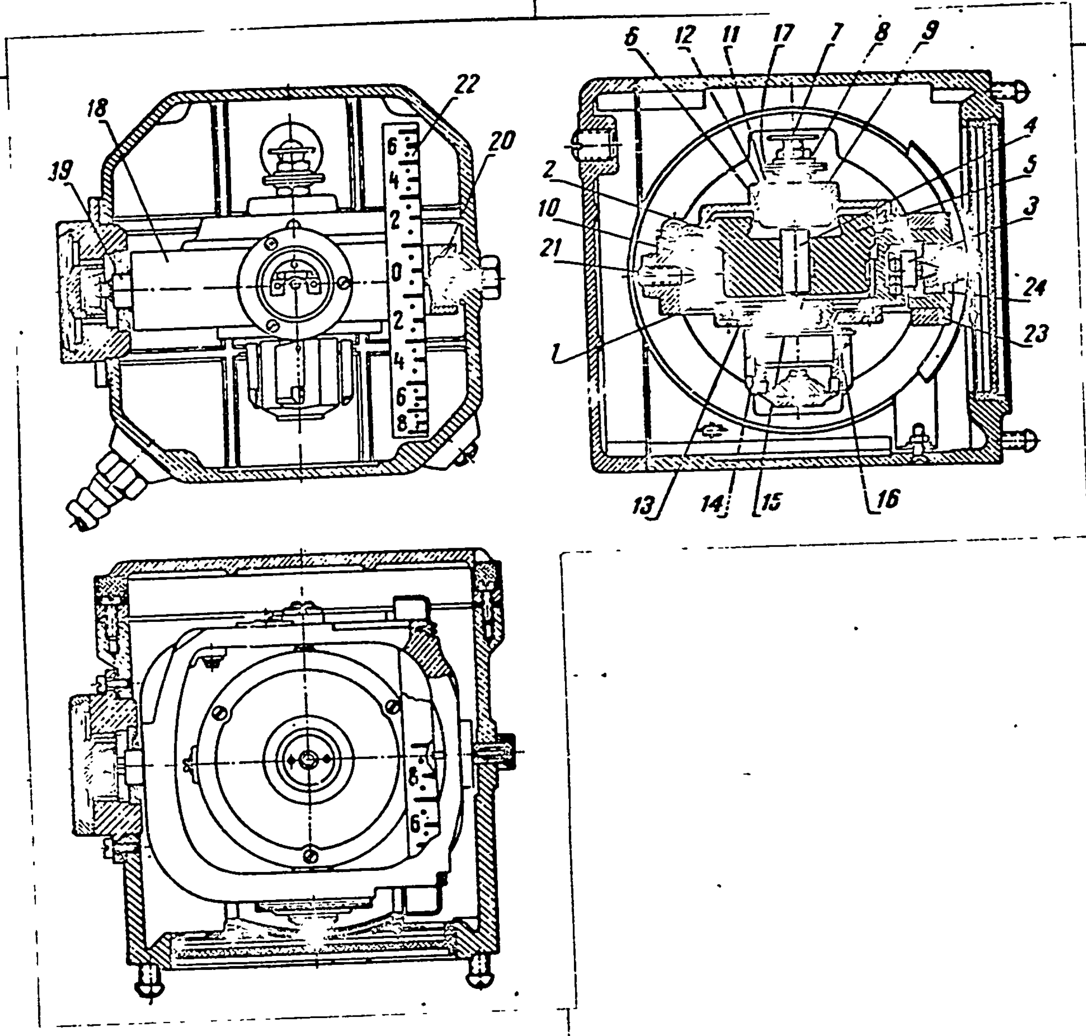

Fig.363 - Overall View of a Gyro Horizon

1 - Rotor housing; 2 - Cover; 3,4 - Axles; 5 - Rotor; 6 - Step bearing; 7 - Balancing screw; 8 - Cover; 9 - Spring washer; 10 - Bearing cup; 11 - Gaskets; 12 - Felt washer; 13 - Housing of stabilizer; 14 - Shutters; 15 - Shutter axles; 16 - Gaskets; 17 - Weight; 18 - Frame; 19 - Axle; 20 - Bearing cup; 21 - Axle screw; 22 - Scale; 23 - Gaskets; 24 - Frame plug

side and cleaned underneath, together with the rotor housing. The next step is lap-

STAT

ping the lower end of the housing on a special cast-iron rotating disk, and lapping the upper end on a cast-iron plate. After this, the housing unit is washed in gasoline and dried.

Assembling the rotor housing (1) with the cover (2) is done by the selective method. The cover should go into the housing without any play, and should closely adjoin the ends. If a clear gap is detected between the ends, additional lapping is necessary. Once they are selected, the rotor housing and the cover are marked, the screws are backed off, and filed from the outside in. The air consumption is checked under the same conditions as in the preceding operation. Press fitting of the axle (3) of the rotor housing is done on a special device. Before press fitting, the aperture and the air duct must be carefully cleaned and blown out with compressed air. The strength of the shrink fit is checked on a special device by applying a torque of 25 kg-cm; the axle should not revolve under this force.

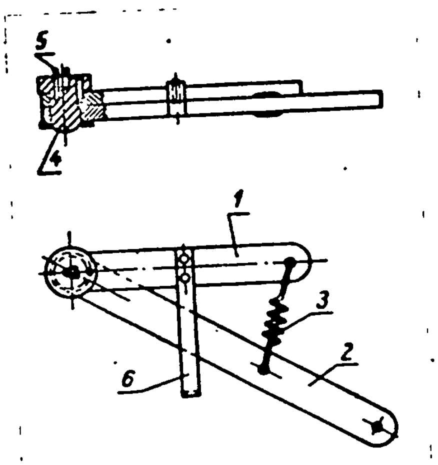

Fig.364 - Device for Checking the Strength of the Shrink Fit of the Rotor Axle Housing

The device for checking the strength of press fitting (Fig.364) consists of two levers (1) and (2), hinge-joined by means of a spring (3). The collar (4) of the device has an aperture by which it is centered along the axle. The collar contains joint pins (5) which drop into the apertures of the axle for passage of air; by these the device is connected with the axle. The long lever (2) sits freely on the collar, while the short lever (1) is rigidly connected with the collar. In checking, the long lever pivots to the support (6); it stretches the spring (3) and through the short lever sets up the necessary torque on the collar.

The accuracy of the press fit is checked with an indicator gage, by turning the rotor housing on the base of the cone of the axle and the opposite aperture under the bearing. The indicator gage, placed along the diameter of the axle, should not show a deviation of more than 0.015 mm. If this is not the case, straightening is required, with a subsequent check of the torque. The air consumption is checked under the same conditions as in the preceding operations.

Shrink fitting the axle (4) to the rotor (5) (Fig.363) is done on a hand press; then the rotor is rolled on all sides in order to eliminate any eccentricity which might occur in the process of press fitting. The operation is done in the back centers which are generously lubricated with grease. After the rotor has been machined, the cones are checked through a magnifying glass which enlarges thirty times; after this we proceed to balancing of the rotor.

Balancing the Rotor

In the production of the rotor, some eccentricity relative to the axis of rotation is unavoidable; in assembling the rotor with the axle, this eccentricity may increase still more, as a result of the eccentricity of the axle itself.

When the rotational speed is high, an unbalanced rotor causes considerable dynamic reactions in the bearings and leads to early failure of the latter.

Apart from eccentricity, nonuniformity of the material also causes unbalance of the rotor.

When the rotor rotates, unbalance will cause vibration. Apart from improper balance of the rotor itself, vibration may result from axial and radial wobble of the bearings, gaps, different diameters of the balls, a skew in the bearing cups, inaccuracy and roughness of the working surfaces, and the like. Axial wobble of the supports causes a reciprocating motion of the rotor along its axis; this sets up dynamic reactions in an axial direction.

