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POWER SPEED REDUCTION UNITS FOR GENERAL AVIATION PART 3: SIMPLIFIED GEAR DESIGN PISTON-POWERED, PROPELLER-DRIVEN GENERAL AVIATION AIRCRAFTS

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ABSTRACT

`The power speed reduction unit (PSRU) is the device that is loaded by the piston engine and the thruster. The thruster, a propeller of a fan, acts on the PSRU to extract the required power at the optimum speed for the aerial vehicle. Inertia, thrust and vibrations load the PRSU. PSRU has been “the problem” of the years before WWII. These problems periodically come back from common design errors or from the introduction of new technologies. For historical reasons, FAR and JAR do not allow the use of belt and chain transmissions in PRSUs for aircrafts. However, recent advances in timing belts make it possible to manufacture lubrication free PRSUs. Multi-Groove-V belts have also been used successfully in helicopters and homebuilt aircrafts. Belt PRSU are critical in design and they will be fully analyzed in another paper. This third paper deals with the general problem of designing the PRSU gear drives on a general aviation aircraft [1-2].

Keywords: PRSU, aircraft, piston engine, gear drive, involute.

Foreword

The Wright brothers used a chain drive PRSU for their first manned flight in 1903. However, PRSU were not generally used on aircrafts until larger engines were designed in the 1920s. Large engines with larger propellers and high crankshaft speeds demanded PRSUs with reduction drives. Types of propeller speed reduction units includes: chain drive; toothed, plain, V and multi groove V belt; single-multiple reduction offset spur and helical gear; single-multiple reduction internal spur and helical gear; planetary cylindrical (spur/helical) gearing with fixed sun or internal gear; Farman/bevel planetary type. The Rolls-Royce Falcon engine of 1915 already featured epicyclic propeller reduction gearing with an integrated overload torque clutch, thus protecting the reduction gears. This PRSU gives an idea of the amount of work done in PRSU development even in early years of aviation history. Most famous WWII engines like the RR Merlin, the P&W Wasp series and the DB605 have PRSUs. The later RR Merlin engines from the same company used opposite rotation reduction gears to provide contra-rotating propellers [3-6]. The Continental Tiara series engines were designed to drive their propellers directly from the camshaft that runs at half engine speed. In this engine the PRSU was integrated in the camshaft drive. In recent years, automotive conversion is becoming extremely convenient for aircrafts, UAV and helicopters powered up to 1,000HP per engine. The extremely high efficiency of CRDIDs (Common Rail Direct Injection Diesels) and the possibility to run on both Jet and diesel fuel has made these piston engines extremely cost-effective. Automotive engines are available in the aftermarket at extremely reasonable price. Due to the downsizing policy of the automotive manufacturers, the use of a PRSU is compulsory when automotive units are used. Typically, aircraft propellers develop peak power near the peak efficient speed-1,250 to 2,900 rpm. In fact, efficiency requires keeping the propeller tip speed below the speed of sound. Many authorities certified aircraft piston engines also use PSRUs integral to their design.

INTRODUCTION

Theoretically, planetary gear approach offers some interesting possibilities including compactness, light weight, reliability due to load-sharing and simple auxiliary shaft for a hydraulic constant speed propeller.

Many of the WWII big radials used planetary reductions (P&W 1830, 2000, 2800, 4360; Wright 1820..) and also the geared Lycoming 480 engines use a planetary reduction. However, the planetary approach has a few shortcomings. In this case the propeller centerline is coincident with the crankshaft centerline. That is desirable for a radial, a rotary, or an opposed engine, but not so fine for “in line” and “V” configurations.

In a normal liquid cooled "V" and “in-line” piston engines, with the heads upwards, the propeller on the crankshaft centerline requires the whole engine to be raised, creating a difficult cowling geometry. Theoretically, the thrust line could be lowered, but the reduction the distance between the thrust-line will destabilize the aircraft. Moreover, the lower propeller shaft will require a taller landing gear. Another problem is that for small power units the required reduction ratio lies in the range from 1.5 to 2.7. This reduction ratio is typically too low for planetary gearing. In fact, The ratios between approximately 1.5 and 2.7 are very difficult to implement because of the very small planet size required and the corresponding very high planet velocity that results. In order to obtain these ratios, a two-stage planetary gearset is required, or in the alternative, a Ravigneau gearset, which has severe planet-bearing issues. So planetary gearings are not a good approach for a "V" or in line engine retrofit. The best configuration to consider is the offset gear reduction. This configuration is used on the Continental GTSIO-520, the Rolls-Royce Merlin, and the Allison V-1710 engines. In these engines, the centerline of the propeller shaft is offset upward from the centerline of the engine crankshaft. These engines use spur (straight) gears [7-8].

