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GEARBOXES OF HELICOPTER POWER PLANTS AND TURBOPROPS

Tutorial

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Коротко викладено загальні відомості про класифікацію, компонування і кінематичні схеми авіаційних редукторів. Описано призначення, устрій і конструкцію окремих вузлів і систем редукторів.

Розглянуто особливості конструкції серійних редукторів ТВД і вертолітних ГТД.

Для студентів, що вивчають курси «Авіаційні двигуни і енергетичні установки», «Конструкція авіаційних двигунів і агрегатів», «Проектування авіаційних двигунів і енергетичних установок», а також переддипломний курс.

Reviewers: Doctor of Science, Professor V. Logynov,
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The tutorial focuses on aircraft gearboxes, their classification, generic schemes and configurations. The authors describe the design and functions of gearboxes and their components, as well as structural features of serial turboprop engine gearboxes and helicopter gas turbine engines.

The tutorial is intended for undergraduate students studying “Aircraft engines and power plants”, “Construction of aircraft engines and accessories” and “Aircraft system and power plant design”.

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1. GEARBOXES

1.1 . General information about gearboxes of GTEs

The turboprop engine propellers, helicopter's main and tail rotors and different engine auxiliaries are gear-driven. A gear drive is a mechanical part that coordinates the rotation of every power consumer shaft to the rotation of the engine rotor.

The propellers and most auxiliaries operate at the rotational speed lower than that of engine rotor. Hence, the rotational speed of the drive must be reduced. For this purpose a gearbox (reduction drive) is used.

The basic principles of gearbox design were studied during the course of "Mechanics". Through the course students learned to design the gearboxes for general purposes. The aircraft gearboxes have some specific features as follows:

– higher cooling intensity since the oiling is greatly increased;

– multi-mode operation resulting in a shorter lifetime;

– problems of operating in precise steady modes (for turboprop engines (TPEs) and turboshaft engines (TShEs) caused by the difficulties of the torque metering unit installation;

– problems of the gearbox installation at the front part of the engine since it greatly affects the velocity triangles and exerts pressure on the compressor face;

– minimized mass, etc.

The maximum rotational speed of gas turbine engine (GTE) rotor ranges within 5000 – 18000 rpm. The optimum rotational speed that corresponds to the highest efficiency of the propeller at the design flight modes lies within 700 – 1200 rpm. Hence, the gear ratio of propeller gearboxes equals 5 –15 (for TPEs). The gear ratio required for the lift rotors is even greater ($i = 30 - 70$) because the optimal rotational speeds of lift rotors are $n_{LR} = 100 - 300\ \text{rpm}$. The maximum rotational speed of propeller can be calculated by the formula:

$$n_P = \frac{60 \cdot U}{\pi \cdot D_P}, \qquad (1)$$

where $U = \sqrt{\omega^2 - V_{fl}^2}$ is a circumferential velocity of blade tip;

V_{fl} is a flight speed of an aircraft at the design altitude;

$\omega = a_s \cdot M_{max}$ is an absolute velocity of propeller blade tip;

a_s is a sonic velocity at design altitude;

$M_{max} = 0{,}95 - 1{,}05$ is limiting Mach number of blade tip

The diameter of TPE propeller (D_P) is less than 5 – 6 m.

Designers usually seek to make gearboxes as efficient as possible to prevent unnecessary losses of power translated from the engine to the propeller, as well as to reduce thermal operational mode of gearbox and heat withdrawal to oil. The optimal efficiency of the aircraft gearboxes is 0,98–0,99. But even at that efficiency levels friction losses are considerable. Suppose the gearbox transfers 10000 kW of power. Friction losses in the gearbox at the given efficiencies are 100 – 200 kW.

The most crucial parameters of the gearbox are mass and diameter.

Mass of modern TPE gearboxes makes up 25–30% of the overall engine mass. The gearbox of helicopter is usually two or three times heavier than the TShE itself. The greater the transmitted power and the gear ratio, the heavier is the gearbox. The specific mass of the TPE gearbox (ratio of the gearbox mass to the power transmitted) ranges within 0,05 – 0,1 $\mathrm{kg}\cdot/\mathrm{kW}^{-1}$.

Diametrical size must be minimal. This is of great importance for the gearbox inside the engine. If the gearbox diameter exceeds the diameter of compressor it is very hard to guide air to axial compressor inlet with minimal hydraulic losses.

Thus, the task for the engineers is to design light, reliable and small gearbox able to transfer power at high efficiency. The problem becomes complicated if the gearbox is expected to transmit great power values or when its gear ratio is high.

The gearboxes driving single lift rotor or double lift rotor are designed basing simple, planetary and differential gears. They can be single-stage or multiple-stage depending on gear ratio.

1.2 . Classification of gearboxes

Gearboxes can be classified by different features:

1. Number of input drive shafts. The most conventional gearboxes have one input and one output shaft. But sometimes designers build gearboxes with one input and two (usually coaxial) shafts for powerful engines (e.g. NK-12).

A branched diagram with two output shafts is commonly employed at helicopters with one lift rotor and one tail rotor. Some airplanes may have power plants that consist of two TPEs driving one propeller via one gearbox. This means that this gearbox has two input shafts and one output shaft.

And finally, many helicopter power plants (e.g. Mi-24) have two engines (TV3-117) that operate with a single gearbox (VR-24). The gearbox drives lift and tail rotors or two coaxial lift rotors (helicopter Ka-25). Hereof it is obvious that gearbox RV-3F has (two engines GTD-3F) two input and two output shafts.

2. Shaft arrangement. The turboprop engines mainly use coaxial gearboxes. Gearboxes with two parallel input shafts are used in doubled engines, whereas gearboxes with two crossing shafts are applied only in power plants of helicopters.

3. <u>Number of stages</u>. According to this feature gearboxes can be one-, two-, three- and four-stage. The last one is used at helicopter power plants. The kinematic configuration of stages can differ.

4. <u>Kinetics of the stage</u>. Stages of gearboxes may be subdivided into three groups: simple, planetary and differential ones. The differential stages additionally can be classified into “loop” (one degree of freedom) and with two degrees of freedom.

5. <u>Gear type</u>. Spur gears of different size are used in the vast majority of gearboxes. As usual, bevel wheel trains are used only in gearboxes with crossing input shafts (gear train of helicopter).

Simple gearboxes

Simple gearboxes can be one- or two stage with offset and coaxial shafts and external and internal teeth.

Simple gearboxes with offset shafts (Fig. 1.1, a, b) find their application when designers need to distant propeller blades from the ground. Simple gear train with internal teeth (Fig. 1.1 a) is more compact than the train with external teeth (Fig. 1.1, b) in case their gear ratios are the same. Simple gear train with internal teeth has greater endurance strength and operates smoother.

Simple gearboxes with coaxial shafts (Fig. 1.1, c) have idler gear z_3. An idler gear does not affect the gear ratio between the input and output shafts. The purpose of an idler gear can be two-fold. Firstly, the idler gear changes the direction of rotation of the output shaft. Secondly, an idler gear can reduce the size of the input/output gears whilst maintaining the spacing between the shafts. Gearboxes with input and output shafts coaxially arranged can transfer the torque via some (usually three or six) equally spaced circumferential idler gears with fixed axes. In this case, gear teeth suffer smaller pressure and shaft bearings affected by the action of gear meshing. Coaxial shafts move the air symmetrically along the axes to the engine inlet.

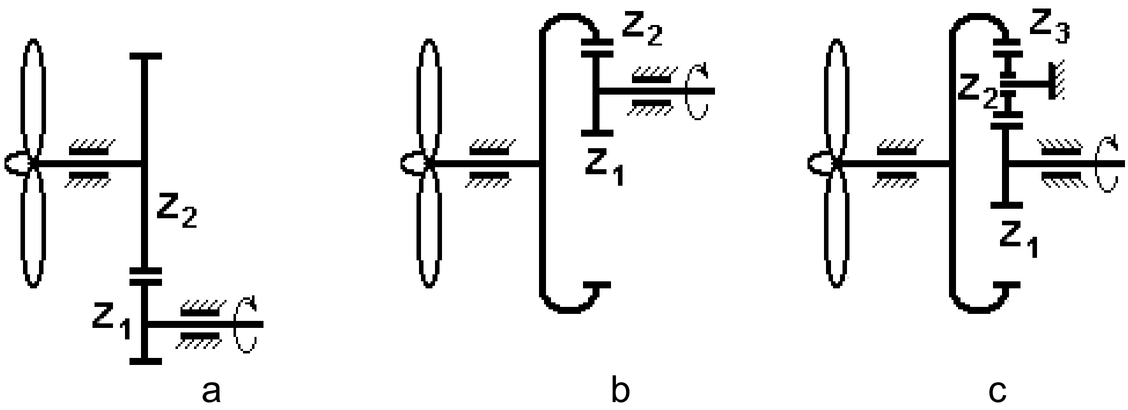


Fig. 1.1. Kinematic configuration of simple one stage gearboxes: a – with offset shafts and external teeth; b – with offset shafts and internal teeth; c – with coaxial shafts

Gearboxes with crossing shafts and bevel gears are used in helicopter drive trains as angle gears or angle countershafts.

Simple two-stage gearboxes (Fig. 1.2) provide greater gear ratios unlike one-stage gearboxes. The first stage of two-stage gearbox is usually made with external teeth; the second stage can have both with external (Fig.1.2, a) and internal teeth (Fig.1.2, c).

Unlike one-stage gearboxes, the input and output gearbox shafts are arranged coaxially by means of the lay shaft with gears z_2 and z_3 instead of the idler gears.

Similar to one-stage gearbox with coaxial shafts, power form driving shaft can be transmitted to the driven shaft via some lay shafts with fixed axes that are equally spaced around the circumference.

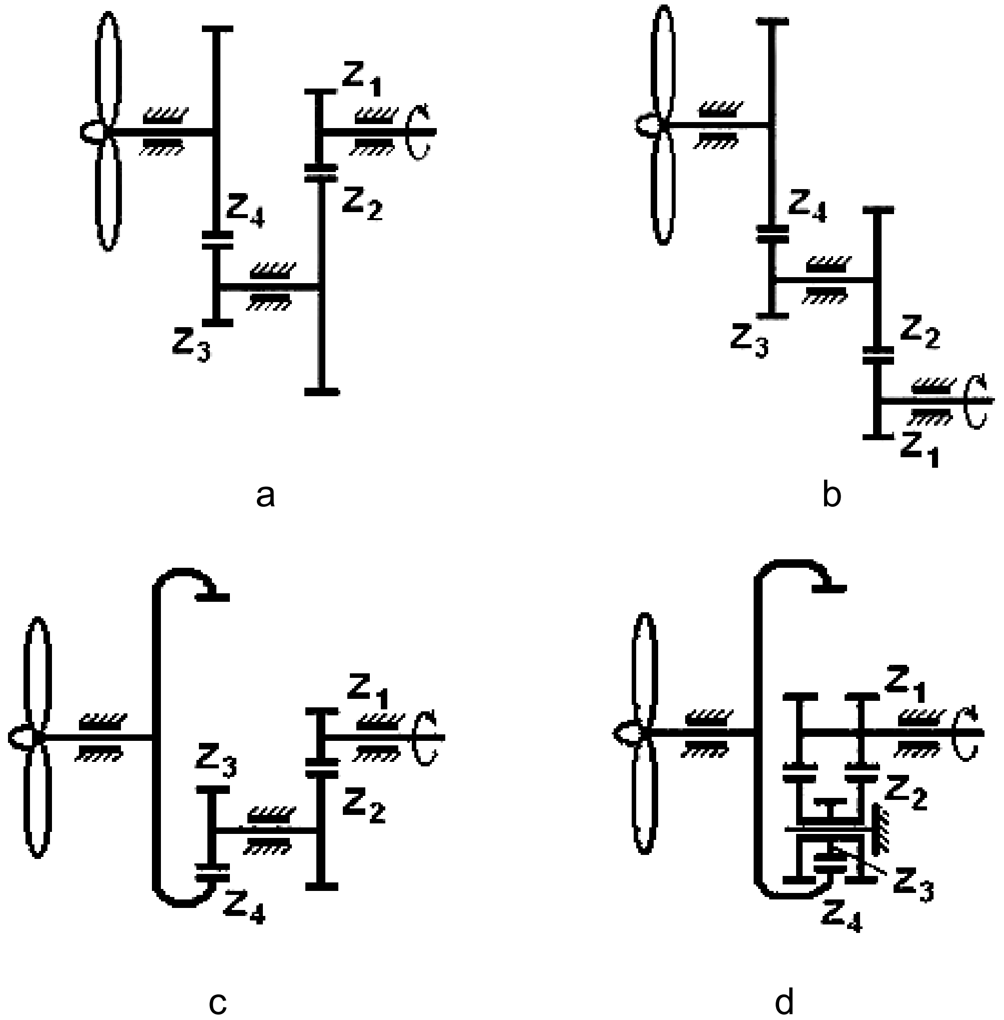


Fig. 1.2. Kinematic configuration of simple two-stage gearboxes:
a – with external teeth at both stages; b – with offset shafts; c – with external teeth at the first stage and internal teeth at the second stage;
d – with split teeth of the first stage

Gearbox lay shaft bearings (z_2 and z_3 in Fig. 1.2, a, c) are non-uniformly loaded under the action gear meshing. This disadvantage can avoided by placing gear z_3 midway between the supports (Fig. 1.2, d). Gear z_2 (Fig.1.2, d) is split and placed symmetrically relative to the supports. Input gear z_1 is accordingly split.

If gearbox has the scheme like it is shown in Fig. 1.2, a, c or d (with three equally spaced in circumferential direction lay shafts), then input shaft z_1 may have no radial bearings. It is supported by three equally spaced in circumferential direction gears z_2. Besides, if gearbox has the scheme like it is shown in Fig. 1.2, d then gears z_1 and z_2 are usually manufactured helical (leading edges of the teeth are not parallel to the axis of rotation, but are set at an angle). One of gears z_1 and z_2 has a positive angle, the other one has the same but negative angle (similar to double helical gears). In this case, gear z_1 is axially fixed without any special arrangements. If needed, the gearbox may have offset shafts (Fig. 1.2, b). The gear ratio of simple one-stage gearbox of any configuration can be calculated by the formula below:

$$i = \pm \frac{z_2}{z_1}, \qquad (2)$$

where z_1 and z_2 is a number of teeth of input and output gears respectively. The ratio is positive for gears rotating in one direction and negative for gears rotating in the opposite direction.

The gear ratio for two-stage gearboxes of any configuration can be calculated by the formula below:

$$i = i_I \cdot i_{II}, \qquad (3)$$

where $i_I = \pm \frac{z_2}{z_1}$, $i_{II} = \pm \frac{z_4}{z_3}$ is gear ratio of first and second stages respectively.

The overall size of a simple one-stage gearbox is considered acceptable if the gear ratio of the gearbox does not exceed three. Sometimes, the specific structure requires the increase of the distance between shaft axes, then the gear ratio grows to 4.

The overall size of a two-stage gearbox is considered acceptable in case the gear ratio of the gearbox does not exceed 6-8 (sometimes it may be equal to 13).

Planetary (epicycle) gearboxes

Planetary gearboxes have planet gears or planet lay shafts whose teeth can be spur or helical. Shafts in planetary gearboxes are generally coaxial. The sun gear (unlike the ring gear) serves as an input gear because such a configuration provides lower gear ratios and centrifugal forces under the action of planet gears.

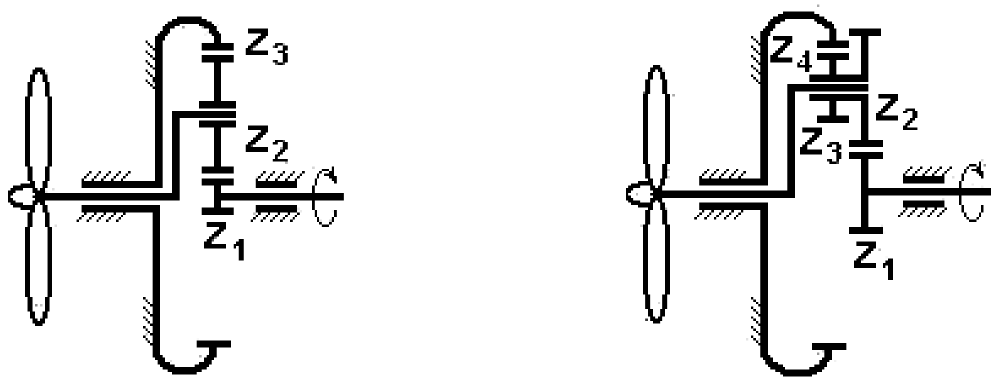
The planetary gearbox with planet gears consists of a sun gear z_1 (z_1 number of teeth, see Fig. 1.3, a), at least three planet gears z_2 (z_2 number of teeth in each planet gear), on a riding planet carrier and together riding gear z_3 (z_3 number of teeth).

The input gear transfers circumferential force to planet gears that similarly to two-class lever, roll on the riding gear and create a circumferential force on the arm of the planet carrier. Planet gears rotate together with and relatively to the planet carrier.

The equation to calculate the gear ratio of planetary gearbox with gears is as follows:

$$i = 1 + \frac{z_3}{z_1}. \tag{4}$$

Number of teeth z_3 always exceeds z_1, that is why gearboxes of the given configuration cannot provide a gear ratio equal to or less than 2. Input and output shaft rotate in one direction (the gear train is not inversive). The overall size of this gearbox is considered acceptable in case the gear ratio of the gearbox does not exceed 4 – 5.



a b

Fig. 1.3. Kinematic schemes of planetary gearboxes:
a – with planet gears; b – with planet lay shafts

Unlike the gearbox with planet gears each planet lay shaft of *planetary gearbox with planet lay shafts* has two gears (Fig. 1.3, b). What is more, the fixed riding gear meshes smaller planet gear of the lay shaft. So, the gear ratio is

$$i = 1 + \frac{z_2 \cdot z_4}{z_1 \cdot z_3}. \tag{5}$$

The overall sizs of planetary gearboxes with planet lay shafts are considered acceptable in case the gear ratio of the gearbox does not exceed 6-8 (sometimes it is equal to 14).

Differential gearboxes

The loop differential drives and two-degree-of-freedom drives are widely used to drive aircraft propellers.