Radial wobble causes dynamic reactions, just as a statically unbalanced rotor does. Radial gaps lead to a shift in the center of gravity.

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Different dimensions of the balls and inaccuracy of the working surfaces (out-of-true, granular raceways of the bearing cups and grain formation on the working surfaces of the rotor axle) lead to a shift of the geometric axis of the rotor and cause dynamic reactions. Dynamic reactions may also result from a deformation in the rotor axle, a defect in the power supply for the gyroscope unit, a change in temperature conditions, and wear of the supports during operation.

The greatest dynamic reactions caused by improper balance of the rotor vary, in the selected radial direction, in accordance with a harmonic law. This basic dynamic reaction is superposed by oscillations, differing in amplitude, frequency, and phase, which produced by the numerous causes mentioned above.

Balancing is divided into static balancing and dynamic balancing. Static balancing is present when the rotor is not rotating; its aim is to bring the rotor into indifferent equilibrium, relative to its axis of rotation. Static balancing is present in devices with bearings into which the rotor is set. The bearings may be ball bearings (the same kind as in the instrument) or knife bearings, which are used for a rotor with a pressed-steel axle.

To determine unbalance in static balance, the rotor is inserted in the bearings of the device, and the working clearances of these bearings are checked. An unbalanced rotor will tip downward with that part of the rim on which there is an excess of material. For correction, a small plasticine ball is pressed on the upper part of the rim. The size of the ball is selected from calculations intended to bring the rotor into a state of indifferent equilibrium.

After this, a hole is drilled into the rim of the gyrowheel in a spot opposite the place where the ball was added. The hole is so calculated that the reduction in the moment of force due to the weight of the removed material corresponds to the moment set up by the weight of the plasticine ball. Then, after the ball has been removed, the rotor is again placed into the device, and the balancing is checked; if there is insufficient equilibrium, the balancing is rechecked. It is important to

STAT

369

have as few holes as possible on the rim of the rotor, since they increase the air friction on the rotor.

Static balancing cannot fully eliminate unbalance of the rotor due to the moment of friction M_{fr} in the bearings of the device; because of this, it is impossible to define the moment developed by unbalance of the rotor $M_{unb} \leq M_{fr}$.

Let us assume that the moment of friction M_{fr} in the bearings in which the rotor was balanced is equal to 0.3 gm-cm. This does not allow determination of the moment of unbalance $M_{unb} \leq 0.3$ gm-cm. Let us determine what eccentricity e the moment of unbalance will correspond to if the weight of the gyrowheel is G = 500 gm,

$$M_{unb} = Ge \leqslant M_{fr}, \quad \text{whence} \quad e \leqslant \frac{M_{fr}}{G} = \frac{0,3}{500} = 0,0006 \text{ cm.} \qquad (18.4)$$

When the rotor is rotating at a speed of 15,000 rpm, a dynamic load P will remain on the bearings of the rotor. This load may be determined by the following formula:

$$P \leqslant \frac{G}{g} \Omega^2 e. \qquad (18.5)$$

For our example we will obtain

$$P = \frac{500}{981} \cdot 1570^2 \cdot 0,006 = 753 \text{ gm}.$$

In addition, by means of static balancing, we can balance the rotor relative to its axle only in such a way that the centers of gravity of the two halves of the rotor will generate the same moment with respect to the axis of rotation, but will be located in different cross sections of the rotor. In this case, during the rotation a moment is generated in the plane of the axis of rotation, and this too will cause dynamic reactions in the bearings.

Dynamic balancing, realized while the rotor is rotating, permits us to balance it dynamically. In addition, as a more sensitive method, dynamic balancing allows spotting of unbalance which cannot be detected in static balancing because of the presence of a moment of friction in the bearings.

Static balancing is done before dynamic balancing and is necessary for detecting and eliminating coarse inequilibrium.

Dynamic balancing may be done on hand devices or in special setups.

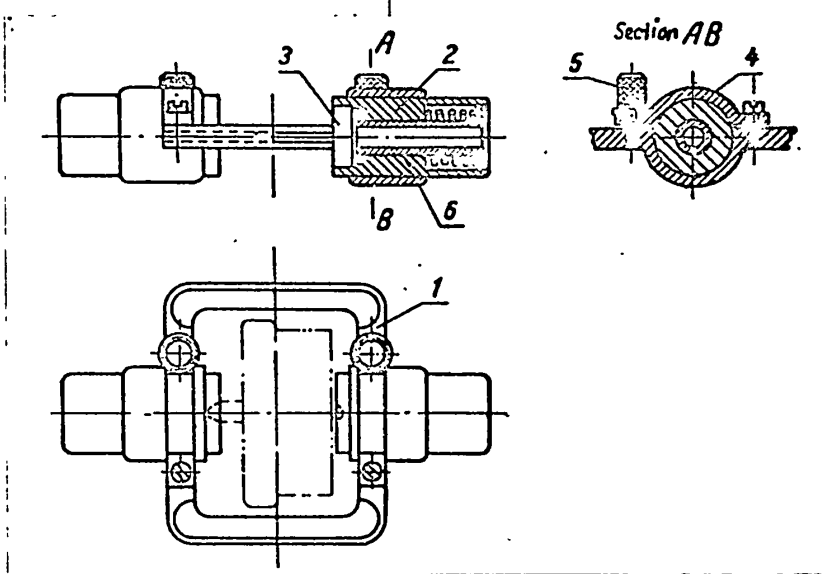

Fig.365 - Device for Balancing

The device for balancing (Fig.365) consists of a frame (1) whose apertures contain two rods (2) on a single axis. The rods may be moved in an axial direction; this is necessary for setting the rotor and for regulating the clearance between the rotor axle and the bearings (3). After regulating, the rods are fixed by means of the lathe dog (4) and the screw (5). The rod has knockout die (6) for removing the bearing when it is to be exchanged. When in operation, the device is placed in the hands of the operator. The rotor in the device is made to rotate by an air jet or by mechanical means.

At first the rotor picks up a slight speed; this is then increased to the speed required by the technical conditions. If, at low speeds, the device begins to vibrate violently in the hands of the operator, the rotor is stopped, since a further increase in speed may lead to destruction of the bearings. After the rotor is started, the operator, holding the device in his hand, will feel the vibration. Then the rotor is stopped and a plasticine ball is pressed on the end of the wheel rim, where the greatest vibration occurs.

If, on re-starting the rotor, the vibration increases, the ball is moved along the rim until a place is found where the ball will produce the least vibration. At the same time the size of the ball is selected, i. e., the quantity of plasticine which will produce the least vibration. When the desired results are obtained on one end of the rim, the entire process is repeated in the same sequence on the other end of the rim. If, in balancing, an increase in vibration of the device at the opposite end of the rotor is observed, plasticine balls must be placed on both ends.

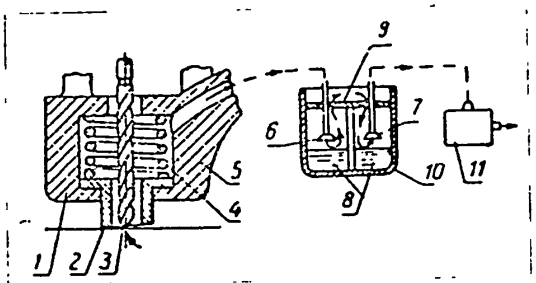

Fig.366 - Special Device for Protecting the Bearings from Falling Chip in Drilling

When the vibrations are no longer felt, the rotor is removed from the device. Then, on the opposite end, in a direction diametrically opposite to the ball, a hole is drilled, just as in static balancing. Finally the rotor is checked at a speed somewhat exceeding the operating speed.

