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POWER SPEED REDUCTION UNITS FOR GENERAL AVIATIONPART 2: GENERAL DESIGN, OPTIMUM BEARING SELECTIONFOR PROPELLER DRIVEN AIRCRAFTS WITH PISTON ENGINES

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ABSTRACT

The power speed reduction unit (PSRU) is the device that is loaded by the generating unit and the thrusters. Propeller induced, gyroscopic and inertia loads are extremely important for PRSU bearing selection and life evaluation. Engine powers become easily a secondary factor for bearings and housing design. For this reason, it is important to select the best bearing assembly for the specific application with the required propeller. After a general discussion about PRSU and housing design, a very simplified method for bearing life calculation is introduced in this paper. It is based on similar, proven and extremely successful design of existing PRSUs. This method compares the life of this design with the new one. Aerobatics and general aviation loads are also compared. This paper demonstrates that the selection of a CFRP fixed pitch propeller for aerobatics keeps the load approximately to the same level of a general aviation aircraft. This is true in the case of plywood-reinforced off-the-shelf propeller for the general aviation load history. Aluminum alloy propellers are to be discarded for aerobatic use.

Keywords: PRSU, piston engines, general design, bearings, propeller.

FOREWORD

The use of a reduction unit is common in aviation history. Most famous liquid cooled V12 WWII fighter engines like the RR Merlin and the DB605 have PRSUs. In recent years' automotive conversion are becoming extremely convenient for small, experimental homebuilt aircrafts. The extremely high efficiency of CRDIDs (Common Rail Direct Injection Diesels) [1][2] and the possibility to run on both Jet and diesel fuel has made this option extremely convenient also for UAV and helicopters and in general for Army operated aerial vehicles. Automotive engines from 45 up to 1,000HP are now available. Due to the downsizing policy of the automotive manufacturers, the use of a PRSU is common when automotive are used. As it was shown in previous papers the possibility of choosing the transmission ratio often improves the overall efficiency of the power plant installation. Automotive engines, in develop peak torque at low revolutions per minute (rpm), typically near 2,500 rpm. For this reason, original TCs (Turbo Charger) [3][4][5] are replaced with larger ones and the engine mapping is retuned for the new application. In fact, aerial vehicles require power and torque at high rpm. This fact, along with fixed working points, makes it possible to increase significantly the power output. Traditional aircraft engines, where the propeller is fastened directly to the engine crankshaft, develop peak power near the peak safe and efficient speed for the propeller-1,250 to 2,900 rpm. This speed is a typical maximum rpm for a single engine aircraft propeller. If fact high efficiency requires to keep the propeller tip speed below the speed of sound. However, in order to achieve maximum efficiency, propeller rotational speed is linked to aircraft and engine installation drag.

Many authorities certified aircraft piston engines also uses PSRUs integral to their design.

INTRODUCTION

It is the propeller and the use of the aircraft that define the PRSU housing size and dimensioning. In fact, slow aircraft require large propeller with low disk loading. Large propeller has extremely large moment of inertia that will load the housing and the bearings with huge loads. Another important factor is vibrations.

In fact, engine torque pulses induce fatigue load the gearbox components. However, metal propeller blades are extremely unforgiving of being excited near a resonant frequency. Therefore, a very important reason to control and evaluate engine torsional excitation is to eliminate the pulse excitations applied to the PRSU propeller blades through the gearbox, multiplied by the gear ratio. Propeller blades have several resonant frequencies. The frequencies excited by thrust vibrations are different from the ones excited by torsional vibrations. So thrust and torsion induces vibration on PRSU on propeller and on engines and engine accessories. Mysterious and random failures may take place on engine parts with "random" logic. Perfectly working engine may be found defective in a particular installation. This is typical of pulsating loads. Metal propeller blades are especially susceptible to destructive vibration due to natural frequency. This is due to virtually absent damping that leaves resonant vibrations build in amplitude rapidly. Another reason is that aluminum alloys have no fatigue limit. Therefore, even at very low stress level high frequency fatigue will make aluminum alloy blade fail. Gearbox housing are generally designed for stiffness and not for stress. Even in this case of relatively low stresses vibration may induce cracks on gearboxes. However, this type of failure is far less critical

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than the blade one. Usually, oil leakage reveals in advance the housing failure problem. Much more serious is the propeller problem.