The differential two-degree-of-freedom gearbox with planet gears (Fig. 1.4, a) is very similar to planetary gearbox (see Fig. 1.3) but the latter has a riding gear linked to the rear propeller. This drive is kinematically uncertain because rotational speeds of propellers can be different at a given rotational speed of the turbine. If the rear propeller is loaded until it stops, then the drive becomes planetary. If the front propeller is stopped then the drive becomes a simple drive with an idler gear. To provide equal rotational speed of both propellers, it is necessary to have two governors, each of which is cinematically linked to its own shaft.

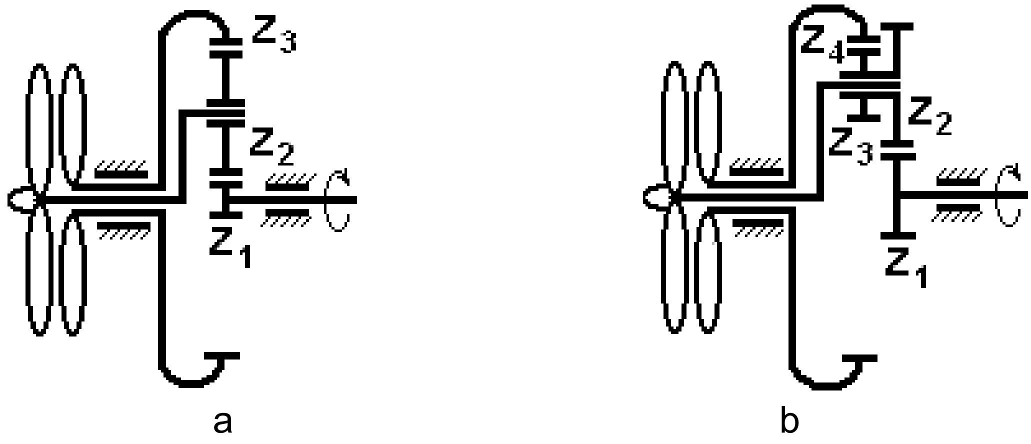


Fig. 1.4. Kinematic schemes of differential two-degree-of-freedom gearboxes: a – with planet gears; b – with planet lay shafts

The gear ratio of differential two-degree-of-freedom gearbox can be calculated as follows:

$$i = 1 + 2\frac{z_3}{z_1}. \qquad (6)$$

The differential gearbox with the gears of the same size ensures greater gear ratios than the planetary one. Maximum gear ratios may reach 8 – 10.

The differential two-degree-of-freedom gearbox with planet lay shafts (Fig. 1.4, b) is similar to the differential gearbox with planet gears. The gear ratio can be calculated as follows:

$$i = 1 + 2\frac{z_2 \cdot z_4}{z_1 \cdot z_3}.$$

Analysis of eq. (6) shows that the gear ratio of differential gearbox with two degrees of freedom with planet lay shafts is greater than the ratio of the differential two-degree-of-freedom gearbox with planet gears. The overall size of the gearbox is acceptable in case gear ratio of the gearbox does not exceed 10 – 12. To equate loads acting on planet lay shaft bearings , gears z_1 and z_2 are designed split and symmetrically placed relative to gear z_3.

Loop differential gearboxes for coaxial propellers

The differential gearboxes “looping” (bereaved of one degree of freedom) is provided by linking the two shafts. The gear train becomes regular which means that the velocity, torque and power ratios of these gears become constant. The propeller control system becomes simpler; the only one governor is needed.

There are three different ways to loop the differential gearbox (Fig. 1.5):

1) propellers are linked (Fig. 1.5, a);

2) input shaft and front propeller are linked (Fig. 1.5, b);

3) input shaft and rear shaft are linked (Fig. 1.5, c);

There are many constructive solutions to implement the above looping methods.

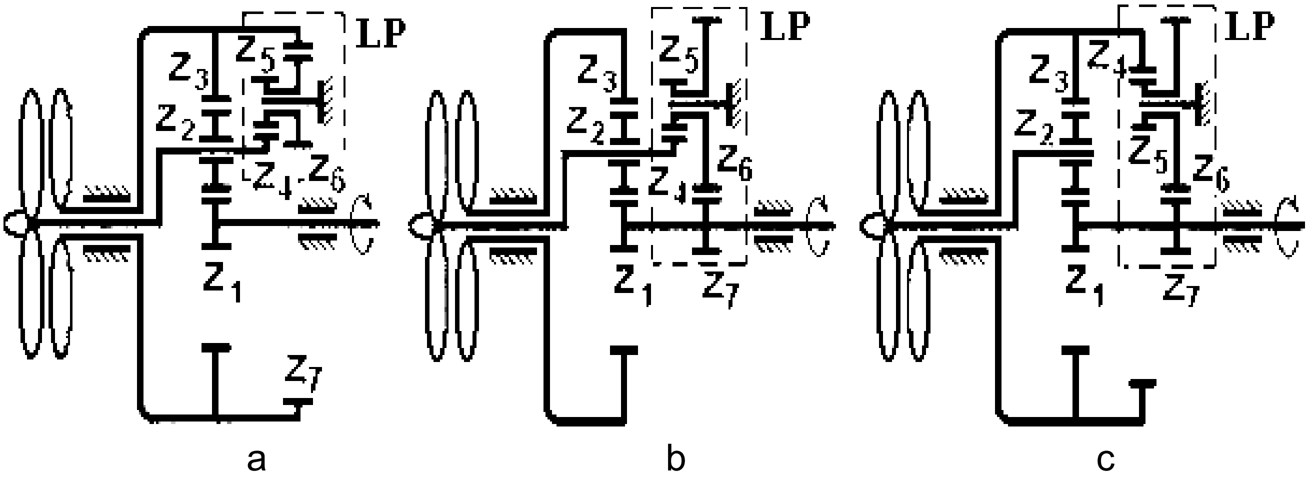


Fig. 1.5. Kinematic configuration of the loop differential gearboxes with two output shafts: a – two output shafts are linked; b – input shaft and front shaft are linked; c – input shaft and rear shaft are linked

Looping "a" was intended for the last stage of the RV-3F gearbox of the Ka-25 helicopter. If we compare looping "a" (output shafts are linked) with loopings "b" or "c" (input shaft is linked to one of the output shafts) taking into account that $n_{\text{prop front}} = n_{\text{prop rear}}$,we will obtain that "a" is more preferable. The gearbox "a" is easily designed compact because the gear ratio of the looping part must be equal to one even propellers have different rotational speeds.

The looping part of "b" "c" turns out to be bulky, because in this case $i_{LP} = i_{GB}$. If $n_{\text{prop front}} = n_{\text{prop rear}}$ then $N_{\text{prop front}} = N_{\text{prop rear}}$. The front propeller gear train is unloaded. The power is delivered to the rear propeller by two power fluxes – through major and looping parts:

looping "a"

$$N_{LP} = \frac{N_{ENG}}{2 \cdot i}; \tag{7}$$

looping "c"

$$N_{LP} = \frac{N_{ENG}}{1 + i}. \tag{8}$$

To reduce the forces and moments acting on the looping part of the gearbox, looping parts can be duplicated (two or more looping parts working in parallel).

Loop differential gearboxes drive one propeller

This gearbox was widely used in the Soviet, Russian and Ukrainian engine designs because it is rather cinematically effective, constructively simple, compact, light, easy to manufacture and reliable. The looping part of this differential gearbox is arranged between ring gear and planet carrier.

Sun gear z_3 (see Fig. 1.5, a) can be linked to propeller via simple gear train z_4, z_5 and z_6, as is shown in Fig. 1.6, a.

The formula to calculate the gear ratio of the gearbox is

$$i = 1 + \frac{z_3}{z_1} + \frac{z_3 \cdot z_6}{z_1 \cdot z_4}. \qquad (9)$$

The diameter of the gearbox is thought acceptable in case the gear ratio is less than 12 – 15.

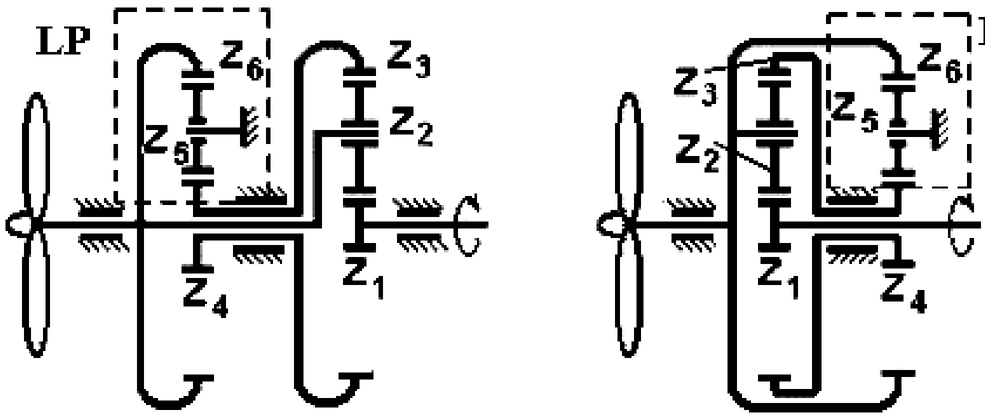


Fig. 1.6. Kinematic configuration of loop differential gearboxes that drive one propeller:
a – with looping part right downstream the propeller;
b – with looping part right after differential stage

The active torque is transmitted to output shaft by two power fluxes:

$$M_{PROP} = M_1 + M_2, \qquad (10)$$

where M_1 and M_2 are torques that are transmitted via planetary and simple gearbox parts respectively.

It is obvious, that

$$M_1 = M_T \left(1 + \frac{z_3}{z_1}\right),$$

$$M_2 = M_T \cdot \frac{z_3 \cdot z_6}{z_1 \cdot z_4}.$$

The analysis of eq. reveals that $M_2 > M_1$, i.e. simple gear train is loaded heavier.

For example, if $z_1 = 46$, $z_3 = 104$, $z_4 = 60$, $z_6 = 108$, we have M_1=45 % and M_2=55 % of total torque M_{PROP} transmitted via output shaft (shaft of propeller).

This type of gear train is also widely used to obtain moderate gear ratios. To obtain moderate gear ratios the loop differential gearboxes that drive one propeller are more preferable, because:

– the overall size of the gearbox is smaller, whereas planetary gearbox gear ratios stay the same;

– the diameter of z_1 can be selected bigger, whereas the overall size and gear ratio remain the same; the circumferential force acting on gear meshing and the forces acting on idler bearings are also lower.

So, differential loopings with two linked output shafts (the link is provided by the simple gear train with spur teeth) is widely used nowadays because the parameters of this gearboxes can be varied greatly.

1.3 . The number of gear teeth

It should be noted that each range of gear ratios has “gaps”. “Gaps” are gear ratios that cannot be obtained. It is obvious that each gear must have an integer number of teeth, whence it follows that gear ratio cannot be an irrational number (the irrational number is any real number that cannot be expressed as a ratio of integers; informally, this means that the irrational number cannot be represented as a simple fraction).

When selecting number of teeth one must take into account that:

- the teeth number for each meshing gear shall ensure the needed gear ratio;
- specific gear design requires specific number of teeth;
- coaxial arrangement shall be provided;
- non-interference between the meshing gears shall be provided.

The above requirements reduce the number of teeth that can be selected. The dimensions of gears, preliminary determined by the velocity vector diagram, must be adjusted according to the number of teeth selected. Finally, the gear dimensions are chosen after strength analysis has been done.

As it was mentioned above, the final gear ratio may be somewhat different from the pre-calculated ratio. But all the three geometrical requirements (specific design, coaxial arrangement and non-interference) must be strictly met.

<u>Specific design.</u> If planet lay shafts of simple, differential or planetary gearbox are symmetrically placed relative to its axis, and if their gears are equidistant relative to each other, then Kudriavtsev equality must be met to provide the meshing between all the planet gears and sun gears:

$$\frac{z_2 \cdot z_4 + z_1 \cdot z_3}{k \cdot z_2} \pm \frac{z_3}{z_2}\left(E_\alpha - n_\alpha\right) = E, \tag{11}$$

where k is number of planet lay shafts (gears); E_α is the closest integer greater than $\frac{z}{k}$; $n_\alpha = \pm(0,1,2,3,...)$, E is an integer;

Upper signs are valid for cases when sun gears have different teeth, lower signs are valid for sun gears that have identical number of teeth.

The mounting condition for planet gear (i.e. $z_2 = z_3$) is simplified:

$$\frac{z_1 + z_4}{k} = E. \tag{12}$$

Specific design requirements for gearboxes with two coaxial output shafts must be taken into account for each gear train (for each power flux). Specific design requirements for loop differential gearbox with one output shaft to drive the dual propeller (K is the number of looping parts) must be met for both differential and looping parts

Coaxial arrangement. Coaxial arrangement means that axle spacing (A) in all gear rows must be equal (gears will not be corrected):

$$A = R_1 \pm R_2 = R_3 \pm R_4 = R_5 \pm R_6. \tag{13}$$

Coaxial arrangement for planetary drive (in case idler teeth are not split) is as follows:

$$R_1 \pm R_2 = R_4. \tag{14}$$

Sign “+” shall be chosen if gears have external teeth, and inversely sign “-” is used for gears with internal teeth.

It is obvious, that coaxial arrangement requires the following:

$$(z_1 \pm z_2) \cdot m_{12} = (z_3 \pm z_4) \cdot m_{34} = (z_5 \pm z_6) \cdot m_{56}, \tag{15}$$

where m_{12}, m_{34}, m_{56} are pitches of gears 1 and 2, 3 and 4, 5 and 6 respectively.

The number of teeth selected for each meshing gear shall provide the needed gear ratio. To prevent idlers interference, the following equation must be met:

$$\frac{2 \cdot \pi \cdot A}{k} > D, \tag{16}$$

where D is an external diameter of the sun gear in the plane of the largest planet gear.

To prevent idlers interference with the main shafts (for any k), it is necessary that

$$D < A - d_{sh}, \tag{17}$$

where d_{sh} is an internal diameter of the sun gear in the plane of the largest planet gear.

In case when there is no central shaft in the plane of the largest planet gear (this case occurs rarely), the condition is simplified to

$$D < A. \tag{18}$$

To conclude, it becomes clear that not only the correlation $i = i_{given}$, but also the requirements for specific design and coaxial arrangement shall not be strictly followed, since the number of teeth can be modified and due to the ability of the involute gear to operate well even the center-to-center spacings are not precise. Only the non-interference requirement shall be strictly met.

2. CONSTRUCTION AND STRENGTH OF MAJOR ELEMENTS OF GEARBOXES

The main gearbox components are gears, planet carriers, shafts, shaft supports and casings. Their configuration may also include torque metering unit, propeller-drag sensor and lubrication system. Conventionally, the main gearboxes of helicopters have overrunning clutches.

2.1 . Gears

The major gear types include sun gears, riding gears, idler gears (planet gears, gears of trains).

Spur gears with involute profile found a widespread application in gearboxes, but in some instances other types of gears are applied (helical and double helical gears). Spur gears can be manufactured with high precision Helical and double helical gears are stronger, more vibration-proof and have a lower noise level. However, they require more complex manufacturing techniques than spur gears. Gears can be flanked (i.e. part of theoretical profile is changed) to avoid striking between the meshing teeth, to decrease the noise level, to provide smooth meshing. They can be also modified (i.e. standard sizes may be changed) to prevent tooth undercutting for gears with small number of teeth, to improve strength parameters and to decrease friction losses. The bottom lands of gears are designed to have big fillets to decrease the stresses in areas with stress concentrators.

The modules of gears must range within the limits of 2,5…5,0. The total depth is relatively great ($(2,2...2,8)\cdot m$). Deep teeth have great bending pliancy that equalizes the loading due to transmitted torque. The circular thickness depends on transmitted circumferential force and may reach (10…20) m. When the circular thickness increases, the gears can suffer misalignment, uneven loads and circular wear. The misalignment usually results in the edge contact of gears. The number of teeth, their diameters, the number of idler gears in gearboxes are determined according to the needed gear ratio. All the requirements shall be also met for planetary and differential gearboxes (see par. 1.3).

The Sun gear is attached to the input shaft of the gearbox. Its initial pitch diameter must be as minimum as possible, in order to obtain the smallest overall size of the gearbox and low circumferential speed (v_1). The maximum circumferential speed must not exceed $120-150\frac{m}{s}$, otherwise dynamic forces acting on the meshing drastically increase.

The minimum possible pitch diameter D_1 has the next limitations:

– the gear shall have enough teeth to meet the no-undercut requirement (minimum number of teeth is 17–20);

– the minimum possible diameter of input shaft is limited by the maximum torque that can be transmitted through the shaft and by the growing circumferential force acting on the meshing teeth.

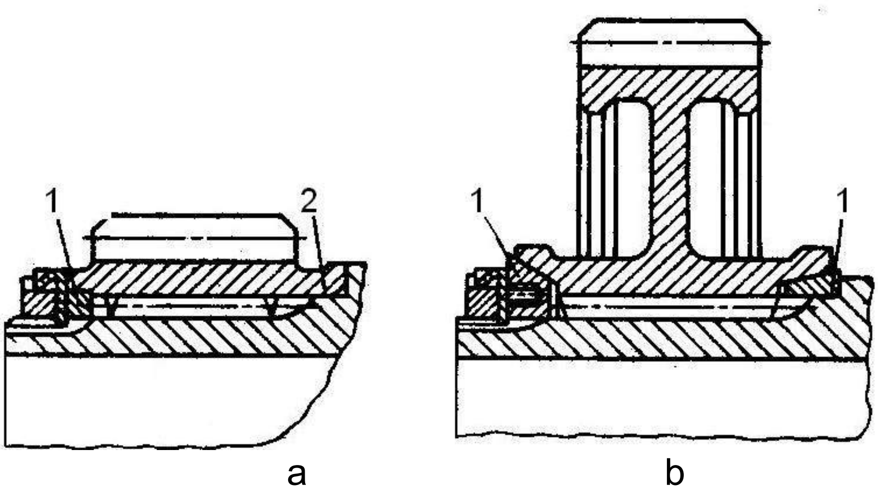


Fig. 2.1. Sun gear: a – centering of the gear by the conical ring and centering fillet; b – centering of the gear by conical split ring; conical ring; 2 – centering fillet

The sun gear and input shafts are usually made separate (Fig. 2.1), and only in some instances (e.g. small gear diameter) they are manufactured as a single piece. The integrated structure facilitates the gear manufacturing process.