Such balancing of the rotor is based on the subjective evaluation by the operator and depends to a large extent upon his experience and his ability to detect insignificant vibrations. In addition, the procedure is laborious, since the balls are pasted on by guess work at first; the place selected for attaching the ball can be defined as "incorrect" only after the rotor has been started.

If their axles are elliptical or if they have unevenly milled holes, some rotors do not, in general, yield to balancing. For this reason the axles of a rotor, as well as the rotor itself, must satisfy stiff requirements as to accuracy in their execution.

STAT

35

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In balancing a rotor, smoothness of the bearings is highly important. After several rotors have been balanced, the bearings are washed and lubricated with oil. The axle cones are rubbed with cotton waste, then with tissue paper. Clamping the axles when regulating the clearance is not allowed. After balancing, the cones of the rotor axle are examined and polished.

To eliminate the possibility of chip dropping into the bearing, a special device is used with the drilling machine; it consists of a fixture, an oil filter, and a vacuum pump. A diagram of such an arrangement is shown in Fig.366.

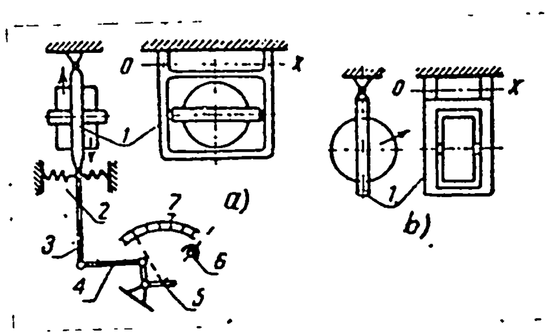

Fig.367 - Special Setup for Static and Dynamic Balancing

The end of the spindle of the drilling machine is mounted to hollow casing (1) of the fixture, in which the movable collar (2) slides. The drill (3), attached to the spindle of the machine, passes through the inside of the collar. The spring (4) forces the collar against the rotor, thus reducing the excess clearance. Through the socket (5), a hose is connected to the hollow cylinder; the other end is connected with the receiving stud (6) of the oil filter (10). The air, passing through the chamber (8) with its oil and strainers (9), is cleaned of chips and dust. The vacuum pump (11) is connected to the outlet tube (7) of the oil filter. The vacuum pump is started simultaneously with the machine, and all the chip and metal dust is sucked from under the drill into the oil filter. For static and dynamic balancing, a special setup is used; a diagram of it is shown in Fig.367. The setup consists of a frame (1) which is able to rotate on a pivot about the axis OX.

In the vertical position, i. e., in a position of equilibrium, the frame is fixed by two springs (2). The lower end of the frame is connected with a mirror (5) through a lever (3) and a rod (4). Turning of the frame about the axis OX causes the mirror to turn. When an unbalanced rotor rotates, it will set up a moment about the axis OX, a moment which will change in value and direction with a period equal to the period of rotation of the rotor. At the same time it will cause swinging of the frame, and consequently of the mirror. A ray of light incident on the mirror from the lamp (6) will be reflected from it and, in the form of a pinpoint of light, will fall on the frosted-glass scale (7). When the mirror oscillates, the light spot will change into a line. For high sensitivity of the setup, the period of oscillations of the swing system should coincide with the period of rotation of the rotor, so that the phenomenon of resonance occurs.

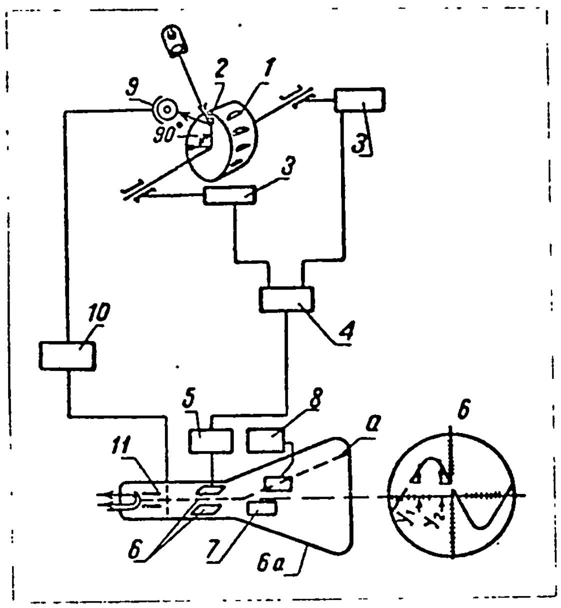

Fig.368 - Diagram of the Setup for Balancing the Gyroscope Rotors by the Method of Acad. A.N.Krylov

To determine the dynamic unbalance, the rotor is fastened in the frame in the position (a) since, in this position, the moment of the forces of unbalance acts on the springs alternately in both directions.

To determine the static unbalance, the rotor is attached in the frame in the position (b); in this position, the dynamic unbalance will not be noticeable. The balancing principle is the same as in the position (a). It is impossible to define the spots which have an excess or a deficiency of mass on this setup. The device is useful only for determining the amount of unbalance from the length of the diffuse track of the light spot. At present, balancing machines are used which permit not only a determination of the amount of equilibrium, but also the spots which have an excess or a deficiency of mass.

Setup for Balancing a Rotor by the Direct Measuring Method

This method of balancing rotors was first reported by Academician A.N.Krylov in 1935.

The setup for balancing the rotor is shown schematically in Fig.368. The end face of the rotor (1) is marked with two black dots (2) staggered at a 90° angle. Oscillations due to reactions in the supports are transmitted through the flexible system to the pickups (3). In the pickups, whose principle of action is based on the excitation of an electromotive force in the turns of the coil, an emf is induced when the permanent magnet in this coil is shifted. The frequency of this emf is equal to the oscillation frequency of the supports, and its amplitude is proportional to the amount of the reactions.

Across the integrating circuit (4) and the amplifier (5), the emf induced in the pickup is fed to the vertical scanning disks (6) of the oscillograph tube (6a). To determine the oscillations of the supports from the time or from the angular position of the rotor ωt, voltage from the special generator (8) is supplied to the horizontal scanning disks (7) of the oscillograph tube. On the screen of the oscillograph tube we will obtain a sinusoidal curve whose amplitude will characterize the amount of unbalance. The sinusoid is obtained on filtering the component oscillations of higher harmonics.

The position of the unbalance is determined in the following manner: A ray of light, reflected from the end face of the rotor with its black marks (2), is directed onto the photoelectric ell (9). The light oscillations, transformed into electric signals, pass through the electronic amplifier (10) onto the screen (11) of the oscillosgraph tube.

These signals will stop the flow of electrons (a) at the instant when one of the black mark enters the field of the photocell.

In this way, for one turn of the rotor, the screen of the oscillograph will have a sinusoidal curve with two small gaps.

STAT

337

The position of the gaps on the curve characterizes the distribution of the marks on the rotor and the direction of the unbalance.

The ordinates y_1 and y_2 will coincide with the components of unbalance along diameters drawn through the marks on the ends of the rotor.

The direct measuring method is the most nearly perfect and the most progressive method, in comparison with all others.

Assembling the Rotor Case with the Cover and the Step-Bearing Housing

The housing of the step bearing (6) (Fig.363) should move in the aperture without friction produced by the spring washer. The fit of the step-bearing housing in the rotor case corresponds, according to the blueprint, to a sliding fit of Class 2 accuracy. The aperture has a tolerance of +0.023 mm; the shaft has a tolerance of -0.014 mm. The maximum clearance possible is 0.037 mm, but according to technical specifications it is limited to within 0.02 mm. The 0.02 mm clearance may be obtained in two ways.