Considerations on gear type: spur, helical or double helical

Historically, offset helical and spur gear reduction drives are typical of piston engine where transmission ratios are below 3.5.

Spur gears demonstrated their reliability as demonstrated by use in hundreds of thousands of famous aircraft engines that run for trillions of hours.

Therefore, the claim found in a few publications that helical gear trains are more reliable than spur gears is groundless. This claim is based on the greater contact ratio of helical gear drive. However, the typical contact ratio for small (and light) spur gears is around 1.6, which means that 60% of the time there are two pairs of teeth in contact and only 40% of the time the entire load is carried by a single pair of mating teeth. Helical gears, have a contact ratio often in excess of 2.5, but suffer from the inherent problem of edge-loading. In fact, the very early versions of the Merlin used double-helical, but the lack of reliability drove Rolls Royce designers back to a spur gear.

The P&W 1830 and 2000 radials had spur-gears single stage planetary reductions. The P&W 2800 A and B models had a two-stage planetary; the C model used a single stage planetary. In addition, the Wright 1820 had a spur-gears single-stage planetary. The Continental GTSIO-520 uses an offset spur gear reduction that typically last several TBO (1600h) runs. Also the accessory drives of many supercharged WW2 engines, had spur gears this is true especially in the application of the supercharger drive units, having step-up ratios up to 12:1. These relatively small gear drives carriy several hundred HP driving the blowers and are subjected to unbelievable acceleration loads. In addition to widespread use of spur gears in piston engine applications, they are also used in many propeller reduction units of turboprop engines. However, the main problem of spur gears is energy density. The oblique contact is more progressive and reduces the shock at teeth engagement. The larger inertia moment at root reduces tooth-bending stress and the larger contact ratio improves pitting durability. The results are smaller gears. Since housing deformation goes with the cube of the housing size, smaller housings are stiffer and lighter. Even if helical gears require stiffer housing, this result can be obtained by double walling or ribbing. Modern casting technologies use these techniques even in high rate production crankcases of diesel engines. In addition, gear quality had an important improvement in the last 50 years from WWII. Gears with ISO quality up to 5 (AGMA 12) is now common even in automotive production. The open issue about helical gears is the efficiency, notoriously lower than the one of spur gears. Overheating problems have always been present in aerospace. Therefore, high helix angles are to be avoided. Another important issue of helical gear is axial thrust. The output shaft provides for propeller thrust absorption anyhow, but the design must contrast significant thrust loads on the input shaft. On engine-driven input shafts, the thrust is critical. In fact, input shafts should tolerate axial displacements from engines and dampers. For thrust control, a simpler design is the double helical gear drive (Figure1). The double helical gearing have problems with low torque (power) since face width becomes extremely small. Practically it is convenient over 300HP for piston engines running at 6000rpm. The gap between the two opposing helical gears is fundamental for lubrication and air escape. The traditional Herringbone, Chevron or Citroen double helical without the gap are problematic for both the manufacturing and the lubrication. The problem of the early RR Merlin engine is related to the design and manufacturing that, fifty years ago, were quite critical [9-13].

Table-1. Gear material comparison.

Material	HB surface	HB core	Pitting ultimate [MPa] **Sc**	Bending ultimate [MPa] **Sf**
Thr. Hard. Alloy Steel	320	320	740	580
Surf. Hard. Steel	565	265	1160	680
Carburised Steel (best)	692	330	1500	920
Carburized Steel (standard aero.)	-	-	1330	740
Nitrided Steel	668	337	1450	1050
Thr. Hard. Carbon Steel	210	210	550	440

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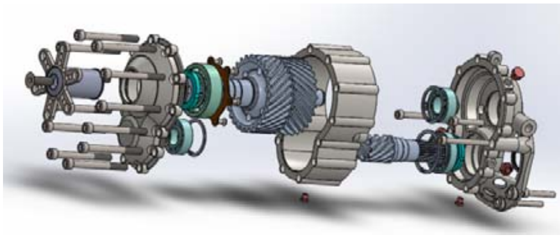

Figure-1. Double helical PRSU.