The sun gear can be attached to the shaft rigidly (spline, flange or pin joints) or form a movable joint. Due to this the torque acting on each planet gear equalizes. Besides, small misalignment of shafts, sags of input shaft do not turn to misalignment of gears. This is advantageous because the load acting on the tooth is uniformly distributed along circular thickness of the tooth. Axial displacements of gear relative to shaft are constrained by the spring rings.

The riding gear with internal teeth is shown in Fig. 2.2. Depending on the kinematic layout of the gearbox, the riding gear can be fixed (attached to the casing of the gearbox) or rotating (linked to the propeller hub). The gear is attached to the casing or the hub by moving splines. The casing is manufactured from light alloys. Hence, to avoid casing destruction a steel intermediate sleeve is pressed in the casing. In many planetary gearboxes the riding gear is attached to the casing via hydraulic cylinders of torque metering unit. The riding gear is manufactured as small as possible to improve its elasticity. The riding gear is deformed radially under forces acting on meshing. This helps to equalize the load transmitted via lay shafts that work in parallel.

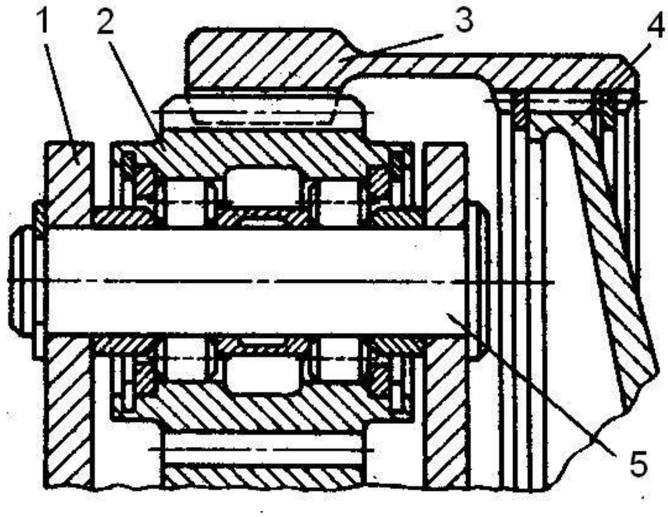


Fig. 2.2 . Riding gear: 1 – planet carrier; 2 – planet gear;
3 – sliding annulus of riding gear; 4 – shaft hub; planet gear axis

Idler gears in the gearboxes with coaxial shafts are equally spaced in the circumferential direction. The number of idler gears (lay shafts) shall not be less than 2-3 in order to transfer the torque with parallel fluxes and decrease the forces acting on the teeth of gears, to unload the bearings of main shafts from reaction forces that appear in the process of meshing when the torque is transmitted.

To facilitate the assembling process of coaxial gearboxes, designers widely use the following design of the lay shaft: one gear of planet (idler) layshaft is pinned to or taper-tightened with another one only after they were assembled in the gearbox (Fig. 2.3).

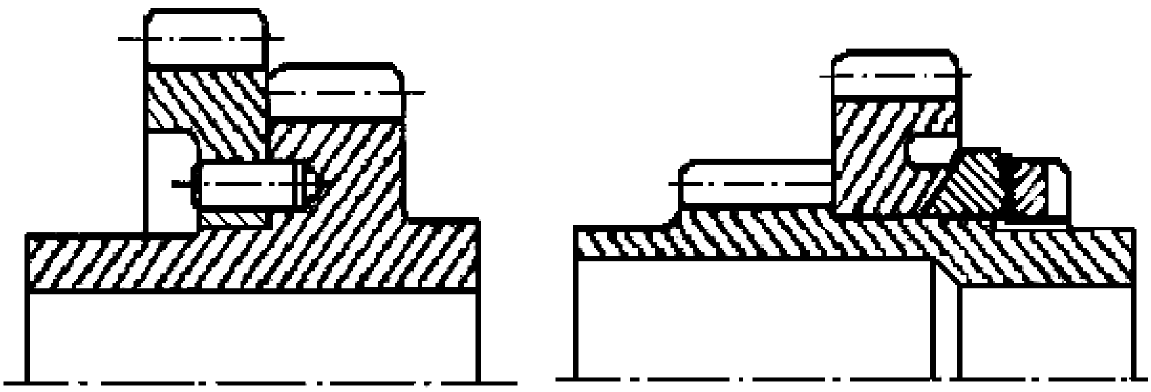


Fig. 2.3. The layout of the planetary lay shaft

The gears are manufactured from chromium-nickel-tungsten and nickel-chromium-molybdenum steels12Х2Н4А, 18ХН4ВА, 40ХНМА, 38ХМЮА. After the teeth have been cut, the working profile (in the form of an involute of circle) is carbonized (to a depth of 1,0…1,5 mm), nitrided (to a depth of 0,3…0,8 mm), or cyanided. The teeth are accurately cut. A positive or negative profile deviation from true involute must not exceed 0,01…0,015 mm. The pitch deviation from the major pitch must not exceed 0,01…0,015 mm. To provide equal loads, which are transmitted via lay shafts that work in parallel, planet gears are assembled according to the selection principle (idler gears are selected to have same clearance when meshing with sun and riding gears).

The clearance shall not exceed the nominal value of 0,05…0,10 mm for the gear set. At the final stage of manufacturing process, the teeth are grinded and lapped to remove burns caused by grinding.

The *teeth strength* is calculated in the mode of maximum engine power. For standard turboprop with no power limitations the designed strength corresponds to the aircraft low-altitude flight with maximum speed and low air temperature ($T_{amb} = -40°C$). The designed power of high-altitude turboprop is determined under the condition of limited power mode.

The analysis aims to obtain the contact and bending stresses. The longitudinal distribution factor (taking into account the axe misalignment and manufacturing errors) is predetermined as great as 1.1, planetary gears distribution factor is as great as 1.15, the equivalent loading factor that considers engine operation in different modes is as great as 0,8…0,9. The contact stresses in the pitch point characterize the working profile ability to stand fatigue flaking. The contact stresses in available designs are $\sigma_{cont} = (8-14)\cdot 10^8 \frac{N}{m^2}$, $\tau = (3-5)\cdot 10^8 \frac{N}{m^2}$. To reduce the contact stresses it is necessary to increase the diameter size and the width of tooth rim.

The bending strength analysis determines the teeth sizes to ensure sufficient fatigue strength. Bending stresses in available designs are $\sigma_{bend} = (1-4.2)\cdot 10^8 \frac{N}{m^2}$; safety factors are 1,4…3,0. To reduce the bending stresses it is necessary to decrease the number of teeth and increase their modulus.

2.2 . Planet carrier

Planet carrier is a cage-like structure with gaps for inserting planet gears. The planet carrier of the NK-12 turboprop gearbox is presented in Fig. 2.4, the anatomy of the planet carrier is presented in Fig. 2.5.

To meet the specific design requirements and facilitate the production, planet carriers are designed to be detachable. Planet carriers are manufactured separately from the shaft and then bolted to it through flange connection. The bridges between the gaps shall be rigid enough to avoid the front side surface turning relative to the rear side surface under the action of circumferential forces. This turning results in the misalignment of planet gear axes and non-uniform longitudinal load distribution along the gear teeth.

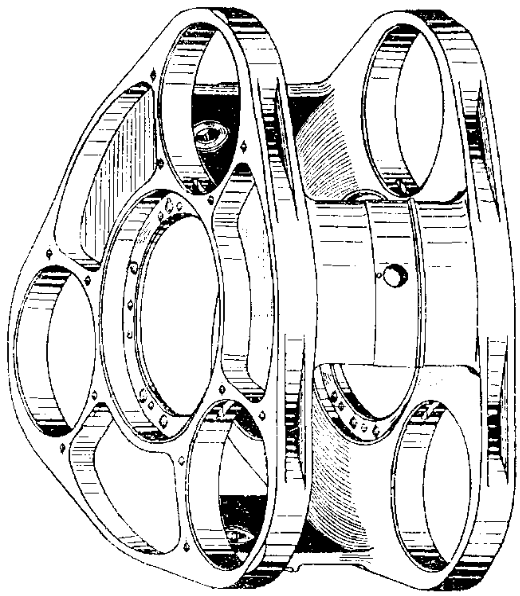


Fig. 2.4. Planet carrier

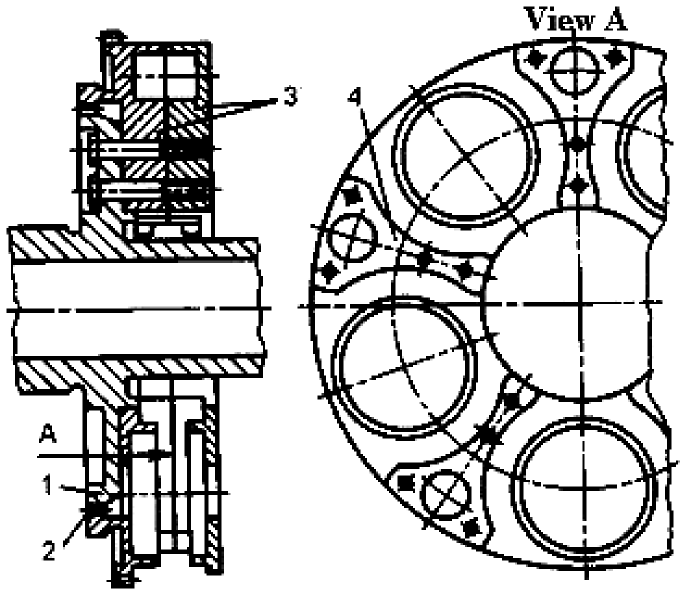


Fig. 2.5. The anatomy of the planet carrier

2.3 . Shafts

The gearbox shafts are input and output (propeller) shafts. The input shaft is quite often manufactured as a torsion shaft with splines that join it to the engine rotor and to the input gear of the gearbox. The torsion shaft reduces dynamic loading on the gear teeth. The torsion shaft suffers no axial displacement relative to the engine rotor by the bearing or by resting the neighboring parts. The output shafts are designed hollow. There are oil system pipelines to control propeller pitch in the internal cavities of output shafts. The flanges in the front part of shafts fasten the bushes of propellers.

The following forces are considered in the strength analysis of shafts:

– torque moments;

– propeller thrust that results in tensile stresses in thrust bearing area;

– propeller inertia that results from aircraft maneuvers and bends the shaft;

– gyroscopic moment that appears during aircraft maneuvers and bends the shaft;

– lateral force due to oblique propeller fanning (this mode corresponds to the yawed aircraft flight). For coaxial propellers of big diameter (5 – 6 m) this force is $(4-6)\cdot 10^4\,\mathrm{N}$.

The designed mode is the maximum power mode when aircraft flies at operating overload (3–4) with oblique propeller fanning. The strength analysis for gearbox shafts is very similar to the strength analysis for compressor and turbine shafts. Stresses in shafts of available designs are $\sigma = \left(0{,}5 - 2{,}5\right) \cdot 10^8 \, \mathrm{Pa}$, $\tau = \left(0{,}5 - 3{,}0\right) \cdot 10^8 \, \mathrm{Pa}$, $\sigma_{SL} = \left(2{,}0 - 3{,}5\right) \cdot 10^8 \, \mathrm{Pa}$.

The fatigue strength safety factor in case of symmetrical loading is equal to $1{,}2 - 1{,}6$.

Shafts are manufactured from alloyed steels. Shafts are cadmium plated or oxidized to prevent corrosion. Shafts are copper plated in the areas of possible hardening (movable spline joints).

2.4 . Casings

The casing serves to accommodate gears, shafts, shaft supports and other gearbox elements. It joins them together to form a separate structural assembly. The gearbox often contains aircraft drives and engine auxiliaries. The annular duct is machined in the gearbox casing to guide the airflow to compressor inlet (only for engines with gearbox at the inlet). In case of a simple gearbox with two diametrically opposite power fluxes two separate ducts are provided to deliver air to compressor inlet. This design is advantageous because this gearbox does not increase the diametrical size of the casing.

When a new casing is under development, special attention is paid to its high rigidity. Insufficient rigidity of casing results in gearshifts and problems in meshing. Casings with stiffening ribs are cast from aluminum or magnesium alloys. Dividing plates in the casing are manufactured detachable from the casing itself to meet the design requirements. If gear or shaft bearings are housed in the dividing plates, the designers will provide the failsafe centering and fixing for the dividing plates in the casing. Magnesium casings are exposed to fluorination with further coloring of their outer surfaces. The hole for the output shaft goes out from the gearbox shall be sealed by oil-seal rings or cups, a valve stem thread or a disk, or their combination. The gearbox casing is bolted or studded to the casing of compressor (through flange connection). Joints of casings are sealed with self-vulcanizing heat-resistant sealants. The sealants shall not be affected by air, oil or fuel.

3. AUXILIARIES

3.1.Torque metering unit

The torque metering unit (TMU) is used in aircraft TPEs and helicopter GTEs. It is designed by the pilots to measure the torque during the take-off and in flight and by the engineers at development and testing stages of manufacture. The TMU has different functions depending on the flight modes:

– in take-off mode the TMU indicates the power sufficient for taking-off;

– at high flight speeds the TMU may limit the maximum acceptable power depending on the gearbox strength;

– at cruising speeds the TMU helps the pilot to keep the most efficient rate of fuel consumption;

– in case of engine failure the TMU switches the propeller blades to feathering position and prevents the aircraft crash.

TMUs are subdivided into balanced piston TMUs, electronic phase shift TMUs and electromechanical TMUs. The most conventional TMUs used in aircraft engines are balanced piston TMUs because of their simple structure and high operational reliability.

Let`s consider the lever-type TMU (Fig. 3.1) as a subsort of balanced piston TMUs.

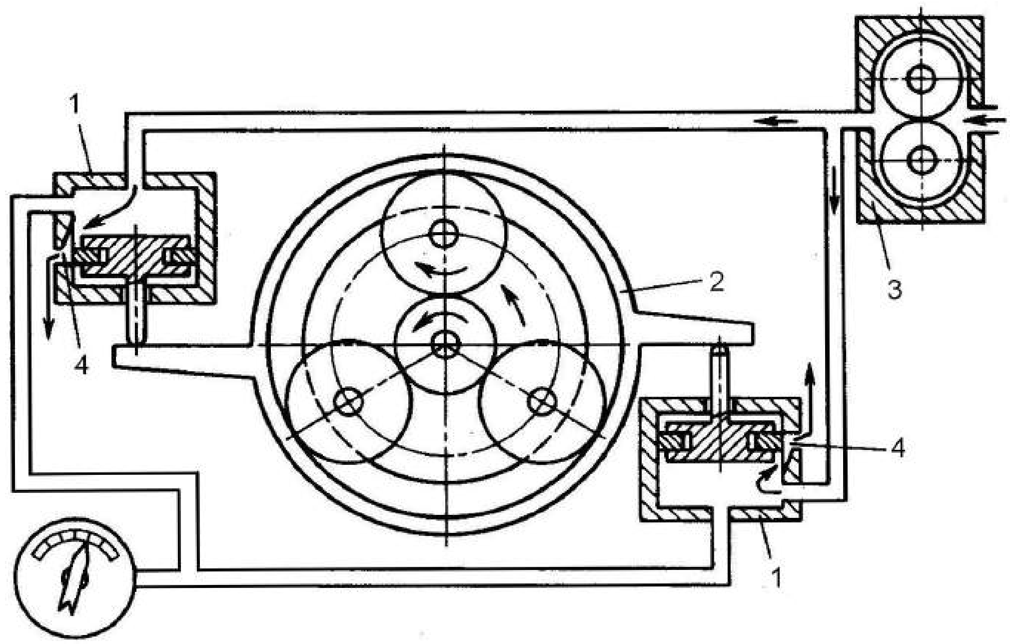


Fig. 3.1. The layout of lever-type balanced piston TMU:
1 – hydraulic ram; 2 – idler casing; 3 – oil pump; 4 – apertures for oil removal

This type of TMU is used in gearboxes whose gears have fixed axes (e. g. gearbox of AI-20 turbofan). The lever-type TMU measures the torque acting on the gearbox casing. The torque is balanced by the counter torque that emerges due to the oil pressure in hydraulic rams.

When pressure increases, the piston starts moving in the hydraulic rims. The piston gradually closes the apertures for oil removal that results in pressure rise inside the hydraulic rims. The required oil pressure in the system is provided by a special oil pump of the TMU attached to the gearbox casing. The oil pressure is measured by manometer whose scale can be calibrated in units to measure torque or even power (if the rotational speed in all modes is constant).

In case gearbox has no gears with fixed axes (e.g. differential gearbox of the NK-12 turboprop coaxial propellers), the torsion-type TMU is used. It transforms the torsion angle of gearbox input shaft to oil pressure. The angle of elastic torsion φ is proportional to the torque M that is transmitted via the shaft:

$$\varphi = \frac{M \cdot L}{I_\rho \cdot G}, \qquad (19)$$

where I_ρ is a polar moment of inertia;

G is a shear modulus;

L is the distance between the sections used to measure the relative torsion.

The torsion TMU may have a layout as presented in Fig. 3.2. It has spring 1 inside the hollow shaft 7 which transfers the torque. Unlike shaft 7 spring 1 is doesn’t transfer the torque.