When the first method is used, the manufacturing accuracy is considerably increased as a result of the fact that the class of accuracy of the fit is raised; however, this makes production considerably more expensive and requires more accurate equipment. With a method such as this, machining the parts becomes uneconomical and even unfeasible with the equipment we now have.

The second method retains the greater tolerance as economically acceptable for production, but in this case selective assembly must be used. Selective assembly may be done by direct selection or by preliminary sorting of the parts into groups.

In subsequent operations, the balancing screw (7) is screwed into the rotor case with shellac and is safetied with the nut (8); then the guide pin is shrink-fitted and the spring gasket (9), lubricated with oil, is inserted (Fig.363).

Checking the quality of the assembly is done by exerting finger pressure on the housing of the step bearing; under the effect of the spring, the housing should move

STAT

329

without rubbing.

Press-Fitting the Bearings

The bearing is taken apart and washed. Then a check is made to see if the bearing cup (10) (Fig.363) goes into the aperture. Under hand pressure, the cup should go into the aperture to $\frac{2}{3}-\frac{3}{4}$ of its length. If the above conditions are observed and the cup does not fit into the aperture, it is reamed to the necessary size. After this, the gasket impregnated with MVP oil is put in its socket. Press-fitting the cup may be done by hand, with light blows by a watch hammer, or else on a press.

After this, the press fit of the cup is checked for end wobble. Permissible wobble is 0.015 mm. After scavenging the cup with dry filtered air, we proceed to assembling and lubricating the bearing. To keep the bearing from becoming fouled in the process of assembly, tissue paper is placed under the washer of the bearing.

Press-fitting of all the other bearings is done by the same method. In press fitting the upper bearing, it is impermissible to increase the diameter of the housing of the step bearing. This housing should move freely; the permissible clearance is not more than 0.02 mm.

Final Assembly of the Gyro Unit

The gaskets (Fig.363) and the elastic washer (9) are placed into the cover (2) of the housing. Then the felt washers (12), impregnated with oil, are set in the housing of the step bearing (6); after this, the step bearing is set in the cover of the housing. A gasket, lubricated with oil, is also put on each bearing. After this, the rotor (5) with its axle (4) is inserted in the housing (1). The axial clearance is regulated by the gaskets (11) and is set within the limits of 0.04 - 0.07 mm. The amount of clearance is stipulated, on the one hand, by the requirement of keeping the shift in center of gravity to a minimum and on the other hand by the necessity of assuring normal operation of the instrument at subzero temperatures.

The amount of axial clearance is checked on a special device with an indicator gage. A schematic sketch of the device is given in Fig.369. The rotor (1) is lifted by means of the counterpoise (2) which acts on the rotor over the lever (3). The counterpoise is lowered and raised, so that the axial clearance can be determined from

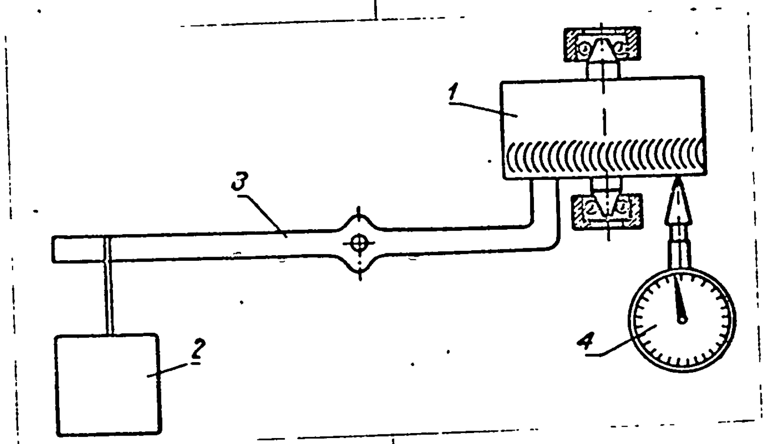

Fig.369 - Device for Checking Axial Clearance

observation of the pointer. After the axial clearance agrees with the technical specifications for the unit, the following points are checked:

1. Air consumption, which should be within the limits of 46 - 54 ltr/min at a pressure of 90 mm Hg.

2. Operation of the rotor when the jet is small. Instead of the usual pressure of 80 - 90 mm Hg, we establish a pressure of 10 mm Hg and check the wear of the rotor at each hole. By this method, the bearing and the quality of balancing are regulated.

3. Smoothness of rotation of the rotor. The rotor is run for 4 - 5 min; at a pressure of 80 mm Hg it should run smoothly, without impact or vibrations.

4. The rotor run-out, regulated by checking the rotor travel at inertia. The rotor is run for 5 min at a pressure of 70 mm Hg. Technical conditions have established the inertia run-out of a rotor at a temperature of 18 - 20°C as lasting not less than 8 min and not more than 22 min. An upper limit is set because a high run-

STAT

out means a large clearance. The normal inertia travel of a rotor at subzero temperatures is estimated at 2 - 2.5 min.

After inspection, the rotor is disassembled, and the working parts of the bearings are examined under a magnifying glass. A slight rolling of the balls along the raceways is allowed. In checking the rotor, it is measured with a standard caliper. A rotor which meets all requirements is re-assembled and is checked a second time in the same sequence (on the first four points).

Measuring the Rotational Speed of the Rotor

The rotational speed of the rotor can be measured with a stroboscope (Fig.370). The stroboscope is a disk (3) which revolves rapidly at constant speed; its rotational speed can be measured with a tachometer (4). A mark (2), in the form of a spiral,

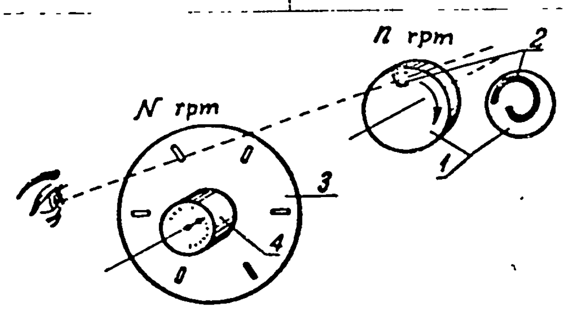

Fig.370 - Stroboscope

is made on the rotor (1). If the rotor rotates evenly at n revolutions per minute, then while observing the rotor through the slots in the rotating disk, the rotational speed of the disk can be so regulated that the mark on the rotor will seem stationary. Evidently, this will be the case only if the rpm of the rotor is equal to or a multiple of the frequency of its appearance in the slots in the stroboscope disk.

If the number of slots is P, we will have the relation

$$n=kNP, \tag{18.6}$$

STAT

where N is the rpm of the stroboscope disk;

k is any whole number indicating how many full revolutions the rotor has completed in the time between two consecutive appearances in the slots of the stroboscope disk.