Gear material comparison

Carburized steel is the material of choice for gears in helicopters and aircrafts. These maximum performance gears in aircrafts operate under higher speeds, loads, and surface temperatures than many other gears and are subject to scoring, surface pitting, and tooth bending fatigue. Gear tooth scoring occurs under high speed and load conditions and increases significantly when the temperature exceeds the maximum allowed for the lubricant. Aircraft PRSUs that operate in warm climates face oil temperatures between 100 and 200°C. In addition, the need for survivability of the aircraft operating under reduced and/or starvation oil conditions is recognized. AISI 9310 steel is the material used most frequently to manufacture gears for aircraft today. The material is carburized steel with a soft core. Gears made from this material exhibit good endurance characteristics. However, because AISI 9310 loses much of its hardness at temperatures beyond 120°C its application to new advanced aircraft systems is limited. However, AISI 9310 and similar steel alloys are widely used in automotive gear drives. Therefore, the cost-effectiveness of these material for purchasing and manufacturing is extremely high.

Therefore, materials and process selection are key issues in optimal design of aircraft products. Recently newer materials are replacing many materials, which have long been used in industry, in order to meet demands of cost reduction and better performance.

The most important mechanical material properties usually encountered in material selection process are fatigue strength, tensile strength, yield point, hardness, toughness and behavior at high temperature.

Optimal design of gears requires the consideration of material and geometrical parameters. The choice of stronger material parameters may allow the choice of finer geometrical parameters and vice versa. The important difference between these two parameters is that the geometrical parameters can often vary independently, while material parameters are often inherently correlated to each other. For example, the variation of the bending fatigue ultimate stress is linked with the surface hardness for surface hardened steel. In aircraft PRSUs, the choice of materials is limited to a list of pre-defined candidates due to limited production numbers. Table-1 shows five materials with their characteristics in a gear material selection process. In a more practical approach, only carburized and nitrided steel can be used. Therefore, the available options of material for gears are only three: high quality carburized, standard quality carburized (AISI 9130) and extremely high quality ion-nitrided. Automotive carburized gears are hobbed then shaved. The form of the resulting tooth already includes the shape variations due to carburizing and tempering. Due to limited production numbers, aerospace gears are cut, carburized, hardened, ground and cryogenic treated. The deep cryogenic treatment on steels increases the wear resistance and releases residual stresses. Hot hyping on the blank is also common. In racing gearboxes, ion-nitrided gears were introduced. In this case the blank is hobbed, then quenched and grinded. Ion-nitriding and shot peening is selectively applied to obtain the best performance result. This process has also the advantage that it is possible to obtain experimentally a good tooth profile correction. In fact, for optimal results, the tooth profile is corrected for the displacements of housing, bearings and shafts. This result can be obtained by running-in the unhardened gears through a few laps on a circuit. The gears are then measured and the corrections are applied prior to the ion-nitriding process in the final gears. A very important advantage of ion nitriding is the resistance to high temperatures. The ultimate stress reduction for pitting at 300°C is only 20%. For these reasons, nitrided gears are widely used in racing.

Engine induced loads

While propeller induced loads are approximately constant, with the exception of occasional overloads and shocks due to turbulence, a piston engine produces a very uneven output. The degree of unevenness depends on the number of cylinders, the crankshaft geometry and the firing order.

A piston engine generates horizontal, vertical and torsional vibrations along with rocking moments. The torsional component of the output loads the PRSU gears.

A single cylinder four-stroke engine generates a variable torque whose peak value of torque output is approximately 15 times greater than the mean value. In these engines, the torque curve contains also a negative peak, which is approximately 5 times the mean engine torque. As the number of cylinders increases, the peak amplitudes decreases and the waveform tends to become more similar to a sinusoid. This is true for "even-fire" engines in which the firing of each cylinder follows its predecessor by the same angle of the crankshaft.

In common even-fire, inline, four-cylinder engines, one cylinder fires every 180-crankshaft-deg. With the common firing order “1-3-4-2”, the instantaneous torque curve contains two peaks 3 times above mean torque and two negatives of about 2 times below.

This is a "second order" excitation, with two complete approximately sinusoidal torque cycles per rotation of the crankshaft. An even-fire in line 6-cylinder shows a torque waveform with three 250% positive peaks and 3 50% negative one. A 120° V12 produces six power pulses with peaks and valley of 40% the mean torque. For certification purposes a four cylinder is the minimum possible. In fact, the loss of one cylinder should not stop the engine. Therefore, the maximum gearing overload is

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the one of the four in-line engine with peaks of 3 times the mean torque.

