REDUCTION GEARS

Valeri G. Nesterenko
Faculty "Engines of aircraft", Moscow aviation institute (engineering university), Russia.

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Summary

In this paper are explained fundamentals of development and design of RGs of gas turbine and piston engines applied in a structure of energy systems of different function, including engines for aircrafts and marine turbines. The working conditions, designs of basic elements of RGs and requirements, presented to them, are examined. Methods on structural design, criterion of evaluation of efficiency and information on characteristic damages of RGs at maintenance are adduced.

1. Introduction

The RG of a power plant is a mechanical toothed transmission ensuring the coordination of rotational frequencies of a power shaft of the engine with the optimal rotational frequency of a consumer of power. To consumer of power in aviation power plants it is possible to refer to the following: propellers of aviation planes; lifting and steering propellers of helicopters; fans of turbofan engines with large by-pass ratio; prop fans of TPFEs; assemblies set in rotation by the engine. The RGs for assemblies are differently named as drives of assemblies.

The kinematic effect of the RG is accepted to evaluate by gear ratio **i**, equal to ratio of rotational frequencies of the rotor of engine $\mathbf{n_{eng}}$ and consumer of power $\mathbf{n_p}$: $\mathbf{i = n_{eng} \cdot n_p^{-1}}$. Depending on the kind of consumer of power and power plant, the optimal rotational frequencies and, therefore, the gear ratios of RGs essentially change. The main requirements of the RG of jet engines are: high efficiency at small overall dimensions and mass; high reliability within the limits of installed service life; good manufacturability in production, repairability and serviceability.

Efficiency of RGs of jet engines are very high and lie within the limits η_{RG} = 0.98 – 0.995. However, at large transmitted power, friction losses can reach considerable values. So, at power of TPE **N** = 5000 kW and η_{RG} = 0.98 friction losses account for 100 kW. For heat rejection owing to friction losses, the RGs of TPE engines are provided with powerful lubrication systems pumping of oil through which is more in several times, than in jet engines of appropriate power and parameters of cycle. Despite of high constructional perfection of modern RGs, their mass makes a considerable proportion of mass of the engine. So, for TPE’s $\mathbf{m_{RG}}$ = (0.2 – 0.3)·$\mathbf{M_{eng.}}$, and for a helicopter GTE mass of the RG in 2 - 3 times exceeds the mass of the engine. The high reliability of RGs is provided by sufficient safety coefficients and necessary rigidity of its elements, application of high-alloy steels, surface strengthening of contact surfaces, usage of automatic safety devices preventing overload of the RG (of automatic machines of limitation of power and rotational frequencies, devices of drag-actuated feathering etc.). Providing of high manufacturability envisages fulfillment of the complex of constructional and technological measures permitting to simplify essentially production, repair and maintenance of a product without lowering of its reliability and efficiency. There is a number of signs, on which is realized classification of aircraft RGs: according to the kinematics chain are distinguished simple, planetary, differential, combined RGs. On arrangements concerning the engine, the RGs are classified according to built-in, offset and combined; on mutual arrangement of axes of the RG and engine are distinguished coaxial RGs and RGs with parallel axes (in airplane TPE’s), with intersected and crossed by axes (in helicopter GTEs). By kind of tooth are distinguished RGs with straight, helical bevel and herringbone teeth and by shape of profile of tooth - RGs with involute profile and profile formed by arcs of circles (transmission of Novikoff).

2. Reduction Gears of air jet engines and helicopter turboshaft engines

2.1. Function and basic performances of RGs

The application of propellers as movers of AC's with GTEs results in the necessity of application of RGs of greater or smaller complexity because of essential difference of rotational frequencies of propellers and setting them in motion with gas turbines (Table 1).