It is clear that, by merely calculating N, it is impossible to determine the number of revolutions n of the rotor, since the value of k is unknown. For this reason, the rotational speed of the disk is increased or diminished until the marks on the rotor again seem stationary under observation through the slots. This will occur when the number k is decreased or increased by one unit. After defining, from the tachometer pointer, the corresponding rotational speed N_1 of the disk we will obtain

$$n(k-1)N_1P. \qquad (18.7)$$

Excluding k from these two equations, we will obtain

$$\frac{n}{N}-\frac{n}{N_1}=P,$$

whence

$$n=\frac{PNN_1}{N_1-N}. \qquad (18.8)$$

8. Assembly of the Damping Unit

The faces of the stabilizer housing (13) (Fig.363) on which the flaps (14) will be installed should be lapped for greater surface smoothness and evenness. To obtain a good hermetic seal, the upper end of the housing is also lapped. The flaps are weighed and paired; according to technical specifications the difference in weight in one pair should not exceed 20 mg. Different weights lead to the displacement of the center of gravity of the pair of flaps, making it impossible to install the flaps symetrically along the openings. Assembling the flap axles (15) with the housing is done by the fitting method, since it is important that a small radial clearance of 0.05 to 0.03 mm is left, which is difficult to obtain by the full interchangeability method. The aperture in the damper housing is reamed until the proper surface smoothness and the required clearance are obtained. The clearance is checked by setting the axis of a flap in the aperture. Assembling the flaps with their axis is done in the following manner: The flap is shrink-fitted on one end of the axle. In doing this, bending of the axle must be avoided. The end of the axle should protrude 1 - 2 mm from the flap. Then the gasket (16), 0.13 mm in thickness, is put on; after this, the axle is introduced into the aperture in the housing. On the other side the same kind of gasket is put on and the second shutter is shrink-fitted. Plates of 0.13 mm thickness are placed under the ends of the flaps. The flaps are levelled and the required axial clearance (0.01 - 0.025 mm) is established.

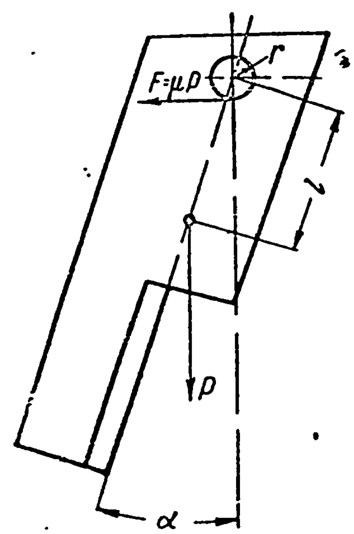

Fig.371

The clearance between the flap and the housing should be preserved along the entire length of the flap, no matter what position the damper is in. Then the overlap of the flap over the openings is checked. When the damper housing is suspended in a horizontal plane, the flaps should half overlap the openings. After the flaps are installed, they are soldered to the axle. The strength of the soldering is checked for torque which, according to the technical specifications, should be not less than 1 kg-cm. After final assembly of the unit, the overlap of the openings, the radial and axial clearances, and the clearances and friction in the flap supports are all checked according to the technical specifications.

Accuracy in the vertical installation of the flap determines the accuracy of the instrument operation. Friction in a flap axis of rotation causes an angle of stagnation. As is seen in Fig.371, the flap misses reaching the vertical by an angle α, at which the moment of the force of gravity $Pl \sin\alpha$ balances the moment of friction $P\mu r$.

$$Pl\sin\alpha = P\mu r \quad \text{or} \quad \sin\alpha \approx \alpha = \frac{\mu r}{l} \qquad (18.9)$$

(Since the angle is small, we treat $\sin\alpha$ as equal to α). Consequently, the angle of stagnation due to friction in the flap axle will be expressed as

$$\alpha_{st} = \frac{\mu r}{l}, \qquad (18.10)$$

where μ is the coefficient of friction in the axis of rotation of the flap;

r is the radius of the aperture in the flap;

l is the distance between the center of gravity and the axis of rotation of the flap.

The dimensions r and l are indicated by the designer so that the technologist can reduce the angle of stagnation of the flap, chiefly by decreasing the coefficient of friction μ, which depends on the smoothness of machining of the friction surfaces. To reduce the force of friction F in assembly, the necessary clearance should be established not only in the radial direction but also in the axial direction. In addition, we must see to it that the aperture and the axle of the flaps are correct in form, so that there is contact along the largest possible surface area. If, in assembly, the axle of the flaps is bent, incorrect positioning of the axle in the bearing and rubbing at various points will result.

9. Assembly of Gyroscopic Instruments

Let us examine the general problem of assembly, as before, with the assembly of a single gyroscopic instrument, namely the gyro horizon (Fig.363), as typical example.

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Balancing the Gyroscope Unit (with Damper)

Balancing a gyro unit is done to indifferent equilibrium within the limits of the angle of swing of the pendulum flaps. The balancing is done in two steps (the first in the vertical plane and the second in the horizontal).

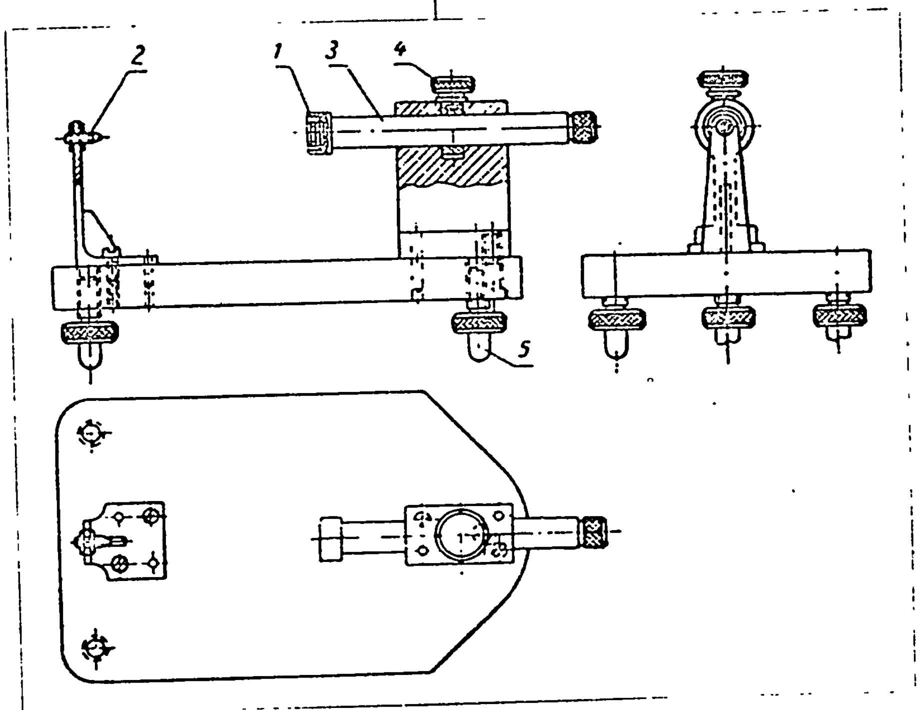

Fig.372 - Device for Balancing the Gyro Unit in the Vertical Plane

By balancing in the vertical plane, the center of gravity of the unit is shifted to the vertical plane which passes through the axis of rotation of the rotor casing. This operation is done on a special device (Fig.372) in which the gyro unit is placed in the bearing. The bearing (1) is connected with the axle of the rotor casing, and the bearing of this casing is connected with the axle (2). Rotation in the bearings should be regulated to compensate axial movement of the rod (3), so as to ensure free rotation of the gyro unit without noticeable radial play. After this regulating, the rod is fastened by means of the nut (4). The regulating screws (5) check the device so that the axis of rotation of the gyro unit is horizontal.

To obtain the necessary balance, small pieces of lead are cut off the balancing weights which are fastened on both sides of the rotor casing (1) (Fig.363). The gyroscope assembly is brought to a position at which the pendulum flaps (14) half overlap the slots in the damper housing (13).

Balancing in the horizontal plane is done after the gyro unit has been balanced in the vertical plane, i. e., when the center of gravity is already located in the vertical plane which passes through the axis of rotation of the rotor casing, but may still be located above or below this axis. This balancing must make the center of gravity coincide with the axis of rotation of the rotor casing. The gyro unit should be located in an indifferent position within the limits of the angle of swing of the pendulum flaps. The operation is done on the same device, by moving the weight (17) (Fig.363) along the balancing screw (7) until the gyro unit, within the limits of the angle of swing of the pendulum flaps, will remain in any of the preset positions.