Propeller manufacturers go through extensive analysis and testing to be sure that their propeller will survive the fatigue environment produced by a specific engine installation. In case of design error, pieces will be departing the aircraft in an extremely short time. This is typical of shortened blades. This is a faulty, shortcut technique to increase propeller disk loading in fast aircrafts.

In addition to being loaded by engine and PRSU vibrations, a propeller produces torsional excitation which varies with blade speed vector, aircraft attitude, engine mount characteristic, and finally by engine torsional excitation which are applied to the propeller.

If you record a counterclockwise rotating propeller, being driven by a piston engine, with a frontal very high speed camera, you will see the following slow motion video. As a propeller blade rises into the topmost position, the engine began its compression stroke. At this point the torque is at its minimum. Therefore, the engine decelerates. The blade, due to its high inertia tends to maintain its speed, but the propeller hub, connected through the PRSU to the crankshaft, is slowing down. The elastic blade, being a cantilever beam, deflects counterclockwise as the result of the blade momentum being opposed by the decelerating hub. Now, just as the blade reaches the maximum displacement, the cylinder began is active combustion phase and the crankshaft torque quickly reaches the maximum positive value. At this point the crankshaft accelerates the prop shaft, which in turn, through the hub, tries to accelerate the blade. Therefore, with very short delay, the blade begins to bend in the opposite direction (clockwise), elastically coming back from the previous counterclockwise position. The elastic energy adds up to the acceleration induced by the active combustion phase, increasing the blade deflection due to the acceleration. If the blade natural frequency is tuned to the active energy pulse, resonance takes place and the energy continuous to add up until the failure takes place. The failure can take place in the blade or in the hub in other parts of the engine and its mount. Luckily, the pilot feels the vibration and may act on the throttle to reduce vibration amplitude. Other modes of propeller blade vibration are also present during propeller-PSRU-engine operations.The nearly resonant situation was typical in Bf 109 G, where the harmonic drive that controlled the pitch tended to find resonant point during throttling operations. Therefore, the pilot was instructed to avoid these resonant conditions. In certain aircraft engines continuous operation is not allowed in well-defined bands, usually red on the analogic rev-counter. Metal-blade propellers are especially critical because they have relatively low natural frequencies, very low damping and closely resemble perfect springs. Wood and composite propellers have varying degrees of internal damping, so they are so tolerant to torsional excitation that they can act as a torsional damper.

In any case, power plant is different, and needs to be investigated prior to the tests. A certain propeller, which survives quite well on a Continental IO-520, may have unacceptable vibration problems on a “similar” Lycoming IO-540. For example, a recent Hartzell vibration bulletin warned that a certain propeller, which is certified on a Lycoming IO-360-A3B6D, could not be installed on a Lycoming HIO-360-D1A (LW-11487-S) with special piston to achieve an increased compression ratio 10:1. That engine, with its pendulous torsional absorber counterweights, should have been "torsionally tolerant". However, a relatively small change in engine configuration caused a critical change in torsional vibratory loads.

It is normal practice in the experimental community is that of shortening the blades of a given propeller to fit a new engine. Unfortunately, if the blades are shortened below a certain limit, the resonant frequency of the blades will be increased to the point that engine can excite vibratory stresses, which exceed the endurance limit of the blade aluminum alloy. In general, torsional vibration dampers and decouplers are introduced to reduce torsional vibration stresses. However, these devices may not influence the propeller and care should be taken to match the proper propeller to the PRSU.

Gear reduction system

Offset helical and straight gear reduction are typical of piston engine where transmission ratios are below 3.5. For example, this type of gear reduction is used on the Continental GTSIO-520, the Rolls-Royce Merlin, the Allison V-1710 and the DB 605 engines. In this case, the centerline of the propeller shaft is offset (upward for all except the DB605) from the centerline of the engine crankshaft. Historically, internally toothed driven gears were discarded for the design deficiency of having the most heavily loaded shaft (the propeller shaft) in an overhung configuration. In fact, Allison tried this configuration in their early V-12’s and abandoned it. The traditional (around 1930) PRSU configuration is depicted in Figure-1.

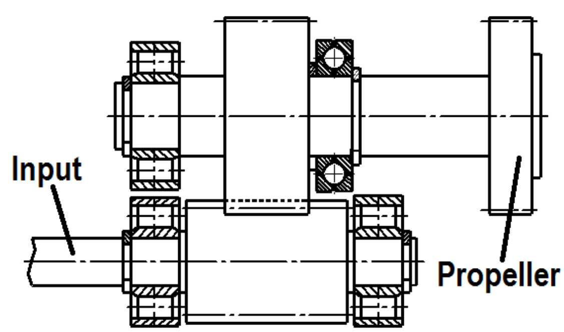

Figure-1. Traditional PRSU design (around 1930).