Type and name of engine of aircraft	Power, N_{eng} (kW) or thrust, (kN)	Rotational speed of rotor: of power turbine / of propeller (rpm)	Type of propeller	Type of reduction gear
turboprop:				
AI-20 (for IL - 18)	2720	12 300 / 1074		planetary
PW 120	1770	20 000 / 1200	pulling	placed out of engine
GE CT7 - 5	1300	21 000 / 1400		
Garryet TPE 331-3	622	41 730 / 2000		planetary
turbopropfan:				
D-27 (for An-70)	10400	8400 / 1000	pulling	planetary
NK-93 (for IL-96)	22400	8500 / 1700	pulling	planetary
turboshaft GTE:				
TM 319	350	37 000 / 6000	carrying	planetary
TV0-100	530	34 250 / 6000/250	carrying	-
MTR 390	1000	27 000 / 8000	carrying	-
TV2-117	1100	12 000 / - /192	carrying	-
D25V	4040	8300 / - /120	carrying	-
turbofan with reduction gear: TFE 731-2	thrust on take off 15,6 kN	19 730 / 10 970	pulling fan	planetary

Table 1. Rotational frequencies of rotors of TPEs, turboshaft GTEs and propeller of aircraft

Lowering of rotational frequency of shaft of propeller is reached by application of RGs with transmission ratio i_{RG} = (7 - 16) for TPEs of the single-shaft scheme and i_{RG} = (60 - 70) — for helicopter turboshaft GTEs with free turbine. These small and light RGs transmitting powers from several hundreds up to several thousand kilowatts, with EC $\eta \geq 0.97$, usually include in its construction complex differential and planetary transmissions.

The RGs can make a part of construction of GTE, and sometimes represent an autonomous part of a power plant of AC, have an own housing, units of retention, system of lubrication and cooling and be connected to the engine by torsion shafts. So, for example, in Figure 1 is shown the scheme of TPE, with RG included directly in the construction of the engine. As cab be seen from the figure, the housing of the RG is a continuation of air entrance housing.

In Figure 1, b the scheme of TPE with the born RG of propeller is shown. As well as in the scheme in Figure 1 the RG is fixed on the engine (with the help of a beam frame) and does not enter directly in the construction of the engine. The transmission of power on a propeller is realized by a rather long torsion shaft. The value of the distance between the RG and the engine in this case is determined by conditions of arrangement of power plant on aircraft. The scheme shown in Figure 1, c, concerns the power plant of a helicopter, which consists of GTE with free turbine setting in motion a lifting propeller through the RG, having autonomous mounting units in the form of a beam girder. The RG in this scheme is an autonomous part of a power plant with its own system of lubrication and cooling.