In the process of balancing, the gyroscope assembly may occupy various positions.

1. The gyroscope assembly remains in the extreme position of inclination when it is tilted to one side, and returns from such inclination, moving to a horizontal position, when it is tilted to the opposite side.

Reason: One weight, attached on one side, is heavier than the opposite one. As a remedy, this part of the weight is cut off.

2. The gyroscope assembly remains in the extreme positions of inclination and moves to these positions when the angles of deviation from the vertical are small.

Reason: The center of gravity is located above the axis of rotation; the balancing washers - the weight (17) (Fig.363) - are too high. The weight must be lowered or, if this is not enough, the number of washers must be reduced.

3. The gyroscope assembly leaves the inclined position and occupies a vertical or near-vertical position.

STAT

Reason: The center of gravity is located below the axis of rotation. The balancing washers (17) must be raised or their number increased.

The balancing is considered complete as soon as the gyroscope aggregate remains in any preset position, within the limits of the angle of swing of the pendulum flaps.

After the weight is balanced, the screw heads and the balancing washers are coated with black spirit varnish.

Assembling the Frame with the Parts

The axle (19) and the bearing cup (20) are press-fitted in the frame (18), and the weights are screwed in. The conditions for shrink-fitting are the same as in

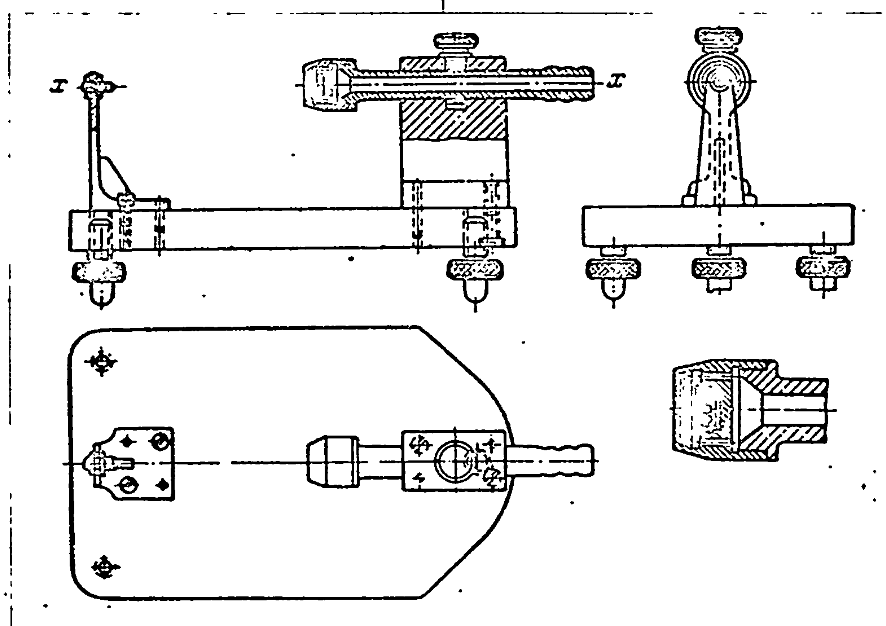

Fig.373 - Device for Balancing the Gimbal Unit in the Vertical Plane

the preceding units. After the frame has been assembled with all parts, it is balanced on the device shown in Fig.373. In design, this device is analogous to the device depicted in Fig.372, except that it is somewhat larger in size and has a duct in the rod for supplying air in the process of regulating. (A description of the

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regulating process is given below.) The process of balancing the frame consists in bringing it to a state of indifferent equilibrium with respect to the axis of rotation; this is done by cutting down the balancing weights.

Assembling the Gyroscope Unit with the Frame

In assembly, the friction and clearances in the axles of the gimbals should be such that, when the gyroscope unit is inclined to the limit operating angle, the number of free semioscillations of the gyroscope unit will not be less than four and not more than seven. For this, the frame is set in a horizontal position. A lower number of oscillations signifies that the clearance is too small, i. e., the axle screw (21) (Fig.363) has been firmly tightened. If, in checking, it is found that the clearance is normal but the number of oscillations is less than four, this signifies that the moment of friction is too high. The pitching scale (22) is mounted in such a way that the zero division of the scale coincides with the center of the axis of the immature airplane.

Balancing the Gimbal Unit

Balancing the gimbal unit consists in bringing it to a state of indifferent in-equilibrium about the axis of rotation of the frame, within the limits of the angle of swing of the pendulum flaps of the damper. The balancing is done by shifting the gyroscope unit along its axis of rotation, changing the total thickness of the gaskets (23) (Fig.363) under the frame plug (24).

For the balancing, a device (Fig.373) with ball bearings which have normal operating clearances is used.

The frame and the gyroscope unit are given different angles of inclination, while observing the behavior of the unit. When the device is tapped with a wooden mallet, a correctly balanced unit will not alter the position it has been given within the limits of the angle of swing of the pendulum flaps.

STAT

When the unit rotates spontaneously, the direction of this rotation must be determined from the angle of deviation; this demonstrates the necessity of decreasing and increasing the total thickness of the gaskets under the frame plug.

Regulating the Instrument

Regulating an instrument consists in checking the correct assembly of a sensitive part of the instrument and determining whether its characteristics correspond to the technical conditions.

In checking, the following technical requirements and conditions must be observed:

1. The time it takes for the miniature airplane to right itself should be not more than 2.5 min at normal temperature.

2. The instrument angle of stagnation should not exceed +1 mm at normal temperature. A check is made no sooner than 5 min after the feed has been connected by tilting the gyroscope to the right, to the left, upward, and downward; in this observation, the amount by which the airplane image misses reaching normal position is established. The error is determined for each individual case.

3. The speed at which the gyro leaves the displaced state can be checked no sooner than 8 min after it has started operating. The gyroscope unit is deflected by an angle of 30° upward and downward, and then to the right and to the left. The time it takes for the miniature airplane to right itself from any 30° deflection should not exceed 6 min. The difference in time required for it to right itself upward and downward, or to the right and left, should not exceed 2 min.

For regulating an instrument, a device (Fig.373) mounted on a rotary table is used. The horizontal position of the axis xx is checked with a level. Air at a pressure of 90 mm Hg.is supplied to the device through the aperture in the rod. A sighting frame, in reference to which the displacement of the aircraft image is observed, is set on the rotary table. The failure of the instrument to correspond to

STAT

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the tolerances and the technical conditions will show up during the original starting of the gyroscope as well as in the checking process. Defects in the balancing and assembly of the units (not discovered at the proper time and detected only when the gyroscope was operating) must be eliminated by regulating.

Checking Stagnation in the Instrument

Friction in the gimbal bearing and in the axles of the pendulous vanes will have an effect upon stagnation in the instrument. Let us examine the angle of stagnation due to friction in the gimbal bearings.

The moment of friction M_{fr} in the gimbal bearings always acts in a direction opposite to that of the motion, and recovery will take place in the rotor axle until the correcting moment M_{corr} and the moment of friction M_{fr} are in equilibrium and the rate of precession returns to zero:

$$\omega = \frac{M_{corr} - M_{fr}}{I\Omega} = 0. \qquad (18.11)$$

The restoring moment of the air jet, which depends on the extent to which the aperture is open, is directly proportional to the angle of aperture of the flaps

$$M_{corr} = \frac{M_0}{\alpha_0}\alpha, \qquad (18.12)$$

where M_o is the maximum restoring moment of the jet when the aperture is fully open;

α_o is the angle of deviation of the flap, corresponding to a fully open aperture;

α is the angle of deviation of the flap, depending on the degree of opening of the aperture.