Propeller induced load

The worst-case environment in which the power operates defines the load model. Therefore, the requirement is a set of operating scenarios. The gear drive is designed to achieve the desired life under those loads and durations.

Table-2 is an example of a general aviation load model used for propulsion system design.

Table-2. General aviation load cycle.

Operation	Load	RPM	Time
Take Off	100%	100%	0.1%
Climb	100%	92%	1%
Cruise	75%	80%	78%
Idle	2%	30%	20.9%

In Table-2, it is possible to see that for approximately 21% of the time the PRSU will run with very small loads. Only for a very limited part of its life (0.1%) the PRSU will face full loads.

Table-3. Number of cycles on gear tooth.

Operation	Time	RPM	Cycles (x1000)
Take Off	0.1%	2500	5
Climb	1%	92%	46
Cruise	78%	80%	2,925
Idle	20.9%	30%	218

Tooth profiles

The most common tooth profile is the involute. Manufacturing of involute gears is the most cost-effective. Cycloid and circular tooth are senseless, while Wildhaber-Novikov profile has a slight advantage. However, this advantage is annulated by manufacturing problems. Asymmetrical profiles should be avoided since turbulence and propeller stop will easily induce high negative loads. Therefore, the best choice is still the involute with profile correction for loads.

Basic concepts on tooth design

ISO and AGMA gear design methods are based on Hertz contact (pitting) and root bending stress (Strength). Limited life design is obtained through the same coefficient Z_N for pitting and Y_N for bending stress. These coefficients (Z_N, Y_N) are identical (Figure-2).

The load-cycle factors Y_N and Z_N, are used to modify the *AGMA* strength for lives other than 10^7 cycles. In our case, the total design cycles are $3.2x10^6$. Therefore, load cycle factors are always larger than 1. Equations (1) and (2) are introduced by AGMA for gear verification. ISO uses the same approach with different symbols and units.

$$C_p\sqrt{W^t K_0 K_v K_S \frac{K_m}{d_p F}\frac{C_f}{l}} \leq \frac{S_c Z_N C_H}{S_H K_T K_R} \quad (1)$$

$$W^t K_0 K_v K_S \frac{P_d}{F}\frac{K_B K_m}{J} \leq \frac{S_t Y_N}{S_F K_T K_R} \quad (2)$$

The coefficients K_0, K_V, K_S, K_T, K_m, and K_R are overload coefficients. K_0 is the overload coefficient, K_V is the dynamic coefficient for "commercial" quality gears. Ks takes into account the fact that very small gears have higher allowable stress than very large ones. K_T takes into account of operating temperatures higher than 120°C. K_m is the shaft misalignment factor. K_B is the rim thickness factor. For aerospace gears, these factors can be assumed unitary with the exception of K_0 for bending stress. In fact, when carburized steel are used for gear and "not aeronautical" bearings are the only choice available, temperatures should not exceed 120°C. Therefore, gears are calculated with the overload included in W^t. Reliability factors and misalignment of shafts are included in the safety factors SF and SH. The rim thickness factor is non-influent for the pinion. The pinion is always the gear that breaks down (at least in calculations). C_f is always unitary. C_H is also unitary, since in aerospace the pinion and the gear have the same hardness. C_p depends on material Young Modulus. Therefore, it is constant for steel type. Actually, it is higher for carburized gears and slightly lower for nitrided ones.

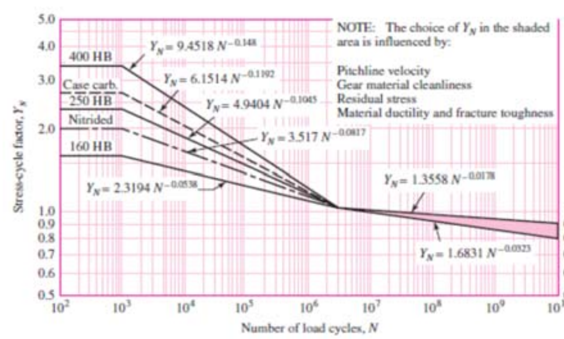

Figure-2. YN and ZN (equations 1 and 2).