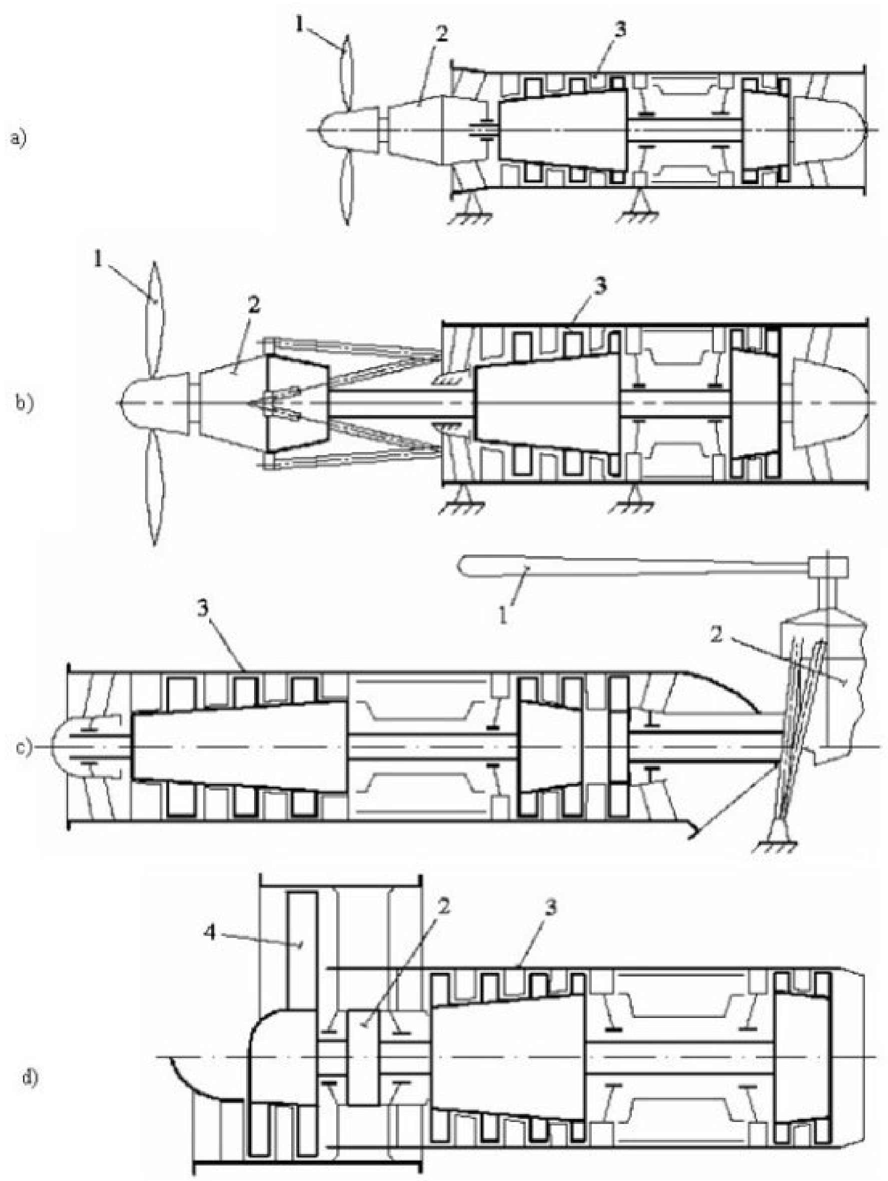

Figure 1. The schemes of placing of RGs: a) and b) - for TPEs; c) - for GTE of a helicopter; d) - for turbofan engine; 1 - propeller; 2 – RG; 3 - engine; 4 - fan

In some cases RGs are expedient to use in the construction of turbofan engines, when the same turbine sets in motion the compressor and fan or separate stages of the combined compressor of the engine rotating with different frequencies (Figure 1, d). For example, at high by-pass ratio of turbofan engine, the mass of a blade of fan increases so that at existing materials and high rotational frequencies of a rotor of the turbine, it is impossible to provide its strength. At the same time lowering of rotational frequency of a rotor increases quantity of stages of the turbine. To decide the task of optimization of construction and creation of slow fan it is possible with the help of the RG, linking rotors of free turbine and the fan.

Gear ratio of such RG is small $\mathbf{i_{RG}} \leq 3$, however it should have small mass and overall dimensions. TPFEs take intermediate position between TPE and turbofan engines. Structurally propfan represents a multi- bladed propeller of small diameter with bent ends of blades. Increased in comparison with usual for TPE number of blades (up to twenty two in existing TPFEs) allows to lower load on each blade. Taking into account, that propfan concerns to high-loaded movers, the RG in this power plant transmits considerably higher powers, than in usual TPE's. The increase of power, transmitted by the RG, with other things being equal conducts to increase of a torque on the shaft and friction losses, increase of loads on gears and bearings, that in turn promotes increased wear of details and heat release.

Striving for lowering of weight and overall dimensions of RGs and for increase of their reliability and durability results in necessity of application for their construction of details (first of all of gear wheels), made with large accuracy from high-quality constructional materials tolerating large stresses. The RGs are a source of torsional oscillations in a system a propeller – RG - rotor of a turbo compressor or free turbine. These oscillations can result in breakage of details of both RG and engine (for example, rotor blades of a turbo compressor). They arise because of inexactitudes in a base pitch of gearing caused by roughnesses in manufacturing of gear wheels, and also deformation of teeth under operation of loads in engagement. It results in an alternation of pitch and angular speed causing high-frequency oscillations in a system.