Stagnation will occur when

$$M_{corr} = M_{fr} = \frac{M_0}{\alpha_0}\alpha, \qquad (18.13)$$

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whence

$$\alpha = \frac{M_{fr}}{M_o}\,\alpha_o.$$

Consequently, the angle of stagnation due to friction in the bearings can be expressed by

$$\alpha_{st.} = \frac{M_{fr}}{M_o}\,\alpha_o. \qquad (18.14)$$

The angle of stagnation due to friction in the axles of the flaps was determined by examining the assembly of the damper housing. It is expressed by

$$\alpha_{st._2} = \frac{\mu r}{l}.$$

Let us determine the value of the angle of stagnation, proceeding from the following quantities. Friction in the gimbal bearings M_{fr} = 0.4 gm-cm.

The maximum restoring moment is M_o = 3.5 gm-cm.

The angle of deviation of the flap, corresponding to a fully open aperture is $\alpha_o = 2.5^\circ$.

The coefficient of friction in the axis of rotation of the flap is $\mu = 0.1$.

The radius of a flap axle is r = 0.5 mm.

The distance between the center of gravity of a flap and its axis of rotation is l = 7.5 mm.

$$\alpha_{st._1} = \frac{M_{fr}}{M_o}\,\alpha_o = \frac{0{,}4}{3{,}5}\,2{,}5 = 0{,}29^\circ.$$

$$\alpha_{st._2} = \frac{\mu r}{e} = \frac{0{,}1\cdot 0{,}5}{7{,}5} = 0{,}0067\ \text{rad.} = 0{,}38^\circ.$$

$$\alpha_{st.\,max} = \alpha_{st._1} + \alpha_{st._2} = 0{,}29 + 0{,}38 = 0{,}67^\circ.$$

The rotor axle may miss reaching the vertical by this angle. This corresponds to the linear value of 0.42 mm on the AGP scale for a 1 mm tolerance for the angle of stagnation.

169

Checking the Instrument for Return of the Gyroscope from a Dip

It is generally known that the time it takes to return from a 30° tilt should lie between the limits of 2 – 6 min. The difference in time required for the miniature airplane to right itself upward and downward or to the right and left, should not exceed 2 min.

The rate of precession ω depends upon the correcting moment M_{corr} set up by the reaction of the air jets

$$\omega = \frac{M_{corr}}{I\Omega}. \qquad (18.15)$$

The reaction of the air jets varies within the limits of a 2.5° angle from the vertical position to full opening of the aperture. Beyond the limits of this angle, the correcting moment will preserve a constant value so that the rate of precession will also be constant and the angle of righting in this interval will be expressed by the formula

$$\alpha = \frac{M_{corr}}{I\Omega} t. \qquad (18.16)$$

A different righting time t at the same angle of tilt, which is 30°, will signify that there are different restoring moments M_{corr}. This may be expressed by the relationship

$$\frac{t_1}{t_2} = \frac{M_{corr_2}}{M_{corr_1}}. \qquad (18.17)$$

It is necessary that $t_1 \approx t_2$, within the limits of the tolerance.

A different rate of precession is explained by different moments of the reactive jets; these may occur as a result of uneven distribution of the nozzles, different size nozzles, surface roughness, different clearances between the damper housing and the flaps, and the like.

When the parts are accurately executed and the assembling is correctly done, the difference in the time it takes the gyroscope to right itself after a tilt lies within the tolerances stipulated in the technical specifications. In some cases, where the difference in the time it takes the gyroscope to right itself does not lie within the limits of the tolerance, the following method of eliminating this defect can be used under workshop conditions. If the rate of precession ω_2 on one end exceeds the rate of precession ω_1 on the other end to the same extent as the difference in the time of precession exceeds 2 min, then the rate of precession can be compensated by adding a weight to the frame; the weight is so calculated that, as a result of the moment of inequilibrium, it will equalize the rates of precession. Rather than adding a weight, however, this amount is cut off from the opposite side.

The moments $M_{corr\ 1}$ and $M_{corr\ 2}$ set up the rates of precession ω_1 and ω_2; since ω_1 is less than ω_2, $M_{corr\ 1} < M_{corr\ 2}$. When the weight on the frame is cut to the extent of P, the frame is unbalanced to the extent of the moment Pl which is added to $M_{corr\ 1}$.

As the axle of the gyroscope approaches the vertical, this moment Pl will remain and will set up a precession which will incline the axis of the gyroscope; the miniature airplane will be tilted through an angle of α. Once the rates of precession are equalized, another error will occur, a tilt of the miniature airplane. This tilt is eliminated by soldering tin on the flaps. The small weight of this solder will change the position of the flap and will return the aircraft image to a horizontal position. But in this case the system becomes unbalanced. Because of this, inertia errors will occur when the airplane goes into a turn. Such a method of eliminating this defect cannot be considered correct. To avoid the possibility of a defect involving the difference in the time it takes the gyroscope to right itself, the required accuracy in the execution of parts and in assembly must be strictly maintained.

Errors Due to Inequilibrium in the Gimbal Rings

If the center of gravity of a frame (or of a rotor casing) is shifted and a moment of unbalance M_{unb} acting about the axle is created, the rotor casing (or the frame) must be made to precess until the correcting moment M_{corr}, increasing as a result of this inclination, compares with the moment of unbalance M_{unb}.

As a result, the unbalance in the frame will cause the casing to deflect through an angle β, which is determined from the condition of unbalance

$$M_{unb} = M_{corr}$$

or

$$M_{unb_1} = \frac{M_0}{\alpha_0}\beta_1,$$

whence

$$\beta_1 = \frac{M_{unb_1}}{M_0}\alpha_0. \quad (18.18)$$

By analogy, if the casing is unbalanced to the extent of M_{unb}, the frame will deviate by an angle of

$$\beta_2 = \frac{M_{unb_2}}{M_0}\alpha_0. \quad (18.19)$$

If one of the moments $M_{unb\,1}$ or $M_{unb\,2}$ is greater than M_0, there can be no equilibrium and the rotor will be "blocked", since the correcting moment will not be able to equalize the moment of unbalance and the precession will not cease.

Errors Due to Oscillation of the Pendulous Vanes

The period of natural oscillation of the flaps is

$$T = 2\pi\sqrt{\frac{I}{mga}}, \quad (18.20)$$

STAT

where $I=\frac{ml^2}{3}$ is the moment of the pendulum inertia relative to the axis of swing;

m is the mass of the shank;

$a = \frac{l}{2}$ is the distance between the center of gravity and the axis of swing;

l is the length of a flap.

Taking $l = 20$ and substituting the numerical values, we will obtain

$$T=2\pi\sqrt{\frac{ml^2}{3mg\frac{l}{2}}}=2\pi\sqrt{\frac{2l}{3g}}=2\pi\sqrt{\frac{2\cdot 2}{3\cdot 981}}=0{,}23\ sec.$$

Under the action of the correcting moment, the rotor axle will oscillate just as the flap does, with the same period of 0.23 sec.

Let us find the amplitude of these oscillations $\varphi = \omega_0 \frac{T}{2}$, on the supposition that one aperture is fully open in the first half of the period and that the rate of precession is constant ω_0 = const = 6°/min. Substituting the numerical values, we will get

$$\varphi=\omega_0\frac{T}{2}=6\frac{0{,}23}{60\cdot 2}=0{,}0115^\circ.$$

In comparison with the 1 mm tolerance for the oscillation of the aircraft image, the error is insignificant; in reality it will be still smaller since, at first, the aperture will be partially open and since, in calculating, we have assumed that the rate of precession will be at the maximum for the entire time.

Errors Due to Leakage

The assembled instrument should be hermetically sealed; this ensures reliability in operation. Jets of air which penetrate inside the instrument when the hermetic seal is not tight will set up moments of external forces which will cancel the accuracy of the instrument readings. The hermetic seal is checked by producing a pressure of 500 mm water column in the instrument, after which the hose is clamped off. The time it takes for the pressure to drop to zero should be not less than

STAT

20 sec.