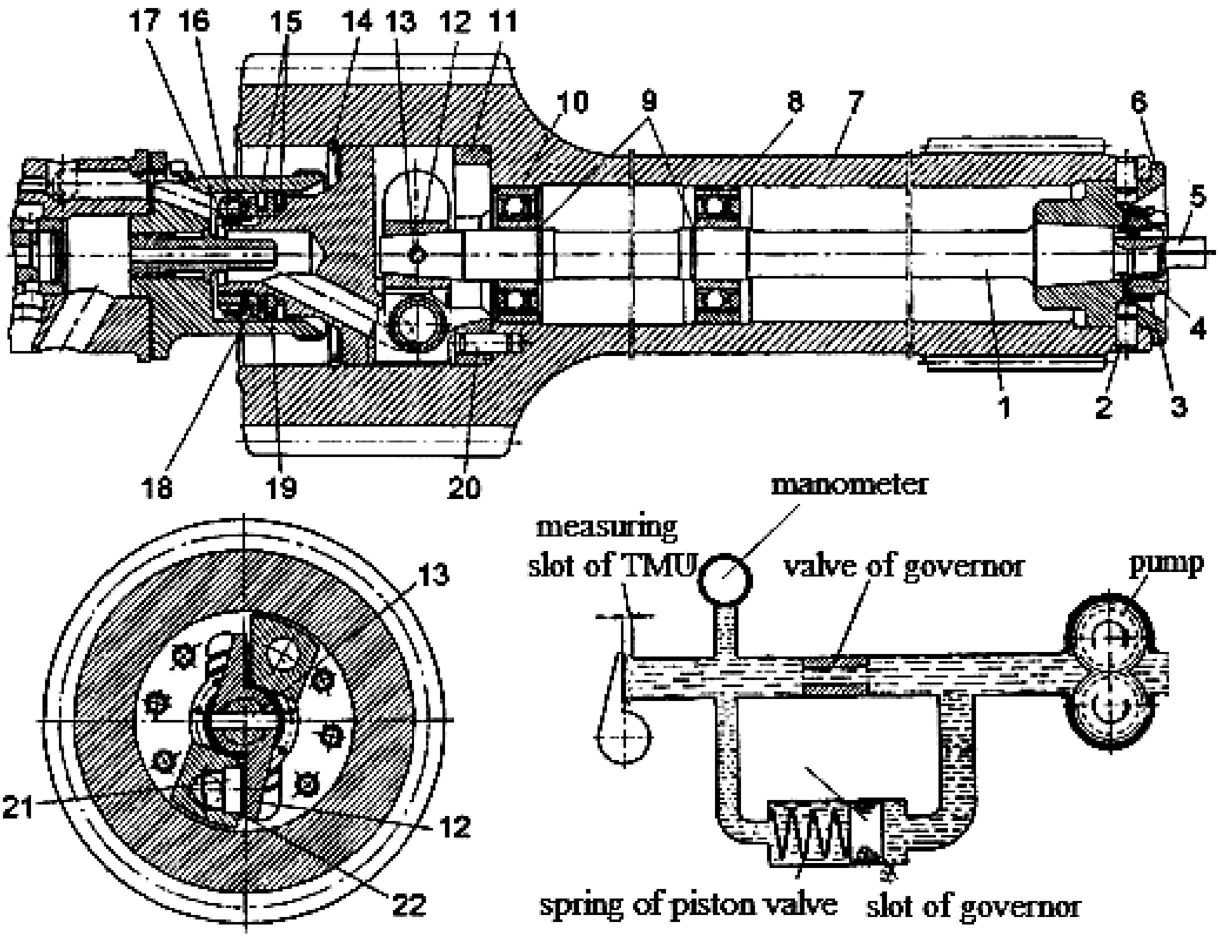


Fig. 3.2. The layoput of torsion-type TMU:
1 – spring; 2 – pin that fixes the bush; 3, 16 – lockings; 4, 17 – nuts; 5 – hexagonal spring shank; 6 – bush; 7 – drive shaft; 8 – rear bearing; 9 – locking rings of the bearing; 10 – front bearing; 11 –TMU casing ; 12 – lobed sleeve; 13 – pin that fixes the lobed sleeve; 14 – locking ring; 15 – oil sealing ring; 18, 19 – ring holders; 20 – pin to attach the TMU casing; 21 – oil supplying channel to deliver oil to slot; 22 –TMU slot

Spring 2 is pinned to the shaft at one side, and at the other side it is attached to the throttle lobed sleeve 12. The lobe of throttle lobed sleeve is manufactured of 12X2H4A steel and then is post-carburized. The oil is pumped by a special oil pump through channel 21 and delivered to TMU slot. The slot is formed by the lobe, the other lobe is used for balancing only.

When transmitted by the shaft, the torque changes, as a result, the elastic torsion is also proportionally changed. This leads to slot reduction and oil pressure decrease that is measured by manometer.

The oil supply system of TMU also has a governor to provide constant oil supply to TMU regardless of the pressure in the system or oil flow pumped to oil supplying system inlet. The governor consists of an orifice and a spring-controlled piston valve that controls oil removal through the slot of the governor.

Electronic phase shift TMU is intended for contactless way of measuring. This type TMU consists of rotating torsion bar with inducers which periodically get to magnetic field of induction sensors. The torsion angle and the correspondent torque are determined by the mismatch of phases of the first and the second inducers.

3.2. Sensor of negative thrust

The sensor of negative thrust is responsible for switching the propeller to feathering mode in case it produces negative thrust, i.e. thrust that is directed opposite to the flight direction. Negative thrust appears in case of engine failure or in some other instances. The operating principle of the sensor of negative thrust is shown in Fig. 3.3.

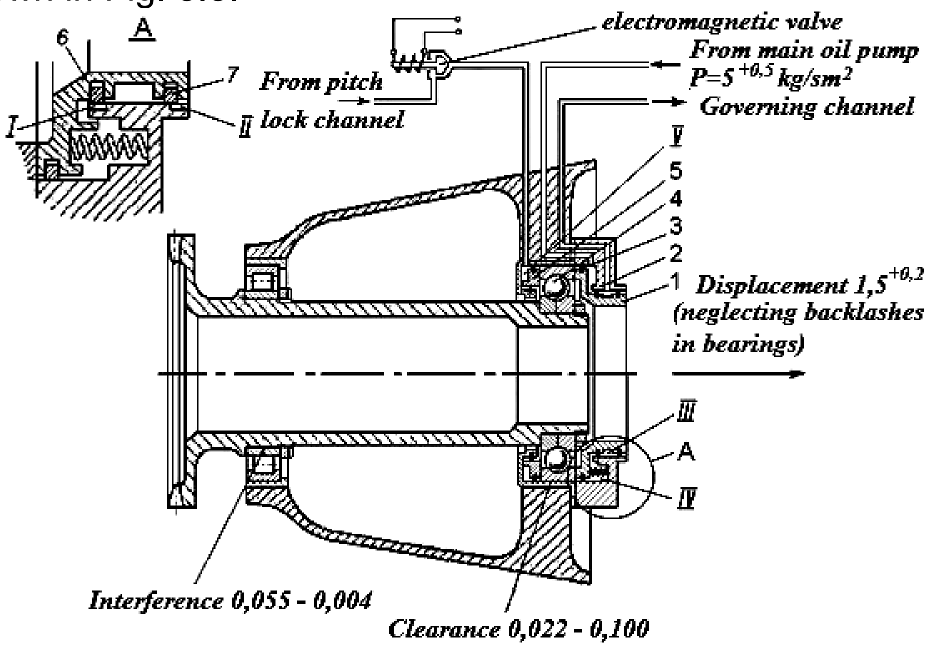


Fig. 3.3. The sensor of negative thrust:
1 – piston; 2 – cylinder; 3, 6, 7 – sealing rings; 4 – ball bearing; 5 – checker piston;
I – slot for pumping oil to command channel; II – slot for removing oil from command channel; III – annular groove; IV – cavity; V – oil cavity of checker

The Sensor of negative thrust is mounted in propeller shaft support. This support transfers thrust to the gearbox casing. When negative thrust appears, the propeller shaft is displaced forming the control action in a form of oil pressure.

3.3. Helicopter gearbox overrunning clutch

The overrunning clutch (OC) provides:

– smooth and shock-free automatic clutching between the output and input engine shafts of main gearbox during the start;

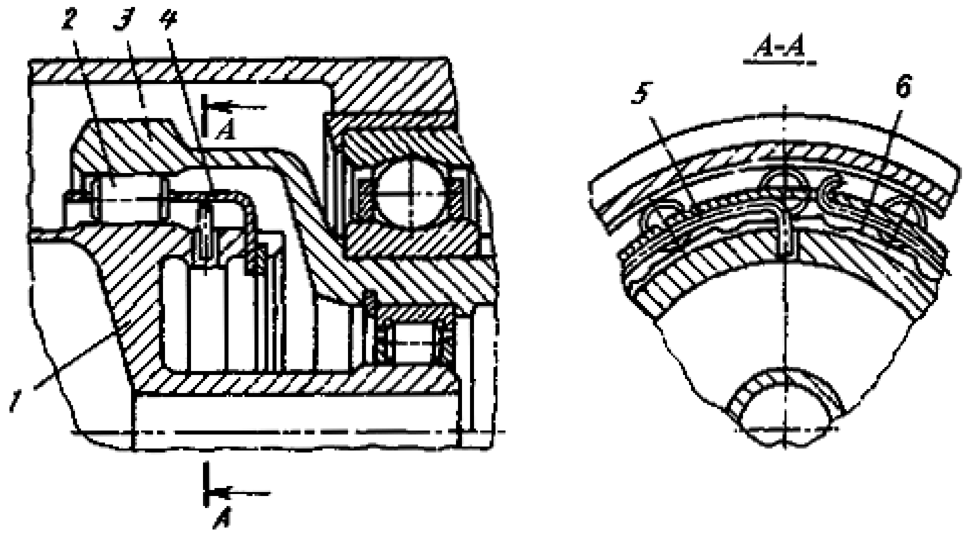


Fig. 3.4. The anatomy of roller OC:
1 – input shaft; 2 – roller; 3 – output shaft; 4 – cage; 5 – spring; 6 – flat

– declutching between the shafts in case of an in-flight failure;

– an opportunity to test engines separately in case the helicopter power plant consists of two engines.

A roller overrunning clutch is most conventional because it is of high carrying capacity and has a small overall size, it has high idling speed and low noise level.

The main structural elements of the roller OC include an input link (gear), an output link (racer), jamming rollers and cage-like pressing actuator (Fig. 3.4). Cage-like pressing actuator is aimed at bringing the rollers in permanent contact with the racer and the input gear to avoid «free play» while jamming, simultaneous jamming of all rollers and smooth distribution of loads in the rollers lengthways as well as between all the rollers.

4. THE AI-20 TURBOPROP GEARBOX

4.1. The gearbox kinematic scheme

The gearbox is intended to transfer excessive power of high pressure turbine to propeller and to coordinate the most efficient rotational speeds between the engine rotor and the propeller.

The gearbox has a loop differential structure (Fig. 4.1).

Gearbox z_1 is mounted on the input shaft. It is meshed with six planet-gears z_2, which in their turn are meshed to gear z_3. Gears z_2 rotate about their axis, driving gear z_3 and making axes of planet carrier rotate. The axes are linked to the propeller shaft.

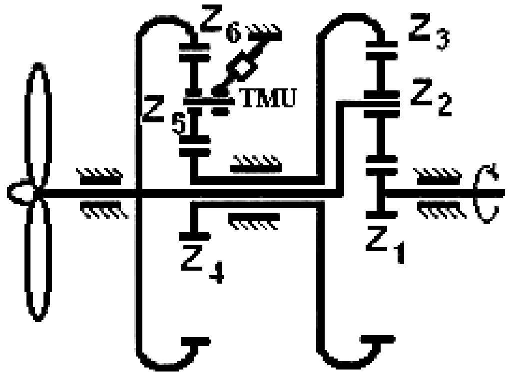


Fig. 4. 1. The kinematic scheme of AI-20 TFE gearbox

Gears z_3 and z_4 form the lay shaft which is meshed with six idlers z_5. The idlers rotate about their axes, which are pressed into the fixed casing of the gear train.

Gear z_5 transmits rotation through the internal toothing gear z_6 to the propeller shaft.

The fixed casing of idlers (z_5) is attached to the gearbox casing through the torque metering unit (TMU).

Thus, the torque is transmitted from the engine rotor to the propeller shaft in two fluxes: via the planet carrier (gears z_1, z_2, z_3 – about 30%), and via the looping gear train (gears z_4, z_5, z_6 - the rest part).

The gear ratio of the gearbox is $i = 11{,}45$.

4.2. The gearbox design

The AI-20 turbofan gearbox consists of the following basic components (Fig. 4.2):

- casing 3 with all the parts and assemblies fitted inside;
- diaphragm 17;
- input shaft 19;
- planetary stage that consists of sun gear 18, six planetary gears 23, inner engagement gear 14, planetary train hub 13 and casings of planetary gears 15;
- gear train stage (closed-loop transmission) with drive gear 10, six idlers 25, inner engagement gear 9, looping train hub 26 and looping train casing 11;

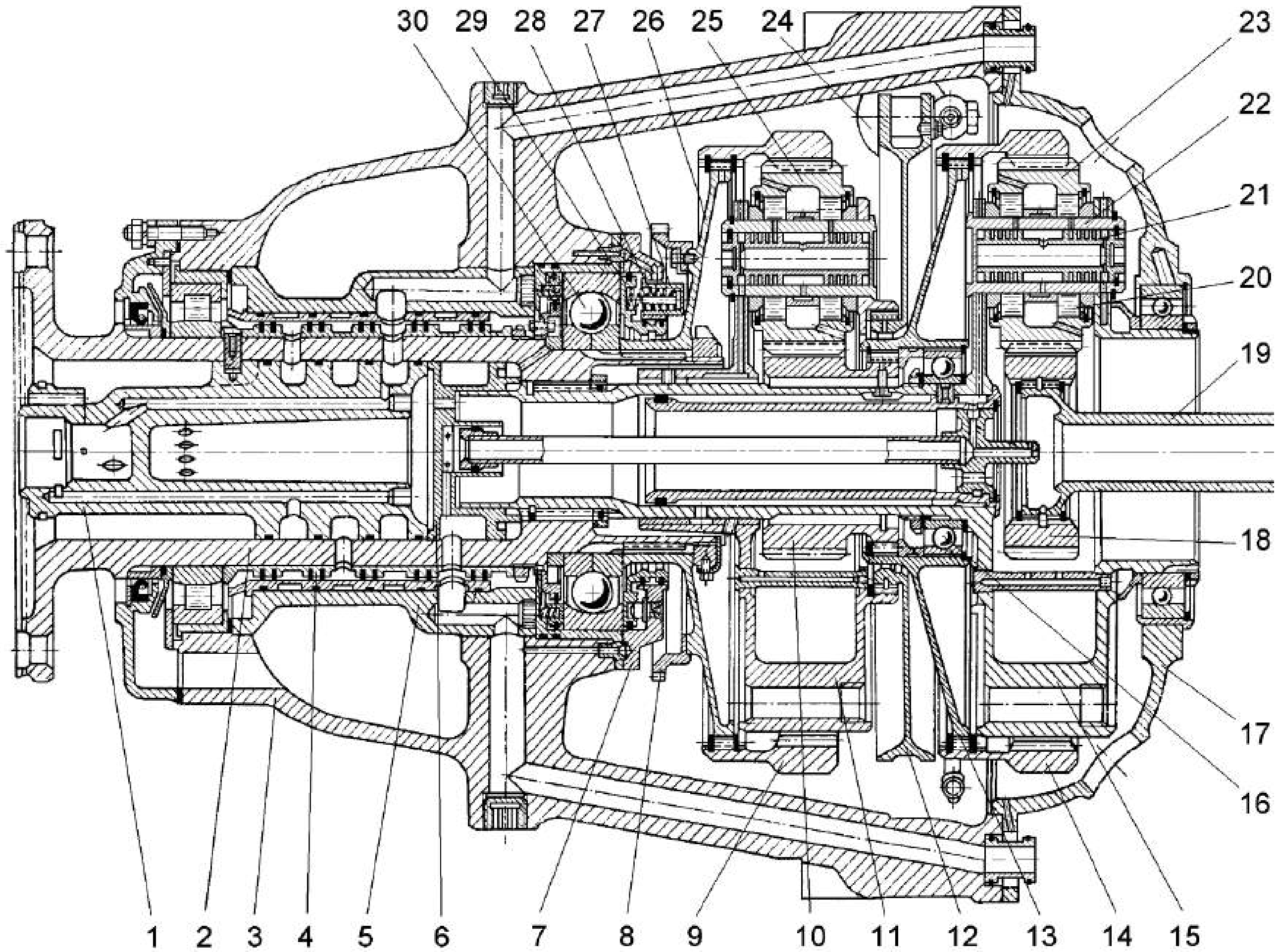


Fig. 4.2. The AI-20 turbofan gearbox

- propeller shaft 2;
- TMU with a gear 12, six cylinders with pistons 24, driving gear 8 of TMU oil pump;
- a mechanism of automatic feathering sensor (detects negative thrust) that involves cylinder 7, piston 29, spring 28 and spring guide 27).

Gearbox casing is a truncated cone. It is cast from magnesium alloy ML5. The channels are drilled in the gearbox bosses for oil supply to control the propeller and to lubricate the gearbox.

The casing has flanges for an attachment of the cover of gearbox lip, a TMU oil pump and an electromagnetic valve. The gearbox casing is studded to the front engine casing through the rear flange.

The internal cavity of the gearbox casing is split into two parts. The front part consists of a propeller shaft and oil distribution components. The rear part contains a gearbox itself, an automatic feathering sensor and a torque measurement unit.

The cast casing of oil dispenser 5 is pressed in the gearbox casing. The bush provides discontinuous oil supply inside the propeller shaft to ensure the control and to cool and lubricate the gearbox components.

The oil dispensing system is sealed enough to make the oil cavities leak-tight when supplying oil from the fixed casing to the rotating shaft. The leak tightness is ensured by the annular sealing with the rotating ring holding bush 4 and sealing bronze rings. Have been casted from a magnesium alloy a cup-shape diaphragm 17 is attached to the rear flange of the gearbox casing.

The input shaft serves to transfer the torque from the engine rotor to the gearbox. It is made of steel grade 10XHMA and thermally treated. It has external nitrogenized involute splines at both sides.

The front splines join the input shaft and driving gear 18. The rear splines join the input shaft with the compressor rotor. The rear splines are covered with copper to avoid peening.

The planetary stage consists of the following basic parts: a sun gear 18, planetary gear casings 15, six planetary gears 23 and their axes 22, an inner engagement gear 14, planetary train hub 13 and parts of bearings.

The driving gear is loosely splined to the driving shaft. The loose fit enables self-centering while the sun gear is intermeshed with planetary gears during the operation. The gear is constrained from the axial displacements by two C-rings.

The casing of planetary gears takes the shape of a hexahedral box with windows to mount planetary gears. The casing is linked to propeller shaft via its internal splines. It is centered in the cavity of bush 6, which is placed inside propeller shaft.

The axes of planetary gears are pressed in six equally spaced cavities in the casing walls. The walls are joined by six struts.

The planetary gears undergo thermal treatment and cementation (only the profile part). The planetary gears are mounted in the casing on two rows of rollers 20. The rollers race on cemented inner surface of the planetary gears and the outer surface of the axes.