It is possible to avoid or essentially to reduce these oscillations at the expense of application of toothed wheels made with a high accuracy on pitch. It is also useful to apply toothed wheels with large values of coefficient of overlapping, for example helical gears, being as well more rigid on bending teeth. In connection with heat release because of friction in engagements of gear wheels and in supports of the RG the special attention is given to the details of cooling and lubrication. The RGs of TPE's are usually cooled at the expense of ventilation of their bodies by air going at the compressor, the cooling of oil is realized in radiators. For cooling of RGs of helicopter GTEs installed in fuselage, special fans and radiators are used.

Aircraft RGs are rather perfect devices with specific mass (relation of mass of the RG to power transmitted to them,) **1 - 2** orders of magnitude lower than for RGs of general engineering. Despite of it, the mass of RG makes a considerable proportion of the mass of the power plant of aircraft and is commensurable with the mass of engines or exceeds it **(**Table 2**)**.

Name of helicopter or aircraft	Type and quantity of engines	Power of engines N_{eng}, (kW)	i_{rg}	Mass of RG m_{rg} (kg)	Mass of engine m_{en}, (kg)	$M_{rg} \cdot \cdot N_{en}^{-1}$	$M_{rg} \cdot \cdot m_{en}^{-1}$
ON-6A	jet	233	-	36	62	0,154	0,58
CH-53A	2 jet	2×2100	-	1326	2×328	0,317	2,00
Mi-8	2 jet	2×1100	62,5	787	2×330	0,360	1,18
Mi-6	2 jet	2×4040	71,43	3200	2×1100	0,400	1,45
Il -18	turboprop	2720	11,49	240	1080	0,088	0,22

Table 2. Parameters of RGs of helicopters and airplanes

A considerable part of the mass of a power plant of a helicopters with GTE is the mass of the cooling system of the RG, $\mathbf{m_{CS}}$, including oil radiator, fan and its drive. Approximately $\mathbf{m_{CS} = 0.05 \cdot N_{ENG}}$, where $\mathbf{m_{CS}}$ - in kg, and $\mathbf{N_{ENG}}$ - in kW. In the design of the RG, a torque meter is included which shows propeller power of the engine during its work on ground and in flight.

It can be electronic of magnetic type (by a phase shift) or hydraulic, where the principle of equilibrium of circumferential force from a torque on shaft of the RG which operates on a rod of shafts and force from pressure of oil under pistons in cavities of shafts is used.

The evaluation of the mass of the RG of a helicopter GTE as a function of the torque on the shaft of a propeller $\mathbf{M_{TOR}} < 15 \cdot 10^4$ in $\mathbf{N \cdot m}$ (where $\mathbf{N} \approx 3000$ kW) can be made, using the formulas: $\mathbf{M_{RG}} = 0.0053 \cdot \mathbf{M_{TOR}} + 200$ (for the helicopter with single propeller); $\mathbf{M_{RG}} = 0.0081 \cdot \mathbf{M_{TOR} + 72}$ (for the helicopter with two coaxial propellers). The main portion of mass of RGs of TPE's of helicopter GTEs is the mass of toothed wheels of the main kinematics chain (up to 30 per cent of mass of the RG).

Then follows a RGs housing — 15 - 18 per cent, shaft of a propeller — 9 - 16 per cent, bearings of the main kinematics chain of the RG — 6 - 13 per cent, housing of planet pinions — up to 7 per cent.

2.2. Transmission ratios of RGs

On the basis of the technical requirements of an airplane with TPE is determined the calculated point of the propeller appropriate to conditions of work of a propeller with a desired value of efficiency $\boldsymbol{\eta_{prop}}$ on a certain altitude and speed of flight.