Hermetic seal is ensured by:

a) Using castings without blowholes or cracks;

b) Care in machining the contact faces of the parts;

c) Lubricating the spots where the parts are joined, with a special lubricant;

d) Installing some parts with gaskets or adhesives.

Dimensional Analysis

In view of the complexity of gyroscopic instruments, special emphasis must be placed on dimensional analysis in planning the processes of their assembly; such an analysis permits a more correct solution of the problems of selecting the most rational methods of assembly.

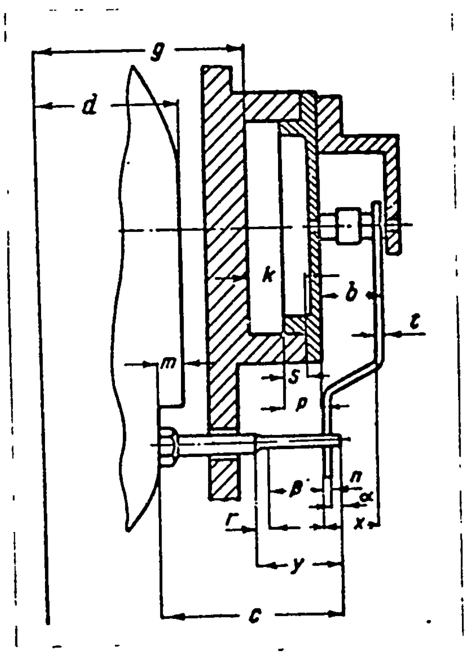

Fig.374

All this can be demonstrated on the example of dimensional analysis during final assembly of the gyro horizon; this is done to obtain the correct positioning of the lathe dog relative to the prong; by means of these, the rotation of the rotor casing is transmitted to the miniature airplane.

To do this, we must determine the position of the cylindrical tip of the lathe dog relative to the thickness of the prong end; this position is determined by the two dimensions α and β (Fig.374).

The dimensions α and β are the terminal links in the two dimensional chains. Let us make an analysis of the tolerances for a concrete example (Table 47). The calculation to maximum and minimum is

Table 47

Computation Data

a)	b)			f)		i)	j)
	c)	d)	e)	g)	h)		
Frame with gaskets	*k*	4,5	−0,08	4,5	4,42	4,46	0,04
	g	41,5	−0,2	41,5	41,3	41,4	0,1
Plate	*S*	0,6	+0,2	0,8	0,6	0,7	0,1
	P	1,8	−0,12	1,8	1,68	1,74	0,06
Gear	*b*	2,5	−0,03 −0,09	2,47	2,41	2,44	0,03
	t	0,7	+0,1	0,8	0,7	0,75	0,05
Prong	*x*	1,8	±0,2	2	1,6	1,8	0,2
	n	0,3	−0,04	0,3	0,26	0,28	0,02
Lathe dog	*c*	19	−0,28	19	18,72	18,86	0,14
	y	7	+0,36	7,36	7	7,18	0,18
	r	3	±0,5	3,5	2,5	3	0,5
Rotor casing	*d*	33,3	−0,17	33,3	33,13	33,215	0,085
	m	3,5	+0,16	3,66	3,5	3,58	0,08

a) Name; b) Dimensions; c) Conventional sign; d) Nominal; e) Tolerance; f) Limit dimensions; g) max.; h) min.; i) Mean size; j) Half tolerance

$$\beta = g + k - s + p + b - t - x - d + m - c + y - r;$$

$$\beta_{max} = 41{,}5 + 45 - 0{,}6 + 1{,}8 + 2{,}47 - 0{,}7 - 1{,}6 - 33{,}13 + $$
$$+ 3{,}66 - 18{,}72 + 7{,}36 - 2{,}5 = 4{,}04;$$

$$\beta_{min} = 41{,}3 + 4{,}42 - 0{,}8 + 1{,}68 + 2{,}41 - 0{,}8 - 1{,}2 -$$
$$- 33{,}33 + 3{,}5 - 19 + 7 - 3{,}5 = 0{,}91.$$

Thus the tolerance for β - δ_β = 3.13 will be

$$\alpha = d - m + c - g - k + s - p - b + t + x - n;$$

$$\alpha_{max} = 33{,}3 - 3{,}5 + 19 - 41{,}3 - 4{,}42 + 0{,}8 - 1{,}68 -$$
$$- 2{,}41 + 0{,}8 + 2 - 0{,}26 = 2{,}33;$$

$$\alpha_{min} = 33{,}13 - 3{,}66 + 18{,}72 - 41{,}5 - 4{,}5 + 0{,}6 - 1{,}8 -$$
$$- 2{,}47 + 0{,}7 + 1{,}6 - 0{,}3 = 0{,}52.$$

Consequently, the tolerance for α - δ_α = 1.81.

Let us define the tolerances by another method of dimensional analysis, a method based on the theory of probabilities [according to eq.(16.12)].

When no data are available on the scattering of the dimensions, it can be assumed that the scattering follows the law of equal probability, according to which

$$\alpha_i = 0; \quad k_i = 1{,}73.$$

In this case,

$$\beta = \Delta_{ok} \pm \delta_k = (g + k + p + b + m + y) - (s + t + x + d + c + r) \pm$$
$$\pm \sqrt{\Sigma 1{,}73^2 \delta_i^2} = (60{,}8 - 58{,}325) \pm 1{,}73 \sqrt{0{,}3842} = 2{,}475 \pm 1{,}075.$$
$$\beta_{max} = 3{,}55; \quad \beta_{min} = 1{,}4. \text{ The tolerance for } \beta - \delta_\beta = 2{,}15.$$
$$\alpha = \Delta_{ok} \pm \delta_k = (d + c + s + t + x) - (m + g + k + p + b + n) \pm \sqrt{\Sigma 1{,}73^2 \delta_i^2} =$$
$$= (55{,}325 - 53{,}9) \pm 1{,}73 \sqrt{0{,}1022} = 1{,}425 \pm 0{,}555;$$
$$\alpha_{max} = 1{,}98; \quad \alpha_{min} = 0{,}87. \text{ The tolerance for } \alpha - \delta_\alpha = 1{,}11.$$

As the analysis of tolerances shows, at tolerances of $\delta_\beta > 3.13$ and $\delta_\alpha > 1.81$ ~~the assembling may be done by the method of full interchangeability, as is evident from the calculation to maximum and minimum.~~

STAT

At tolerances of $\delta_\beta = 2.5$ and $\delta_\alpha = 1.5$, the assembling cannot be done by the method of full interchangeability; in this case, it must be done by the method of partial interchangeability, which is based on making use of the theory of probabilities (i. e., for a small percentage the tolerances of the closing links will go beyond the required limits $\delta_\beta = 2.5$ and $\delta_\alpha = 1.5$).

At tolerances of $\delta_\beta = 1.5$ and $\delta_\alpha = 0.5$ in the practical example, the dimensional chains cannot be solved by either the method of full interchangeability or the method of partial interchangeability, since the percentage of rejects will be considerable. In such a case the dimensional analysis can be done by other methods (by matching, by selective assembly, by fitting, etc.).

In this Chapter, we have examined the technology for producing special parts and the assembly of pneumatic gyroscopic instruments. As far as basic parts and units are concerned, the technology for electric gyroscopic instruments is analogous to the above-described assembly, with the exception of the electric motor, the correcting mechanism, the current feeds, and some other special parts and units.

From the point of view of technology, the manufacture of electric motors is of extreme significance and interest. This problem is examined in the next Chapter.

STAT

226