The axis of planetary gear is hollow. One side of the axis has a bead; the other one has an annular groove for a C-ring. There is a hollow cap 21 with a labyrinth-shaped ribbing.

The internal engagement of gear 14 is nitrogenized (only profile part). It is attached to the bush of planetary stage 13. The gear is constrained by lamellar C-rings to prevent the axial displacement. The bush of the planetary stage is joined with the driving gear 10 by internal splines. It is constrained by ball bearing 16 from the axial displacements.

The looping stage (looping train) consists of the following parts: drive gear 10, looping train casing 11, six idlers 25, inner engagement gear 9, looping train hub 26 and parts of roller bearings.

The idlers, their axis, internal engagement gears, the parts of roller bearings are similar to those of the planetary stage. The right wall of the looping stage casing has a central cavity with splines. This is where the TMU mechanism is attached. This mechanism links the casing of the looping stage to the gearbox casing via the TMU cylinders and pistons.

Bush of looping train 26 is joined to the propeller shaft. To avoid guide scratches during the assembly, the splines are covered with lead. The bush of the looping train also drives the oil pump of TMU through gear 8.

Propeller shaft is exposed by transmitted torque, thrust, and bending moment due to the propeller mass and the gyroscopic moment. Propeller shaft 2 is hollow. It is mounted in the gearbox casing. The shaft is supported by a pillow roller bearing in the front part and a radial thrust ball bearing in the aft part. There is an oil relief cup 1 inside the shaft. This cup serves to supply oil for propeller control purposes and to lubricate parts of gearbox.

Propeller shaft ends with flange with face V-splines and holes to fit the propeller hub.

The torque measurement unit (TMU) measures power transmitted to propeller at ground and in flight conditions. To arrange the TMU designers use an immovable looping stage casing. It is linked to gearbox casing and transfers the forces that appear due to torque action. Torque acting on looping stage casing makes up 70% from total torque transmitted from engine rotor to propeller.

Looping stage casing is linked to gearbox casing via annulus gear and six cylinders with pistons 24. Operation of TMU is based on equality of moments. The moment that is transmitted from the gear train casing to annulus gear is equal to opposite moment that is caused by oil pressure in six cylinders. This equality is provided by bleeding part of oil from hydraulic rims through oil removing channels (Fig.4.3). Change of the cylinder position relative to piston results to the change of channel area. The channel area and hence the oil pressure depend on transmitted torque. Thus, the oil pressure in the hydraulic rims is proportional to the torque transmitted via propeller shaft at all modes.

The oil pressure is measured by a pressure sensor. The scale of the sensor is calibrated in units of power.

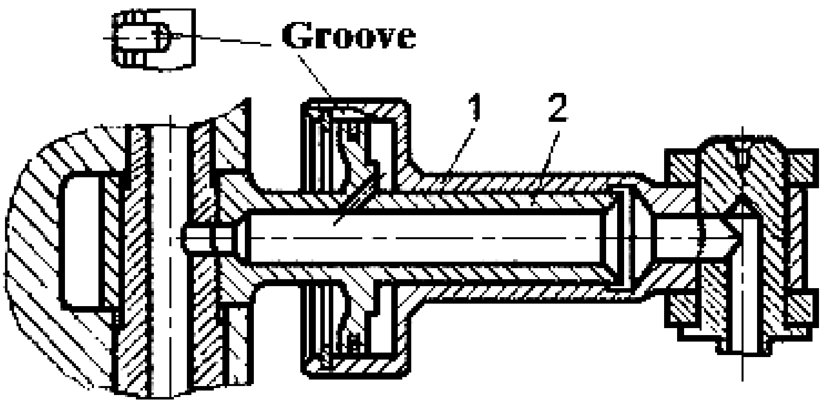


Fig. 4.3. Hydraulic rim of TMU:
1 – rim; 2 – piston

Sensor of drag-actuated autofeathering is the sensor that automatically forms the command to switch propeller blades to feathering position in case of negative thrust of propeller. The negative thrust must exceed the error of the sensor.

If thrust is vectored to the opposite side from the flight and thrust exceeds the error of sensor then negative thrust overcomes the resistance of spring and oil pressure acting on piston 29. Under negative thrust action propeller shaft with piston 29 and ball bearing 30 is displaced to the rightmost position. Therefore, the oil pressure in the control channel drops. If control system detects the pressure drop then it switches propeller to feathering mode and simultaneously cuts off fuel supply to the combustion chamber.

The oil system provides lubrication and cooling of contacting parts, supplies oil for propeller control purposes, and cylinders of TMU.

Oil at high pressure is supplied inside gearbox by main oil pump. It is mounted on the front engine casing.

Oil is sprayed by oil nozzles to lubricate and cool teeth of gears, movable splined joints and high speed bearings.

Bearings of propeller shaft are splatterly lubricated. To lubricate bearings of planetary gears, oil is delivered through special drillings in the casing of planetary gears and through oil distributing cups. The cups are mounted on planetary gear axes.

Have been lubricated the bearings, the oil is removed from the bottom part of gearbox casing and next, bled to cavity of engine front casing. The lubrication system of planetary gear bearings is shown in Fig. 4.4.

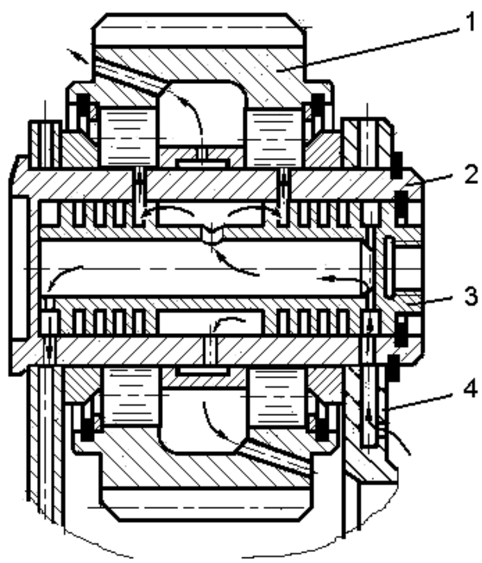


Fig. 4.4. Lubrication system of planetary gear bearings:
1 – planetary gear; 2 – axis; 3 – oil distributing cup; 4 – casing of planetary gears

4.3. The materials of gearbox components

Heavily loaded parts of gearbox are manufactured from high-quality alloyed chrome-nickel and nickel-chrome-molybdenum cemented and nitride steels. The gearbox, axes of planetary gears, bushes – from steels 12 Х2Н4А, 38ХМВА. Casing of planetary gears, casing of looping stage, shafts are made of 40ХНМА. Bolts and studs – from 18ХНВА, 40ХНМА. Gearbox casing is made of magnesium alloy МЛ5.

4.4. The most probable gearbox operational failures

Gearbox failures are mostly caused by low quality of its components, the infringement of the assembling technology, maintenance rules or technical service.

The following defects are mostly detected in maintenance: the destruction of bearings, gears and shafts.

Main reasons for gear damages are:

- jamming because of small clearances in meshing
- foreign objects getting inside of the gearbox;
- manufacturing defects;
- high vibration stresses because of resonant oscillations of gears;

Gearbox malfunctions are diagnosed by foreign noise and ratcheting in the gearbox. The other indicator of an incipient destruction is a metal chip in oil filters.

5. GEARBOX OF NK-12 TURBOPROP

5.1. Kinematic configuration of the gearbox

The gearbox of NK-12 turboprop transfers excessive torque from a high pressure turbine to two coaxial propellers and coordinates the most efficient rotational speeds of the engine rotor and the propeller rotors.

The gearbox of NK-12 is a two-degree-of-freedom differential gearbox with twin lay shafts. The kinematic configuration of the gearbox is presented in Fig. 5.1, the general view is in Fig. 5.2.

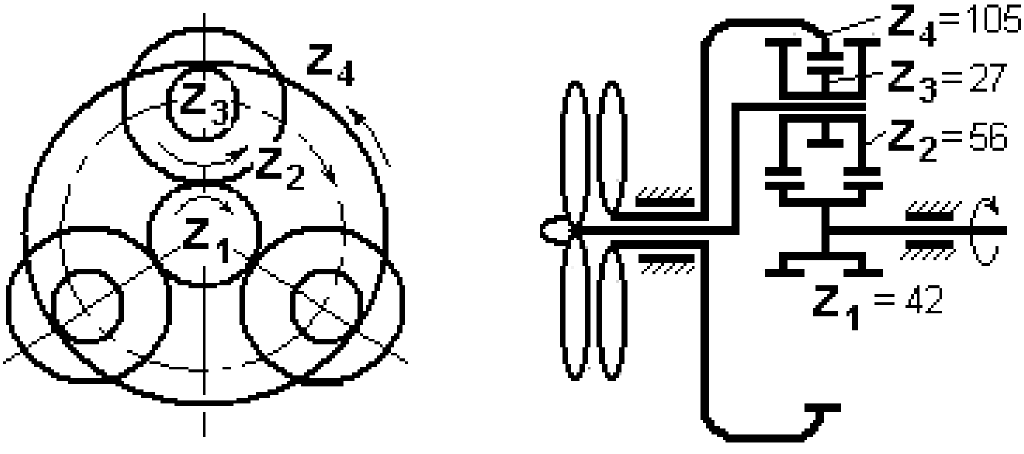


Fig. 5.1. Kinematic configuration of NK-12 turboprop gearbox

The analysis of equation that relates rotational speed of engine rotor and the rotational speeds of propellers reveals that if rotational speed of high pressure turbine (n_{HPT}) stays constant then acceleration of front propeller results in deceleration of the rear one (and inversely deceleration of front propeller makes rear one to accelerate).

If control system of propellers operates at normal mode, then rotational speeds of propellers are equal. This is achieved by an automatic correction of propeller blade angles.

Rotational speeds of front and rear propellers at normal mode are

$$n_{FP} = n_{RP} = n_{HPT}\left(1 + \frac{z_2 \cdot z_4}{z_3 \cdot z_1}\right). \qquad (20)$$

The gear ratio of NK-12 gearbox is $i = 11{,}37$.

The specific feature of differential gearbox with such kinematics is extremely high efficiency ($\eta_{mech} = 0{,}992$). However, torques driving the front and the rear propellers are not equal. The ratio between torques is expressed by the following formula:

$$\frac{M_{FP}}{M_{RP}} = \frac{i+1}{i-1} = \frac{11{,}34+1}{11{,}34-1} \approx 1{,}193 \approx \frac{54}{46}. \qquad (21)$$

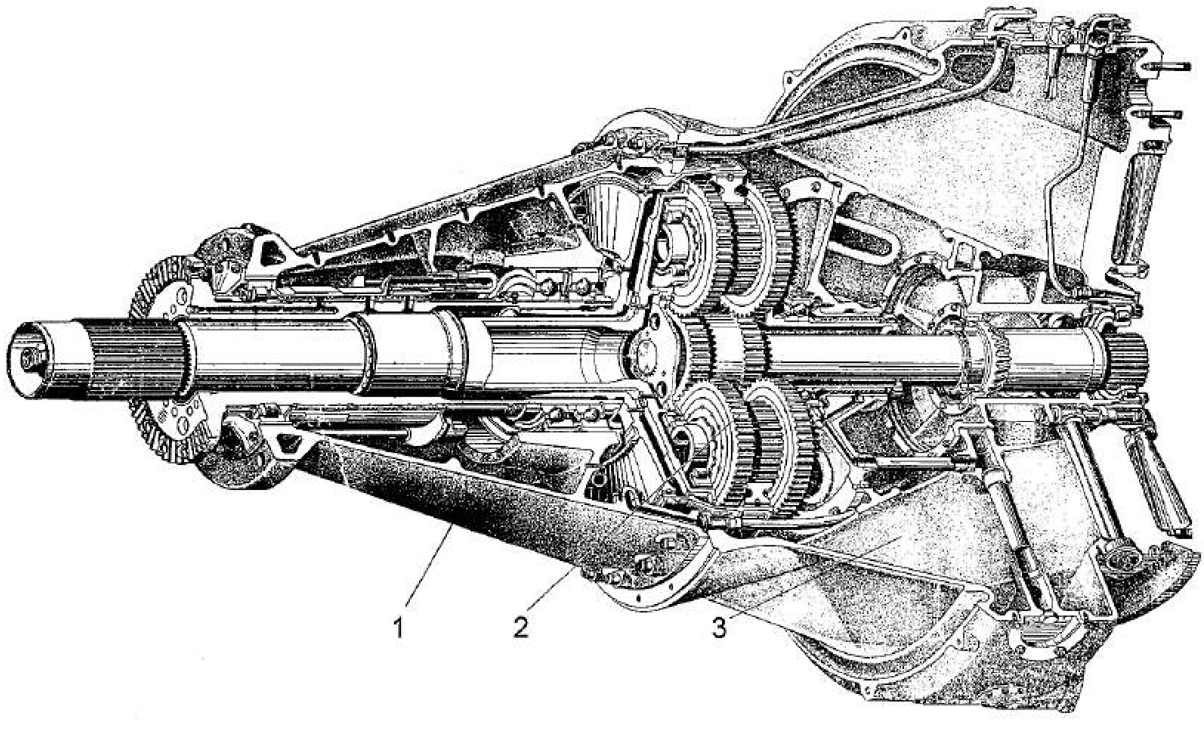


Fig. 5.2. General view of NK-12 gearbox:
1 – casing of the rear propeller shaft; 2 – differential gearbox itself;
3 – casing of gearbox with the drives inside

Therefore, if propellers have the same speed, then the front propeller consumes 54% and the rear one – 46% of total power that is transmitted to the propellers. This fact complicates the structure of the propeller control system.

5.2. The construction of the gearbox

The casing of the rear propeller shaft (Fig. 5.3) is one of the main elements of power frame. The casing of the rear propeller takes thrust of propellers, their weight and other loads that inevitably appear during the engine operation.

The casing of the shaft has a shape of truncated cone. To increase the rigidity of the cone, its inner surface is enhanced by eight longitudinal ribs and one transversal rib.

Roller bearing 2 has no inner racer. The function of inner races is performed by the rear propeller shaft. The outer racer is pressed into a steel bush. This bush is mounted with a negative allowance into the hole of the front flange of the rear propeller shaft casing. It is fixed with three steel pins and bored out together with the casing.

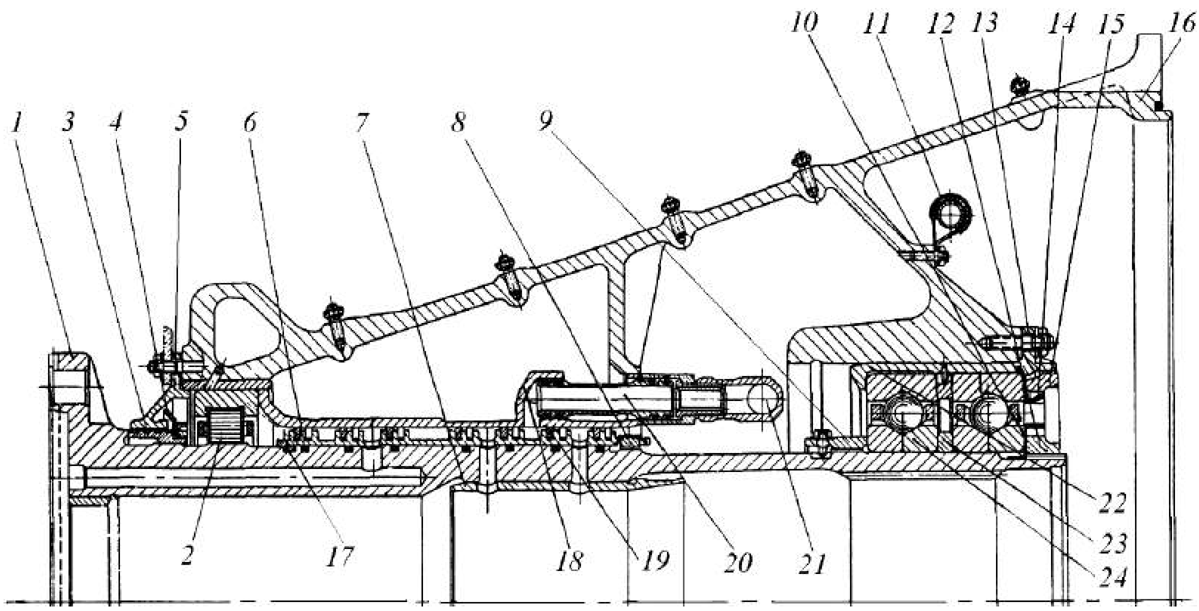


Fig. 5. 3. Casing of rear propeller shaft:
1 – rear propeller shaft; 2 – roller bearing; 3 – labyrinth sealing; 4 – oil-catch ring; 5 – labyrinth cup; 6 – ring holder; 7 – bush; 8, 12, 15 – nuts; 9 – screwed ring; 10, 14 – lockings; 11 – clamps; 14 – flange; 16 – casing; 17 – split rim ring; 18 – oil distribution bush; 19 – oil sealing ring; 20 – pipes to supply oil to oil distributing bush; 21 – segments; 22 – roller bearing bush; 23 –adjusting ring; 24 –ball bearings

Inner racer of ball bearings 24 is manufactured split to increase the bearing capacity. To provide a long-term operation of both bearings a total axial force is distributed between two bearings in the following proportion: the front one takes 50-60 %, the rear one – 40-50 %. The outer racer of the front bearing is loosely fitted in the bush. So, it takes small piece of radial force is acting on the bearings. To distribute the axial force as it was described above, the bearings are sorted and marked by rigidity: front bearing is designated with letter “B”, the rear one – with letter “A”. Besides, the inner racers of bearings have the arrow marked on (acid stamping) that indicates flight direction. These arrows must be directed with the flight direction when assembling.

The rear propeller shaft has grooves and drillings in its front part that results in stress concentration. To reduce the sensitivity of the shaft to the stress concentrators, its outer surface (except racer part) is cemented. The face splines on the flange in the front part of the rear propeller shaft transmit torque to the rear propeller hub. The angular position of propeller hub must be coordinated with the rear propeller shaft to provide matching of the holes for oil supply and removal. This is achieved by means of the pin pressed in the propeller hub. The shaft has corresponding hole in the flange.