The diameter of the propeller and transmission ratio of the RG are determined by using standard diagrams of characteristics of the propeller $\boldsymbol{\beta = f(\lambda)}$, which represent the experimentally obtained set of characteristics of geometrically similar propellers of a certain construction **(**Figure 2**)**.

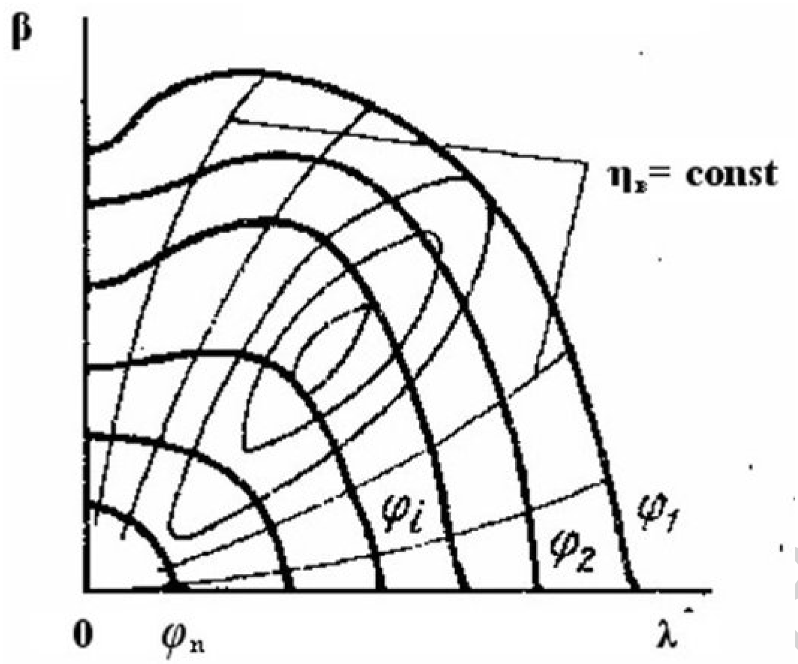

Figure 2. Characteristic curve of the propeller β = f (λ)

Each characteristic **β = f (λ)** on the diagram corresponds to some angle of installation of the blade of the propeller φ. On the standard diagram, the lines of constant EC of the propeller are shown **(η_{prop} = const)**. For given values of speed **V**, altitude of flight **H** (appropriate density of air ρ), power of the engine **N** and rotational frequency of the propeller $\mathbf{n_p}$, sequentially being set, several values of diameter of the propeller $\mathbf{D_{prop}}$, determine power coefficient $\beta = \mathbf{N}\cdot(\rho\cdot\mathbf{n_{prop}}^3\ \mathbf{D_{prop}}^5)^{-1}$ and operational mode of the propeller $\lambda = \mathbf{V}\cdot(\mathbf{n_{prop}}\cdot\mathbf{D_{prop}})^{-1}$ .From the reference diagram find the appropriate value η_{prop} for each of given values $\mathbf{D_{prop}}$ and construct the dependence $\eta_p = f(\mathbf{D_{prop}})$, from which find $\mathbf{D_{prop.opt.}}$. If optimum diameter of the propeller, which was found, is unacceptable (for example, because of its large value), repeat calculations for different value $\mathbf{n_{prop}}$ or with the usage of standard diagram of other set of propellers until an acceptable size of the propeller is obtained. Required transmission ratio of the RG is:

$$\mathbf{i_{RG}} = \mathbf{n_{ENG}} \cdot \mathbf{n_{prop}}^{-1}, \tag{1}$$

Transmission ratio of the RG of a helicopter turbo shaft GTE is determined, using the relation between diameter of lifting propeller $\mathbf{D_{prop}}$ and specific load **p** on the area which is swept by a propeller**:**

$$\mathbf{D_{prop}} = \sqrt{4\mathrm{g}\cdot \mathrm{M_{HEL}} \cdot \left(\pi \cdot p\right)^{-1}}, \tag{2}$$