Therefore, Equation (1) for pitting becomes equation (3). In this equation W^t is the tangential load, F is the face width and l is the geometry factor. d_p is the diametral pitch.

$$C_p\sqrt{\frac{W^t}{d_p F}\frac{1}{l}} \leq \frac{S_c Z_N}{S_H} \quad (3)$$

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S_c is shown in Table-3. The coefficient Z_N remains critical. For maximum load (take off) and carburized steel it is possible to adopt an Z_N =2.8 and S_H=2. It is possible to see that the gear drive calculated in this way is also verified for all the other load levels of Tables 2 and 3. For nitrided gears Z_N =2 and S_H=2. W_t can be calculated from equation (4), where P is the engine output power.

$$W^t = \frac{P}{\omega} = \frac{30 \times P}{\pi \times RPM} \tag{4}$$

The torque fluctuations are not included in the pitting calculations, since pitting resistance depends on viscosity of the lubricant film thickness that depends mainly on temperature. This fact averages the cycle loads.

On the contrary, overload is important for bending stress. In this case, if the overload develops a crack on tooth root, the crack will grow until failure, even in case of reduced cruise loads. Therefore, the strength equation (2) is simplified to equation (5).

$$K_0 W^t \frac{P_d}{F} \frac{1}{J} \le \frac{S_t Z_N}{S_H} \tag{5}$$

P_d is the transverse diametral pitch and J is the bending-stress geometry factor. However, the overload factor K_0 for bending depends on the engine torque curve. In the 4-in line engine, the peak torque is 3 times the average one. Therefore, the factor K_0 is 3 for the 4-in-line engine. The safety factor S_H for pitting and S_F for strength are both equal to 2.

Diesel PRSU overload due to a sudden propeller stop

High compression diesel engine may develop high torque at engine stop. This is because FADEC may have problem to control accurately the slowing down of the engine below 1,000 rpm. In this case, the PRSU may face a sudden stop. For example, a propeller is running at 1,000 rpm and the FADEC cuts off the fuel suddenly. In this case, it is possible that the propeller comes to a full stop in half a propeller turn ($\Theta=\pi$). In this case, equations (7), (8) and (9) hold.

$$\Theta = \tfrac{1}{2}\dot{\omega} t^2 \tag{7}$$

$$\omega = \dot{\omega} t \tag{8}$$

$$T = J_p \dot{\omega} = 1220 \tag{9}$$

The torque T=1,220 Nm (with J_p=0.7 kgm^2) may exceed design maximum torque.

Tooth design

PRSU noise is usually covered by the propeller one. For this reason, it is convenient to use stub gears. In addition, stub gear has a better efficiency. The fundamental characteristic of a stub gear is a reduced tooth. Usually 0.8 the normal addendum. By this smaller tooth depth, the tooth possesses a broader basis and the flexural moment resulting from the applied force on the tooth becomes smaller; hence a greater strength. Along with a slight reduction of the dimensions, this is the principal advantage of the stub gear. On the other hand, the length of the contact line is reduced so the gear drive is noisier. In addition, the distribution of the force across the teeth and across the contact areas is disadvantageous with faster wear of the tooth flanks. The use of a stub gear is typical to gears intended for the transmission of a large torque, but that are not constantly in operation at maximum torque. With modern hobbing machines, the production of such gears does not require special tools.

The hob pressure angle of stub gears is always 20° and the dedendum is usually 1.25 x the module. It is also convenient to adopt the largest root possible. A relative large play between the gears improves gear life and reliability. Chamfered or rounded tooth edges are not convenient.

Temperature control

For PRSU reliability is convenient to monitor oil temperature. For best cost-effectiveness it is convenient to use common automotive derived technologies. In manual gearboxes carburized gears are used (table 1). Carburized steel cannot exceed 120°C. Special lubricants for manual gearboxes have been developed for these gear drives. These lubricants should not exceed 110°C. As the lubricant becomes to degrade, its temperature in the gearbox increases due to a reduced viscosity and friction increase. A careful monitoring of this tendency by the engine FADEC (Full Autority Digital Electronic Control) can easily increase reliability. Automotive grade bearings have the same temperature limit (120°C maximum). The temperature limitation is different for nitrided gearing and aerospace specific bearings (that are also nitrided). In this case, special oils can be used with temperatures up to 200°C. The failure of nitrided gears is also signaled by a temperature increase in the lubricant.

CONCLUSIONS

Piston engine PRSUs for propellers should have gear drive reduction system to be certified by FAA and EASA. Involute gears are used for cost quality and efficiency. Automotive grade carburized steel and off-the shelf bearing are the premium choice for cost-effectiveness. For better performance under overload, nitrided steel and aerospace bearings should be used. A simplified method to design an involute gear drive for a general aviation PRSU is introduced herein. The method starts from the ISO/AGMA gear design equations. The AGMA symbols are used in this paper.

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