Differential gearbox itself performs two functions. Its first function is to transfer the excessive power from the turbine to propellers at the rotational speed that is 11,37 times lower than that of turbine. The second function is to distribute power between the front and the rear propellers. Differential gearbox has three gearings. Sun gear z_1 installed on the input shaft transmits the excessive power to three lay shafts z_2 (see Fig. 5.1). Next, the power from the planetary layshafts is transmitted to the shaft of the front propeller via the planetary gear casing and the planet carrier.

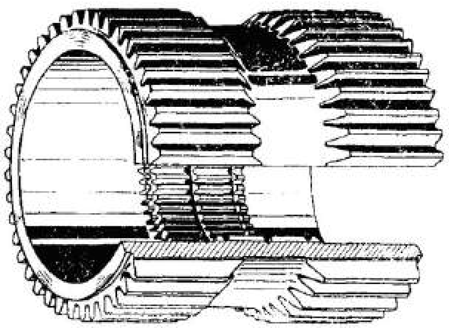


Fig. 5.4. Sun gear

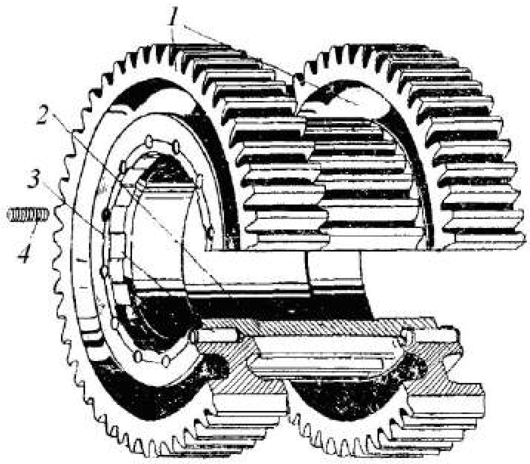


Fig. 5.5. Lay shaft configuration:
1 – gears; 2 – layshaft itself; 3 – pin;
4 – grub screw

Thus, the tooth of each planetary gear which centerline matches the centerline of the layshaft tooth is marked with “0”.

The general view of the sun gear is shown in Fig. 5.4 and the general view of the lay shaft – in Fig. 5.5.

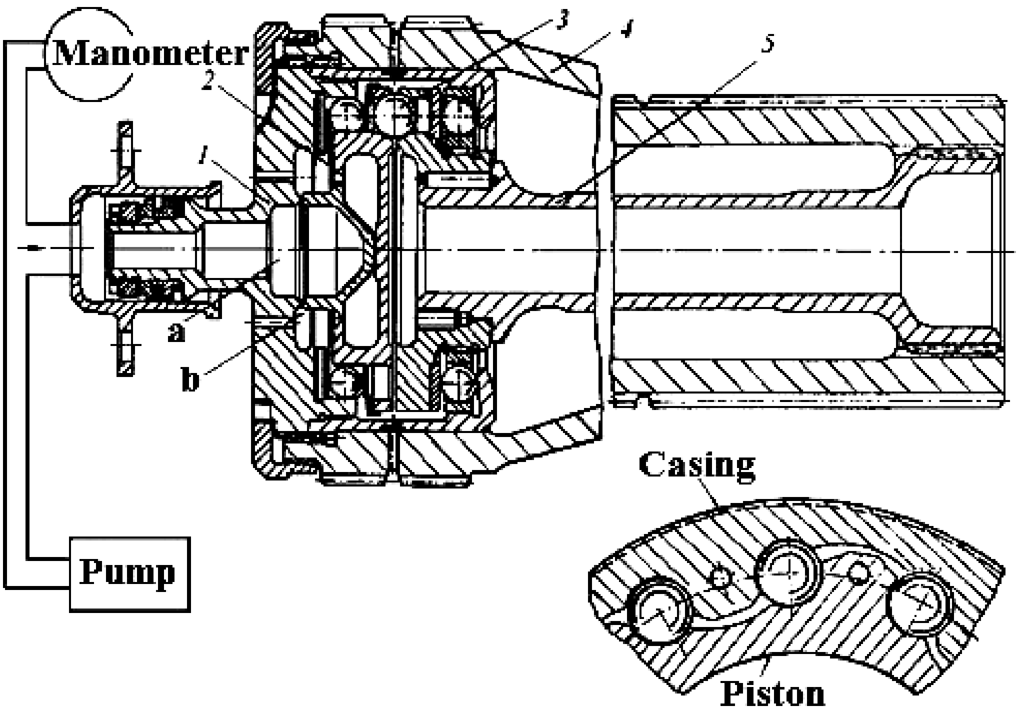


Fig. 5.6. The layout of a torsion type TMU of the NK-12 turboprop
1 – casing; 2 – piston; 3 – balls of ball-type clutch; 4 – shaft; 5 – bar

The power is transmitted to the rear propeller via gears z_3 and z_4 (see Fig. 5.1). Gear z_4 consists of a disk and an annulus loosely splined together. Such design provides minimum striking of gears z_3 and z_4.

Torque measurement unit is of torsion type. Its configuration is given in Fig. 5.6.

Bar 5 is in the hollow shaft 4. The bar does not transfer the torque. The right splined end of the rod is attached to the shaft. The left end of the shaft is free. It is attached to piston 2 via ball-type clutch. This clutch restricts angular displacements and enables axial displacing of the piston along the shaft.

When the shaft is loaded by the torque, its left end is turned jointly with piston 2 relative to rod 5. This makes three balls roll out of their conical grooves with the piston moving to the left. The piston decreases the slot ***α*** that in its turn lets a smaller oil portion through. The amount of the discharged oil is proportional to the torque loads acting the shaft. The manometer that indicates oil pressure is calibrated in torque units.

5.3. The materials of gearbox components

The gearbox casing is casted from aluminum alloy АЛ4. The input shaft, shafts of the front and the rear propellers are manufactured of 12Х2Н4А steel. The shaft that drives the TMU oil pump is manufactured of 30ХГСА steel. The sun gear, the annuluses of planetary gears, the annuluses that transmit the torque to the rear propeller shaft are manufactured of 12Х2Н4А steel. The disk, the fitting bolts and planet carrier are manufactured of 40XHMA steel. The shafts of planetary gears are manufactured of 12X2H4A steel with further chemical improvement of surfaces (cementation), except for the thread. The oil sealing rings are manufactured of БрОС16-5 bronze and the ring holders are made from 38XMЮA steel.

6. VR-24 MAIN GEARBOX

VR-24 is a standalone unit that coordinates two engines of the helicopter`s power plant. The gearbox adds up the power of both engines and transmits it to a lift rotor and to gear train of tail rotor, and drives the helicopter accessories.

6.1. Specifications of VR-24 gearbox

Gearbox type – gear-type, differential, loop.
Amount of stages: three;
first stage – helical-spur gear;
second stage – conical, spiral gear;
third stage – differential, spur gear.
Nominal rotational speeds of gearbox shafts, rpm:
input shaft – 15000 $\pm$ 450;
lift rotor – 240 $\pm$ 7;
tail rotor – 3237 $\pm$ 97.
Total input shaft referred gear ratios:
lift rotor shaft – 62,5;
tail rotor drive – 4,634;
fan – 2,486;
sensor of tachometer D-1 – 6,293.
Overall sizes, mm:
length – 1210;
width – 885;
height – 1765;
Dry mass of the gearbox, kg – 830 +2%.

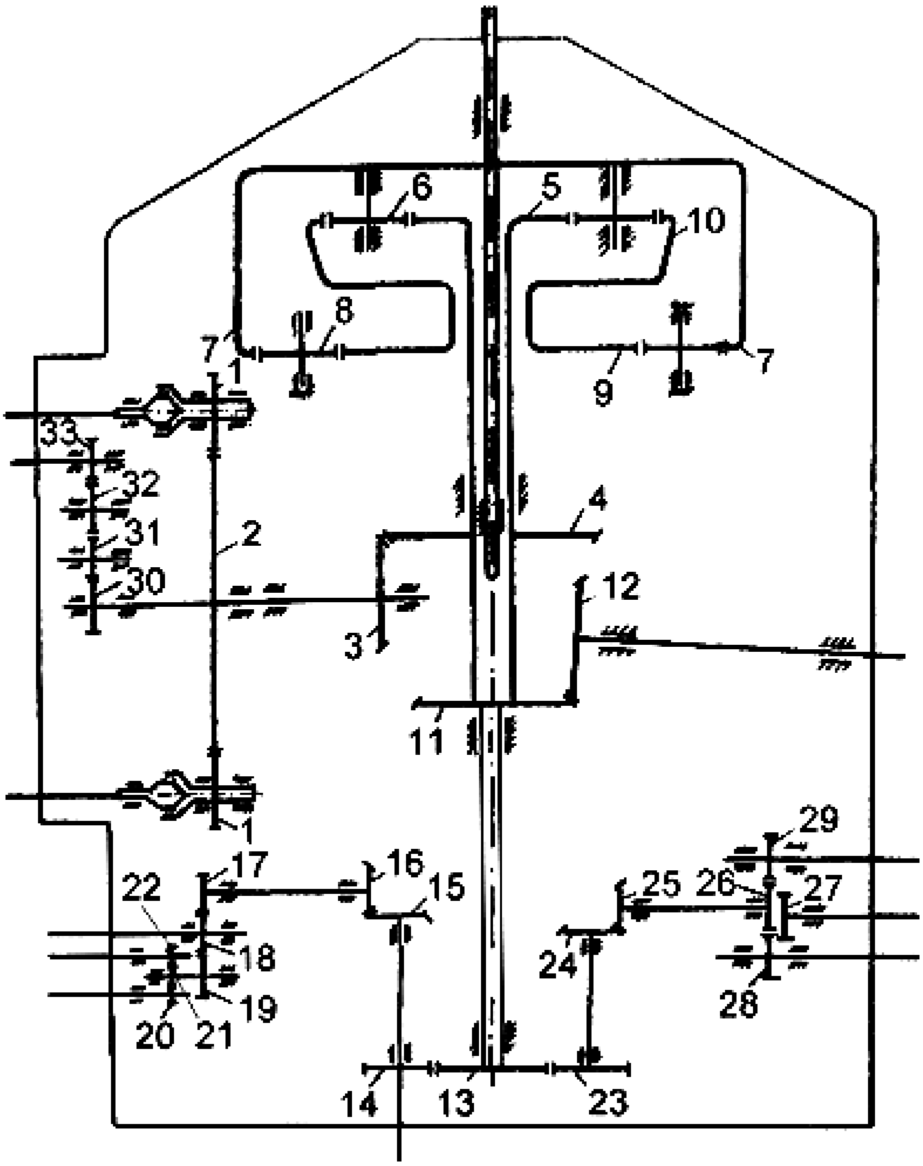
6.2. General structure and kinematic configuration of the main gearbox

The gearbox is a standalone unit that consists of casings, gearing and lubrication system.

The gearing is inside casted casing. The upper part of the casing forms a rigid belt with five flanges to attach the gearbox to the helicopter.

The lift rotor casing is studded to the top of the gearbox. A tray is attached to the bottom of the casing. It receives the bleeding oil. There is an oil unit in the bottom part of the tray.

The torque is transmitted to the lift rotor through three stages of the gearbox (Fig. 6.1).



Gear number	Num. of teeth
1	33
2	35
3	31
4	66
5	31
6	29
7	106
8	24
9	29
10	89
11	41
12	31
13	25
14	62
15	29
16	24
17	32
18	44
19	46
20	27
21	27
22	27
23	62
24	29
25	14
26	32
27	47
28	57
29	47
30	44
31	49
31	49
32	49
33	38

Fig. 6.1. Kinematic configuration of VR-24 gearbox

First stage transfers rotation from two engines to helical-spur gear 2 via a one-way clutch (overrunning clutch) and gears 1 (2 gears).These three gears form the first stage, which gear ratio is 2,88.

The second stage consists of two conical spiral gears 3 and 4. The gear ratio of this stage is 2,13.

The third stage is differential and closed-loop. Gears 5, 6 and 10 form differential part (all gears rotate), and gears 7, 8 and 9 form looping part. Sun gear 5 and bevel gear 4 form the sun lay shaft. Gears 6 (five gears) are planetary gears. The planet carrier is linked to the shaft of the lift rotor.

Gears 8 (seven gears) are the idlers within the looping part.

Thus, at the third stage the torque is transmitted to the propeller shaft by two fluxes: through the differential part (gears 5,6 and 10 account for near 30%) and through the closed-loop part (gears 7,8 and 9 account for near 70%).

The total gear ratio of three stages is 62,5. Hence, if the rotational speed of a free turbine shaft is 15000 rpm, then the rotational speed of the lift rotor is 240 rpm. The torque is transmitted to tail rotor via the first and the second stages and through the step-up gearing. The step-up gearing consists of two conical spiral gears 11 and 12.

Left, right and front casing walls have the holes for the drives of the auxiliaries. This drives transfer the torque to a fan, tachometers, hydraulic pumps and AK-50T1 compressor.

6.3. Gear trains of lift rotor, tail rotor and fan

6.3.1. Gear train of lift rotor

A one-way clutch and a casing of the drive journal interconnect the engine with main gearbox. Left and right engines are interconnected in the same way. The shaft of free turbine ends with a driven torsion bar. The bar is connected to the one-way clutch with spherical splines of the splined bush 8 (Fig. 6.2).

The spherical support and spherical splines allow some misalignment between the engine and gearbox shafts. To prevent longitudinal vibration of driven torsion bar, the gearbox is equipped with spring that pushes it to engine.

The one-way clutch (OWC) disengages one or two engines from the gearbox in case of a failure or in case of the rotational speed decreases at windmilling. It also provides separate starting of the engines. It is a clutch with a common pressing actuator. The rollers of the clutch are pressed to the working surfaces of the sprocket gear and the racer by the tangential springs. These springs provide contact of sprocket gear and cage. The input shaft 7 of the OWC has two supports: the radial thrust support is placed on the journal, the roller one is fitted in the driven shaft 5.

The OWC has sixteen jammed rollers 6. They are separated by the cage and placed in the annular cavity. This cavity is formed by the driving and the driven shafts of the clutch.

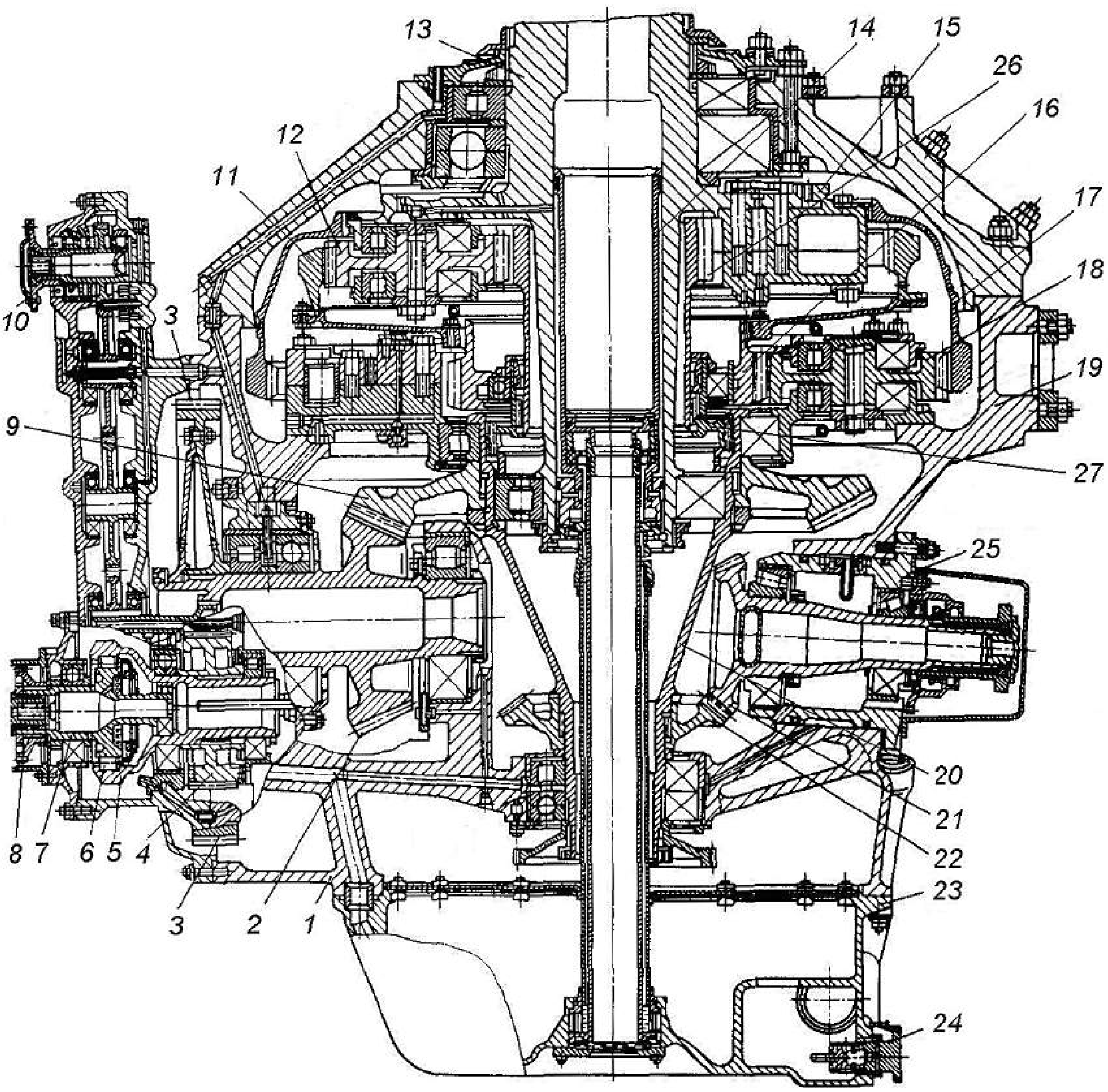


Fig. 6.2. VR-24 main gearbox

The surface of annular cavity that belongs to driven shaft is cylindrical, and the surface of driving shaft is split into 16 segments.

When driving shaft 7 accelerates and reaches the rotational speed of the driven shaft 5, rollers 6 are jammed. Shafts start to work as a single piece part. When for some reasons the rotational speed of the driving shaft decreases, and the driven shaft overtakes it, the rollers are disengaged and shafts are disjointed. The rotational speed of the driven shaft may become higher than the rotational speed of the driving shaft because of propellers` inertia and because of the torque of the second engine.