where $\mathbf{M_{HEL}}$ **-** take-off mass of the helicopter; **g** - acceleration of gravity. Usually value of parameter **p** = 100 - 160 Pa for single-engine helicopters and reaches 500 Pa for heavy twin-engine helicopters. The increase of specific load is desirable, as at this diameter of the propeller decreases. Maximum value **p** for single-engine helicopters is determined from a condition of provision of safe landing on the mode of autorotation of lifting propeller. The speed of vertical movement of the helicopter on the mode of auto-rotation is connected with **p** by relation:

$$\mathbf{V_{HEL}} = \mathbf{1.48}\sqrt{p \cdot \Delta^{-1}}, \qquad (3)$$

where **Δ -** a factor depending on altitude of flight and atmospheric conditions. For twin-engine helicopters practically are ruled out cases of simultaneous failure of both engines, therefore specific load p can be increased. Diameter of lifting propeller is limited also by permissible circumferential speed of tip sections of the blade $\mathbf{U_k} = \mathbf{(}180 - 220)$ m·s^{-1}. Therefore rotational frequency speed is determined by dependence $\mathbf{n_p} = \mathbf{(}60\mathbf{U_k}\mathbf{)} \cdot \mathbf{(D_p)^{-1}}$, and transmission ratio of the RG - under the formula (1).

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Bibliography

1. Under general edition of D.V. Chronin (1989). *Construction and designing of aircraft GTE*, Moscow: Engineering. [Fundamentals of designing of RGs of aircraft GTEs are explained, the computational methods on strength and criterion of estimation of their functionability are adduced.]

2. Under general edition of L.P. Lozitskiy (1992). *Construction and strength of aircraft GTE*, Moscow: Air transport. [The constructions of RGs of aircraft GTE are described, the problems of reliability and control of their technical condition in maintenance are described.]

3. Under general edition of V.I. Zaitsev (1981). *Ship steam and gas turbines*, Moscow: Transport. [Constructions and schemes of RGs of marine turbines with toothed transmissions, in which are combined external and internal engagements, are considered.]

Biographical Sketch

Valeri G. Nesterenko is an associated professor of Engine Department of the Moscow Aviation Technical University (MAI). He took his Ph.D. degree in 1984 and became senior research assistant by speciality “Heat engines of aircrafts” in 1987; senior lecturer of Moscow Aviation Institute (MAI) on chair of construction and design of engines of aircrafts - 1992. In MAI he does teaching work and gives courses of lectures on a number of educational disciplines of speciality “Design of construction of AJE”: “Construction and design of AJE”, “Power plants of aircraft AJE”, “Reliability of AJE” and other. He is the author of more than 70 printed works. Research interests are concerned on energy-machine-building, including aircraft and stationary gas turbine units. He works on research and optimization of: choice of aerodynamic loads of compressors and turbines of GTE, their connection, in particular, with a level of noise, arising at passing of air through the inducer vanes; kinematics chains and strength load of gear wheels of aircraft reduction gearboxes; research and optimization of oil systems of aircraft GTE.

Valeri G. Nesterenko was born in 1939, graduated from Moscow Aviation Institute in 1963. He is the author of more than 70 printed works, including: album “Aircraft modular gas turbine engines”; atlas of schemes and constructions of assemblies of AJE (1991); “Design and calculation of basic supports and shafts of AJE” (1999); “Design and calculation of connections of elements of rotor of GTE” and other. Valeri G. Nesterenko is senior lecturer of Moscow Aviation Institute (MAI) on chair of construction and design of engines of aircrafts with 1992. In MAI he does teaching work and gives courses of lectures on a number of educational disciplines of speciality “Design of construction of AJE”: “Construction and design of AJE”, “Power plants of aircraft AJE”, “Reliability of AJE”. In the present he is the technical adviser of Designer Bureau IACI.