The driven shaft of the clutch 5 has two supports: a ball support is fitted in the front cup, the roller one – in the gearbox casing. The input helical gear 4 is splined to the shaft 5. Both helical gears are meshed with the output helical gear 3. When the torque is transmitted by the spur gears, axial force appears. The helical gear 3 is of a big diameter that is why it requires the supporting flange that is bolted to the gear 3.

Output gear 3 and driving conical spiral gear 2 form the lay shaft. They are coupled together by splines. The lay shaft has three supports. Two of them are roller supports that take only radial loads, one support is ball. The ball bearing is exposed to the axial force that is why its outer racer is loosely fitted in the bucket.

Driven gear 9 is pinned (set pins) and bolted (fitter bolt) to the shaft 20. The attached pins transmit the torque and the fitter bolt transmits the axial force. Ends of bolts are rolled over to prevent untwisting. Ends of pins are also rolled over.

Shaft 20 has one ball and two roller supports. Roller bearings take radial loads, and the ball one is exposed to only axial load acting the shaft. The position of conical gear 9 is adjusted by the tuning washer.

Next, torque is transmitted from the shaft 20 to top sun gear 26 that are engaged by splined bush 27. The splined bush provides self-centering of gear 26. This provides uniform torque distribution between all planetary gears. The planetary gears are mounted in the casing (roller mounts), which is the planet carrier of the differential stage. The casing is manufactured from alloyed steel. The casing consists of upper and lower parts. These parts are bolted together. Flange of lift rotor 13 and planetary gear casing are bolted together.

The casing of planetary gears has the internal and the external splines. The internal splines serve to transfer the torque to the propeller shaft. The external splines join the casing with gear 17. Gear 17 is loosely fitted to the casing, so it capable for self-centering during rotation.

Gear 17 is meshed with seven idle gears 18. The idlers are mounted in the stationary casing. The casing parts are centered and bolted together. The casing of idle gears and the casing of the gearbox are coupled together by studs and bolts with bushes.

Idlers 18 are meshed with central looping gear 16. The gear is transitionally fitted on the external racer of the splined bush ball bearing. Gear 11 is loosely fitted on the shank of the central gear 16 (spline joint). Gear 11 is exposed to the torque from the planetary gears.

Free fit of central gear 16 provides all meshed teeth of being equally loaded.

The shaft of the lift rotor 13 is made of an alloyed steel and has two supports. The radial thrust bearing takes axial and radial force, roller one – only radial force.

Ball bearing is constrained from axial displacement in reference to the lift rotor by a nut. The nut is tightened with well calibrated force. The inner racer of the bearing is fitted in the steel bucket. The bucket itself is pressed in the magnesium casing of the lift rotor. The ball rearing is protected from the dust by a packing box mounted atop. The packing box is protected from the moisture ingress by the titanium screen.

There is an oil supplying tube 14 inside the shaft of the lift rotor. The tube and shaft form the annular duct for oil drainage.

6.3.2. Gear train of tail rotor

Bevel gear 22 with spiral teeth is mounted on the shaft 20. This gear is a driving gear of the tail drive. The driven gear 21 of the tail drive is mounted on two taper roller bearings that are affected by both, axial and radial forces. The shank end of driven gear 21 ends with a flange. It has milled splines that join gear 21 with gear train of tail rotor and the parking brake drum. There are oil removal grooves on the outer surface of the flange.

The casing of the tail rotor has a flangeintended to stud the casing to a gearbox casing.

6.3.3. The fan drive

A splined flange of the propeller drive is fitted on splines of spur gear shank. The driving bevel gear 2 via a set of other gears and the shaft spins this gear. All gears have two roller bearings that are placed in a special lug in the front cup of the gearbox. This lug is covered by the cup of the fan drive.

The fan drive is sealed with oil removing grooves. These grooves are turned in the splined flange 10.

All gears of the gearbox are made of steel. Teeth of the gears are cemented and grinded.

6.4. The gearbox lubrication system

The lubrication system of VR-24 is autonomous, independent on that of the engine. It uses B-3V synthetic oil as a lubricating agent.

The lubrication system is intended to provide oil supply to lubricate bearings and gear teeth. Lubrication is needed to reduce friction and wear out of contacting surfaces, to protect them from corrosion and peening, to remove the heat that appears due to friction, to clean dust from friction surfaces of the gear drives.

The lubrication system consists of an oil pumping unit (one supply and two oil scavenge pumps), a filter with valves, a thermometer, an indicator of the maximum temperature, fuel nozzles, liquid spray diffusers, two oil radiators, a manometer of oil pressure.

The gearbox tray serves as an oil tank of lubrication system. It is filled up through a filler neck, which has a screen filter and a cup. The tray has a check window with marks used for visual inspection of the oil level.

There is a special bay for cool oil from radiators. The bay is separated from the rest gearbox by special preservative screen.

There is an oil pipe in the central part of the tray. The oil from supply pump gets to the oil supply pipe 14 and is delivered inside the shaft of lift rotor. The inner oil-free cavity of the oil pipeline, the oil supply pipe and the lift rotor shaft are used to wire up the deicing system of the lift rotor.

There are three magnetic chip detectors 24 with magnetic core in the bottom part of the tray. They trap steel chips. The size and amount of chips allow diagnosing the gearbox condition in the maintenance.

The magnetic chip detector consists of a magnet and a valve.

When the mechanical engineer demounts the detector, the valve pushed by the spring closes the hole. This prevents oil leaks. To bleed oil from the tray one must mount the hose with the device that unlocks the valve instead of magnetic detector. The oil at high pressure runs through the oil filter from the supply pump to channels in the gearbox casing.

7. RV-3F GEARBOX OF KA-25 HELICOPTER

The RV-3F gearbox serves to the transfer torque from two GTD-3F turboshafts to two coaxial lift rotors of the helicopter and its auxiliaries.

The gearbox is a standalone unit. It has two one-way clutches to provide the operation of either two engines helicopter (autorotation) and only one helicopter engine.

7.1. Basic technical data of RV-3F gearbox

Gearbox type – gear, four-stage, differential, loop.

Nominal rotational speeds of gearbox shafts, rpm:

- input shafts – 19000;
- lift rotor shafts – 237.

Gear ratio between the input shaft and

- lift rotor shaft – 80;
- fan – 4,219;
- RPM sensor (DTE-1) – 7,017.

Overall sizes, mm:

- length – 945;
- width – 960;
- height – 2773.

Dry mass of gearbox, kg – 560 + 2%

7.2. General arrangement and kinematic configuration of the gearbox

Kinematic configuration of the gearbox is presented in Fig. 7.1.

The gearbox is a four-stage one. It has two power inputs from engines and two outputs to drive two coaxial contra-rotating shafts. These shafts have the same rotational speed.

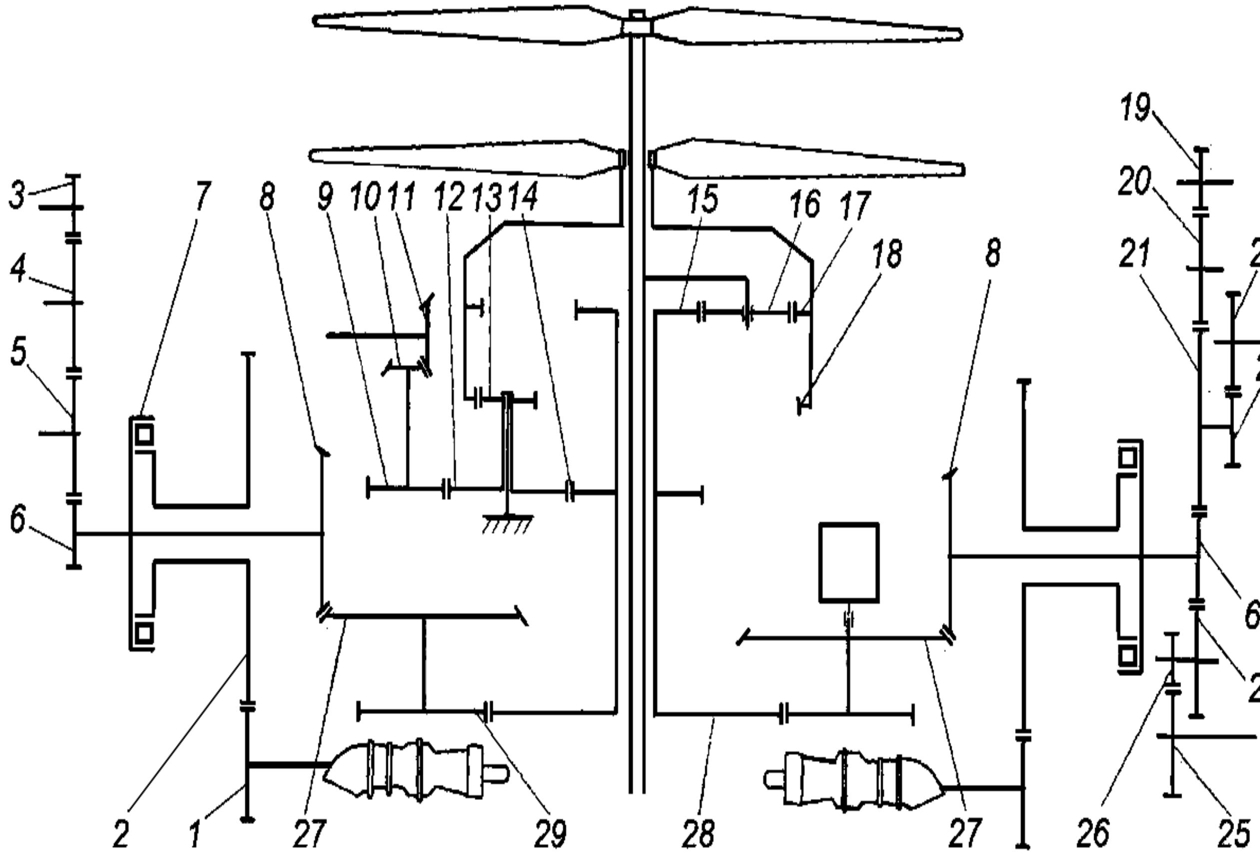


Fig. 7.1. Kinematic configuration of RV-3F gearbox

First stage (left and right) consists of the input spur gears 1 and output spur gears 2 spur gears. The gear ratio of the first stage is $i_1 = \frac{z_2}{z_1} = \frac{89}{26} = 3{,}423$.

The second stage (left and right) consists of two spiral bevel gears 8 and 27. They transmit the rotation from the horizontal shafts to the vertical ones.

The one-way clutches between output gears 2 and bevel gears 8 undock the first stage in case of one or both engines fail. The gear ratio of the second stage is $i_2 = \frac{z_{27}}{z_8} = \frac{38}{21} = 1{,}81$.

Big bevel gear 27 and input gear of the third stage form the layshaft. The third stage also serves to merge two separate power fluxes from two engines. The left and right input gears are meshed with single output gear 28. The gear ratio of the third stage is $i_3 = \frac{z_{28}}{z_{29}} = \frac{55}{24} = 2{,}292$.

Has passed the gear 28, power flux is split into two: the first flow gets to the planetary gearbox, the second one – to the gear train, forming the fourth stage. The planetary-differential gearbox consists of a sun gear 15, six planetary gears 16 attached to the planet carrier and a driven ring gear 17. The input gear 15 is fitted with the output gear 28 with splines. The ring gear is joined with the outer shaft via splines.

Table 1. Gears data

Gear No.	Name	Quantity	Number of teeth	Pitch	Rotational speed, rpm
1	Input gear of the first stage	2	26	3,25	19000
2	Output gear of the first stage	2	89	3,25	5540
3	Gear of fan drive	1	32	2,5	4500
4	Gear of reserve drive	1	61	2,5	2360
5	Gear of the DTE-1 drive	1	60	2,5	2400
6	Input gear	2	26	2,5	5540
7	One-way clutch	1	–	–	–
8	Bevel gear of the second stage	2	21	7,25	5540
9	Gear of the drive	1	33	2,75	2300
10	Bevel gear	1	20	2,5	2300
11	Bevel gear	1	23	2,5	2000
12	Big gear of gear train	6	54	2,75	1406
13	Pinion of gear train	6	18	3,5	1406
14	Input gear of gear train	1	57	2,75	1330
15	Sun gear of differential gearbox	1	38	4	1330
16	Planetary gear	6	25	4	1670
17	Ring gear of differential gearbox	1	88	4	237
18	Ring gear of gear train	1	107	3,5	237
19	Gear of generator drive	1	18	2,5	8000
20	Gear of drive	1	37	2,5	3900
21	Gear of drive	1	68	2,5	2115
22	Gear of compressor drive	1	35	2	1520
23	Gear of drive	1	25	2	2115
24	Gear of drive	1	37	2,5	3900
25	Gear of hydraulic pump drive	1	31	2,5	2010
26	Gear of drive	1	16	2,5	3900
27	Bevel gear of the second stage	2	38	7,25	3060
28	Output gear of the third stage	1	55	6	1330
29	Input gear of the third stage	2	24	6	3060

The Gear train consists of an input gear 14, six lay shafts with gears 12 and 13, and an output gear 18 that is fitted on the outer shaft. The number of planetary-differential gearbox teeth and gear train teeth were chosen to provide equal gear ratios and ensure contra rotation of the shafts.

The gear ratio of the fourth stage for the outer shaft is

$$i_{4\,OSh} = \frac{z_{12} \cdot z_{18}}{z_{14} \cdot z_{13}} = \frac{54 \cdot 107}{57 \cdot 18} = 5{,}65 .$$

The gear ratio of the fourth stage for the outer shaft is

$$i_{4\,BB} = 1 + 2\frac{z_{17}}{z_{15}} = 1 + 2\frac{88}{38} = 5{,}65 .$$

The total gear ratio of the gearbox for the outer shaft is

$$i_{OSh} = i_1 \cdot i_2 \cdot i_3 \cdot i_{4\,OSh} = 80 .$$

The total gear ratio of the gearbox for the inner shaft is

$$i_{BB} = \frac{z_2}{z_1} \cdot \frac{z_{27}}{z_8} \cdot \frac{z_{28}}{z_{29}} \cdot \left(1 + 2\frac{z_{17}}{z_{15}}\right) = 80 .$$

The accessories mounted on the accessory gearbox are driven by two bevel pinions 8 of the second stage.

The gear train (left bevel gear 8 orbiting spur gear 6 ($z = 26$) drives the spur gear 5$(z = 60)$) drives the DTE-1 shaft and the fan shaft. The gear train (left bevel gear 8 orbiting spur gear 6 ($z = 26$), spur gear 5$(z = 60)$, spur gear 4 and spur gear 3) drives the fan propeller. Gear train (right bevel gear 8 – spur gear 6 – spur gear 21 – spur gear 23) drives the compressor AK-50T. Gear train (right bevel gear 8 – spur gear 6 – spur gear 21 – spur gear 20 –spur gear 19) drives generator SGS-40U. Gear train (right bevel gear 8 – spur gear 6 – spur gear 24 – spur gear 26 – spur gear 25) drives hydraulic pumps 435FT.

The gear 12 orbiting gears 9, 11 and 10, drive an autonomous unit of the steering system ARS-10. The gear 27 of the second stage of the gearbox drives gear oil pump MN-RV-3F.

7.3. The construction of gearbox RV-3F

The longitudinal section of the gearbox is shown in Fig. 7.2. Two GTD-3F turboshafts are linked to the main gearbox via one-way clutches (overrunning clutches). They consist of a pinion collar (housing), a sprocket (shaft), a cage, eighteen rollers and a spring. The sprocket is a driving part, pinion collar is a driven one. The left and right engines are identically connected to the main gearbox.

The first right and left gearbox stages are arranged in casings of fast gearboxes (Fig. 7.3). The fast gearbox consists of spur gears (gear 28 is an input gear, gear 44 is and output one).

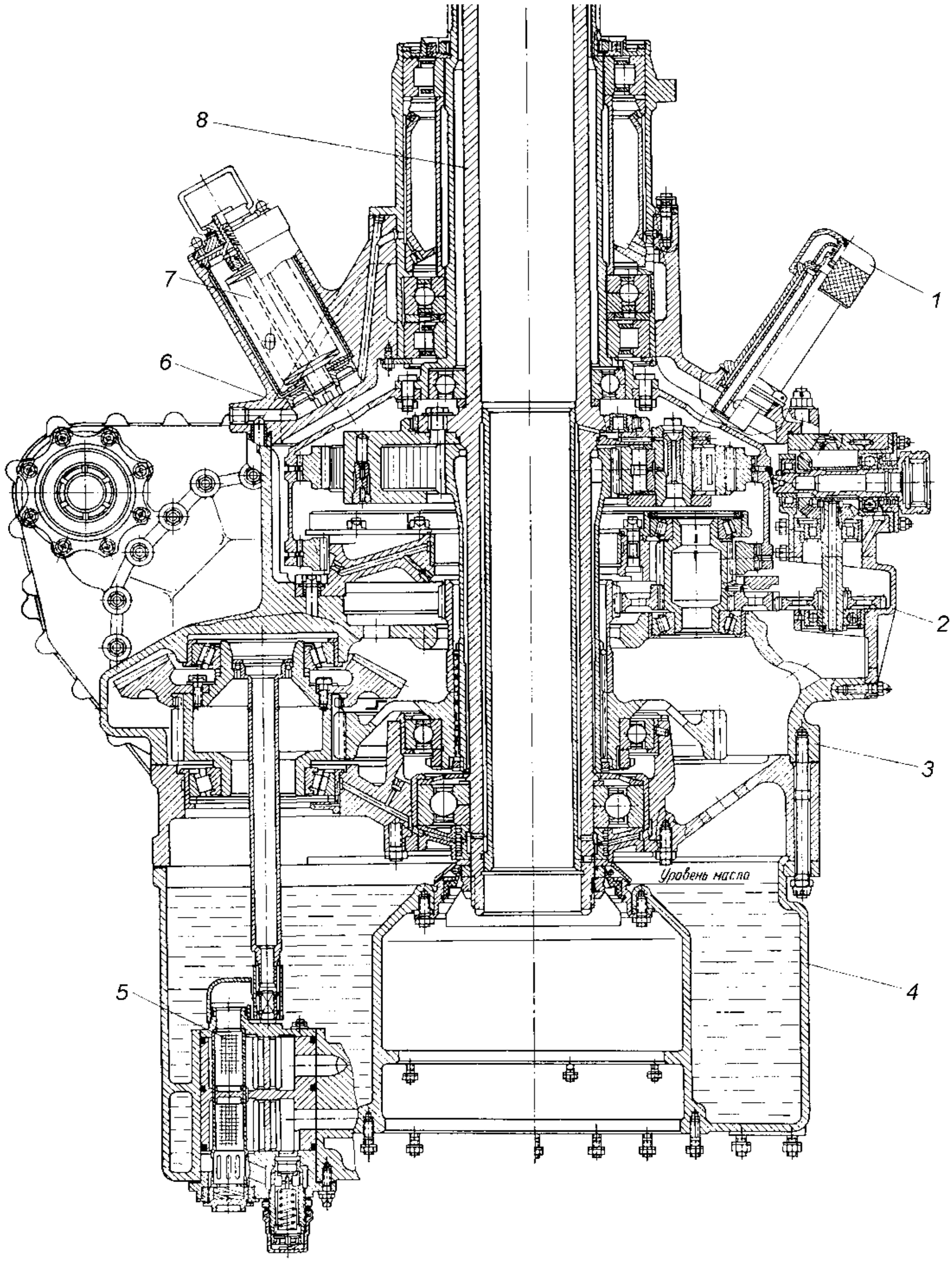


Fig. 7.2. Longitudinal section of RV-3F gearbox (general view):
1 – filler with breather; 2 – drive of ARS10; 3 – intermediate casing of gearbox with diaphragm; 4 – tray of the gearbox; 5 – oil pump; 6 – top casing of the gearbox; 7 – fine oil filter; 8 – inner shaft of propeller

Input gear 28 is manufactured as a single-piece part with the shaft. The shaft has involute splines to fit impeller 8 and front clutch 1. The inner diameter of the output gear bush has two counterbores for bronze rings. These rings serve as ball bearings. They also align gear 44 with the bore diameter of pinion 47 of the second stage.

The outer surface of hub of gear 44 has involute splines. They serve to fit the input shaft (driving member sprocket) of the one-way clutch 43.The second stage of gearbox consists of spiral bevel gears (input gear 8 and output gear 27, Fig. 7.1). The spiral bevel gears are adjusted by matching their side clearance and tooth contact. That is why they are assembled in the gearbox only in sets. The axial position of the spiral bevel pinion is adjusted by matching the rings during the assembling.

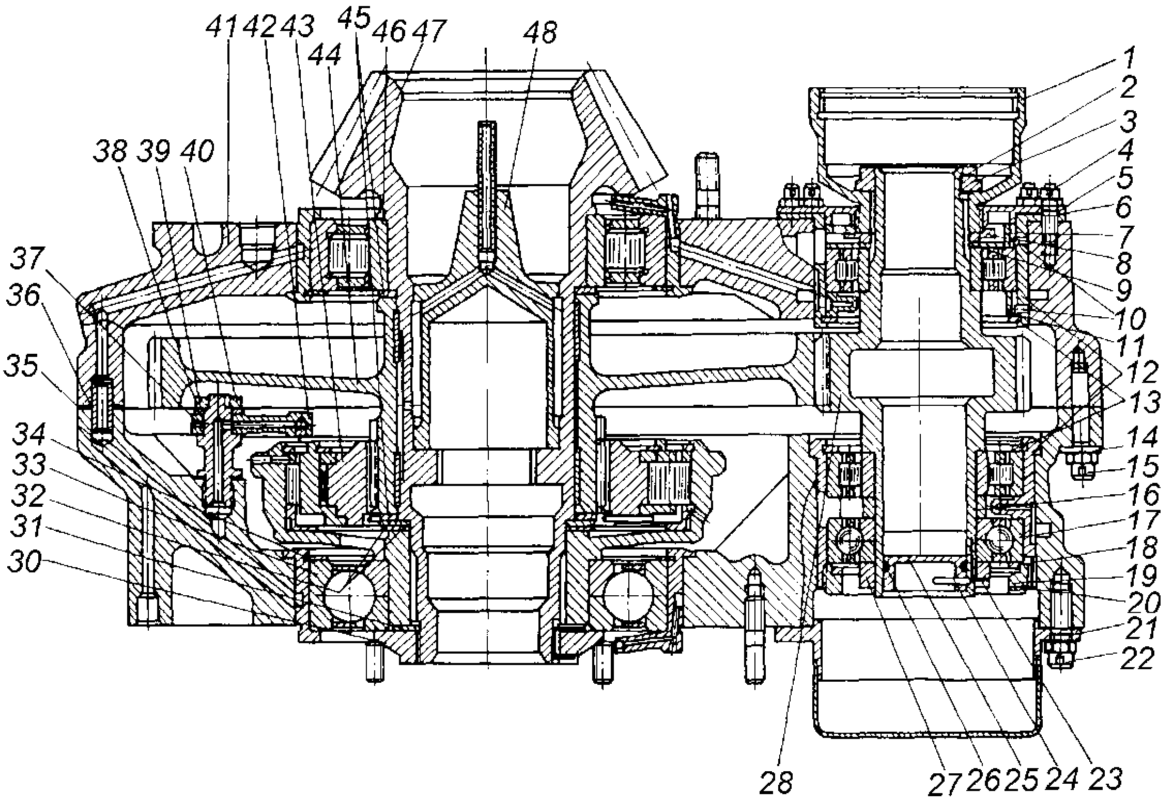


Fig. 7.3. Fast gearbox:
1 – front clutch of gearbox; 2, 20, 23, 24, 31, 37, 40 – lock; 3, 4, 15, 19, 22, 27, 30, 39 – nut; 5 – front cap; 6 – filler; 7 – spacer; 8 – impeller; 9 – adjusting washer; 10 – pin; 11 – oil nozzle; 12, 46 – roller bearing; 13, 34 – stop ring; 14, 38 – washer; 16 – bush of the bearing; 17, 33 – roller bearing; 18 – spring ring; 21 – rear cap; 25 – plug; 26, 36 – sealing ring; 28 – input gear of the first stage; 32 – adjusting ring; 35 – filler; 41 – casing of fast gearbox; 42 – oil nozzle; 43 – one-way clutch; 44 – output gear of the first stage; 45 – floating ring; 47 – input gear of the second stage; 48 – oil supplying pipe

The third stage of the gearbox consists of left and right input gears 29 and one output gear 28 (see Fig. 7.1). There are involute splines in the inner cavity of the output gear. These splines are used to transmit the torque to the fourth stage of gearbox. The fourth stage consists of a planetary component and a gear train. The planetary component decreases the rotational speed and transfers the torque to the inner and partially to the outer shaft of the lift rotor. The roller bearings of planetary gears are two-row. The inner surface of the planetary gear is very accurate and smooth, so it serves as outer racer of bearing.

The fourth stage serves to provide equal speed of both lift rotors, to transfer part of the torque to the outer shaft and to redistribute power fluxes between the propellers during the left and right turns of the helicopter.

7.4. Gearbox lubrication system

The lubrication system of the gearbox is autonomous and circulating. It comprises two-section gear pump (with delivery and exhausting sections), which rotational speed is 3060 rpm, two fine filters, a filler with a breather, a tray, a set of oil channels with orifices and a radiator for oil cooling onboard the helicopter.

The mixture of mineral transformer oil as per GOST 982-56 (25 % of the total volume) and mineral oil MK-8 as per GOST 6457-66 (75 % of total volume) is applied for lubrication and cooling of gearbox parts in summer. The oil MK-8 can be changed to oil MK-22 or MS-20 as per GOST 1013-49. In winter, less viscous mixture of transformer oil (50 % from total volume) and oil MK-8 (50% from total volume) is applied.

The scavenging section of oil pump 5 drives hot oil out from the gearbox. After the oil has passed the radiator, it gets to the bay for cooled oil of the tray 4. This bay has the cast channel, which connects it with the intake hole of the feed section of the oil pump. Then the oil is pumped through a fine oil filter 7, which is fitted in the wells of the upper gearbox casing. Two fine oil filters are arranged in parallel in the system to lower the hydraulic resistance. In case both filters get clogged, oil passes through ball-type bypass valve. These valves provide lubrication and cooling of gearbox parts by non-filtered oil. These valves open if pressure drop exceeds 0,0784…0,1176 MPa. The oil pressure reducer of the pump supply section provides the pressure within a range 0,441…0,049 MPa at operational modes and the pressure higher than 0,196 MPa at the idle mode.

The oil flow through the gearbox equals to 65 - 75 $\frac{\text{liters}}{\text{min}}$. The heat exchange between the gearbox and oil is 3558 $\frac{\text{kJ}}{\text{min}}$.

The oil level in the tray is 25…30 liters in case of the oil radiator is full. Oil must be changed each 100 hours of power plant operation.

The oil system operability is diagnosed by the temperature and pressure level at the discharge of the pump delivering section. There are special places provided for mounting temperature sensor and connecting pipe for manometer in the upper casing.

7.5. Materials of the gearbox parts

The gearbox casing is casted from АЛ5 aluminum alloy. The input shaft, shafts of the front and rear propellers are manufactured of 40ХНМА steel. Sun gear of differential gearbox, annuluses of planetary gears, annuluses that transfer torque to shaft of rear propeller are manufactured of 12Х2Н4А steel. The disk, fitter bolts and planet carrier are manufactured of 40ХНМА steel. The shafts of the planetary gears are manufactured of 12Х2Н4А steel with further chemical improvement of surfaces (cementation), except for the thread. The oil sealing rings are manufactured of БрОС16-5 bronze. The ring holders are made of 38ХМЮА steel.

8. VR-26 MAIN GEARBOX OF Mi-26 HELICOPTER

Shafting of Mi-26 consists of a main gearbox, two one-side clutch, shafts that form tail rotor drive, an interim gearbox and a tail rotor gearbox. The VR-26 main gearbox serves to sum up the power fluxes from both D-136 turboshafts, to transfer the power to lift and tail rotors, to drive the accessories mounted on the gearbox casing. This is the only gearbox, which can transfer power of more than 20000 hp.

The engine design bureaus that were engaged in designing Mi-26 did not succeeded in creating the gearbox of the given mass. So designers of Mil Moscow Helicopter Plant were forced to design unique gearbox themselves. Two kinematic configurations were under consideration: convenient planetary and new multi-flux that has never been used before in the Soviet helicopters. The researches revealed that the second configuration is more suitable to get a light gearbox. Finally, three-stage VR-26 main gearbox had two times higher transmitted power, one and a half times higher transmitted torque than those of the R-7 gearbox (helicopter Mi-6). However, it was only 8,5 % heavier.

The VR-26 main gearbox is a standalone unit that consists of casings, one-side clutches, front and rear bevel gearboxes, accessory drives and lubrication system. The components of main gearbox are manufactured as standalone units that are joined together by flanges and shafts. The one-side clutches provide the automatic disengagement of one or both helicopter engines in case of failures during the flight or in the windmill mode.

The gearbox is a multi-flux modular structure. It has three stages. There are four bevel gearboxes before the main gearbox.

The kinematic configuration of VR-26 is shown in Fig. 8.1.

The torque is transmitted from free turbine shafts of D-136 turboshafts to the gearbox inlet via plate clutches. These clutches compensate the misalignment between the engines and the gearbox of the helicopter. Then, the torque is transmitted to input bevel gears 2 via one-side clutches 1. After that, the torque is transmitted as follows: output bevel gears 3 of bevel gearboxes–>four driving gears 6 of upper gearbox –> eight output gears 7–>gears 5 and gears 9 of the lay shaft –>gears of lift rotor 12 and 23.

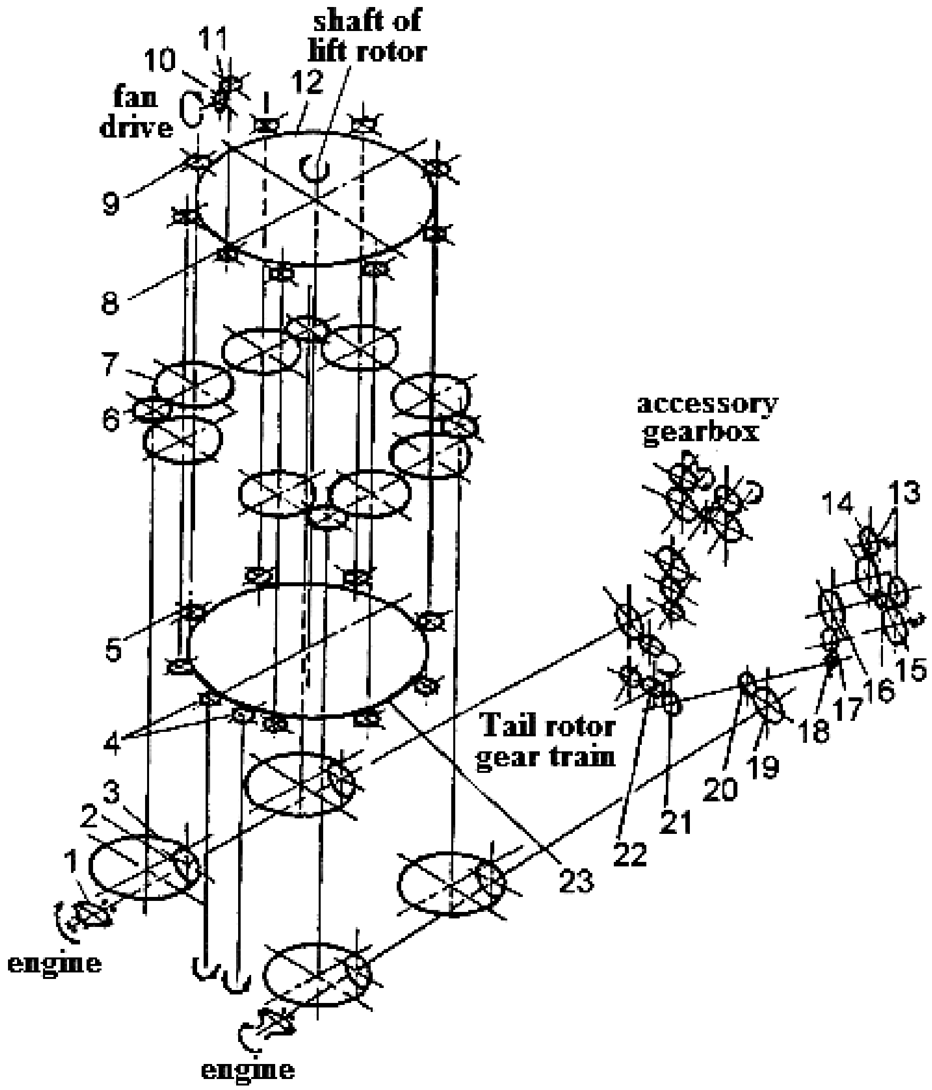


Fig. 8.1. Kinematic configuration of the VR-26 gearbox

Gear 10 drives the fan, gear 23 drives the oil pumps (gear train is 23–>4), gear 19 drives the tail rotor (gear train is 19 –> 20 –> 21 –> 22), and the accessory gearbox (gear train is 20 –>18 –>17 –>16 –>15 –>14 –>13). Gear ratio of lift rotor is 62.5, tail rotor – 3,096, fan –2,915 (all gear ratios are calculated towards the shaft of free turbine).

The gear ratio of the lift rotor shafting is 62.5, of the tail rotor shafting is 3,096, of the fan shafting is2,915 (all gear ratios are calculated relative to the free turbine shaft).

The B-3V oil is used for lubrication. The oil tank contains 180 liters. The oil is cooled in air/oil radiators. The oil flows through these radiators at 600 liters per second. The oil consumption must not exceed 0,5 $\frac{\text{kg}}{\text{hour}}$.

The dry mass of the gearbox is 3640 kg. Overall size is:
height – 2995 mm,
length – 2505 mm,
width – 2000 mm.

The gearbox is mounted in the engine bay behind the engines on separate truss structure.

The gearbox has spherical supports to mount the rear engine attach fitting. There is a fan in the front part of the gearbox under the engines. It cools the oil, the turbine casing and the divergent nozzle. The engines are complemented with big hinged paddles attached to their cowling. They provide an easy and convenient access to the engines for inspection and repair. There is an aisle inside the tail beam. It serves to maintain the shafting of tail rotor without special ground-based equipment.

Gearbox lifetime:

– service life limit (SLL) – 3000 hours;

– repair interval (RI) – 600 hours;

– guaranteed life (GL) – 600 hours;

– life limit in case of maintenance by the operating condition is 1500 hours (time between inspections – 250 hours);

– calendar life limit – 8 years with possible prolongation of the term up to18 years (RI – 2 years).

The non-failure operation time (NFOT) of the VR-26 gearboxes is 7710 hours. This is 3 times better than normal NFOT (the normal NFOT is 2500 hours). The high reliability level of the VR-26 gearbox gives an opportunity to use the helicopter under extremely severe conditions (firefighting, external transportation of goods, flights in mountains).

The VR-26 gearboxes are known several cases of cracks formation in the output bevel gears at the operating time of 1000 - 1100 h. This has shuttered further maintenance of gearboxes and helicopters, correspondently.

To detect the cracks in time during repairs, casings of gearboxes have four apertures ($\varnothing 10\text{мм}$). These apertures are used for periodical visual examinations of gears with optical endoscopes and their checkup with flaw detectors (eddy-current testing).

9. THE GUIDELINES FOR LEARNING THE GEARBOX DESIGN

When studying the construction of aircraft engine gearboxes the students are advised to:

– use the prepared mockups, engineering manuals of engines, posters and e-drawings;

– study and take notes of names and functions of the gearboxes and their main components as components within the aircraft power plant;

– do the layout drawing of the gearbox in the engine as well as the kinematic configuration of the gearbox;

– analyze kinemics of gearbox and determine gear ratio, check “mounting”, “coaxially” and non-interference geometrical conditions;

– study the operation of the assembly “propeller-gearbox” assembly, the way lift rotor hub is joined to gearbox shaft, the way centering and torque transfer are provided;

– study the construction of the main gearbox components including the casing, shafts, input and output gears, planetary gears, planet carriers, bearings, lubrication system;

– study the application purposes and operation principles of the gearbox accessories and draw correspondent schemes;

– learn the manufacturing materials;

– compare the gearboxes by their type, kinematic configuration, structure complexity(number of shafts, gears and bearings) and the ways the gearboxes are attached to the engine.

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Contents

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РЕДУКТОРИ СИЛОВИХ УСТАНОВОК ВЕРТОЛЬОТІВ И ТУРБОГВИНТОВИХ ДВИГУНІВ
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