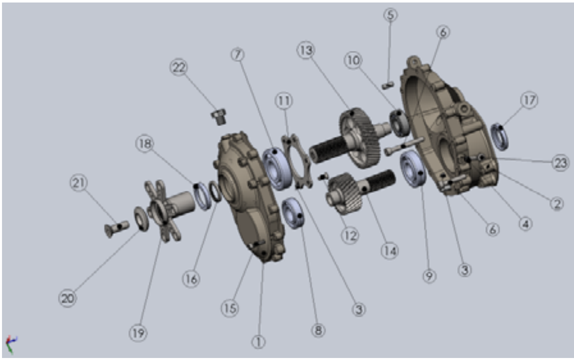

Figure-2. Improved gearbox design (around 1950).

In this configuration, the engine shaft can move horizontally to allow for thermal induced displacement. This is possible due to the cylindrical roller bearing axial DOF (Degree of Freedom) and for the adoption of spur gears. The propeller shaft, that is heavily loaded, has a four contacts ball roller bearing and a cylindrical roller one. The ball roller bearing absorbs axial loads and radial loads from the propeller, while the cylindrical roller bearings are the “masters” of the radial loads. The position of the pinion depends on crankshaft and connection device. Traditionally a flexible shaft from engine to PRSU decouples the torsional vibrations. This “traditional” solution is efficient but has several problems. The first is because cylindrical roller bearings do not tolerate misalignments due to loads and tolerances. This fact compels the design of over dimensioning the roller bearing, reducing in this way the advantage of compactness and lightness of the original design. Also housing is unduly stiff and heavy. Moreover, the traditional design obliges the designer to use spur gears. Theoretically, helical gears are lighter and quieter. In fact, helical gears have a significantly greater contact ratio than spur gears of similar diameter and tooth pitch. However, the decision whether to use helical or spur gears includes, asymmetric tooth loading (edge-loading) on helical tooth pairs which are in partial contact (contact across only a part of their face width), and the necessity for a helical design to include suitable bearings (not washers) to absorb the considerable thrust loads generated by helical gears. On the engine driven shaft (input), the issue of thrust absorption is non-trivial. The output shaft provides for propeller thrust absorption anyhow, but the helical gearing design must accommodate significant thrust loads on the input shaft. This situation is worsened if an intermediate (idler) shaft is added. An apparent good solution is solidly attaching the input shaft to the back of the crankshaft. This solution makes it possible to use the engine thrust bearings. However, it is not a good solution, for several reasons. First, the crankshaft with its journal bearings is never concentric to the bearing centers, so the connection must be designed so as not to constrain the radial movement of the crankshaft. The housing has to be stiffer and heavier, since misalignment control becomes essential. Helical gears cannot compensate for different temperatures on input and output shafts and gears. For this reason, a compromise is used with helical angles lower than 25 DEG. The original roller bearings on the input shaft are replaced by spherical roller bearing that can bear the axial load (Figure-2). The axial movement between the crankshaft and the PRSU is compensated through a spline, usually of the involute type. This device is usually integrated in a torsional vibration damper or decoupler. This solution is shown in Figure-2, where this more modern design is depicted.

PSRU load model

The worst-case environment in which the power plant is intended to operate defines the load model. For this purpose, a set of operating scenarios is defined in the requirements.These scenarios will be included in the flight manual that will accompany the aircraft throughout its life. Each scenario imposes the loads and number of cycles on the various parts. Then the component is designed to achieve the desired life under those loads and durations. The problem is the worst usage concept. It is important to understand that it is fundamental to keep the weight as low as possible.

Table-1 is an example of an aerobatic aircraft load model used for propulsion system design. In this case, the typical flight is very short, from 8 up to 30 minutes. The engine will face thermal cycling problems and the TBO will be reduced accordingly. There is no point to make a speed reducer that outlasts the engine. This reduced life approach is possible for the gears as it will be shown in the next paper (part 3), but unfortunately only partially for bearings and virtually impossible for housings. A method will be proposed in this paper. Unfortunately, housing should be able to perform at maximum load. This means that, even at maximum loads, displacements should be within the design tolerances.

Table-1. Aerobatic loads.

Operation	Power	RPM	Load	Time
Takeoff	100%	100%	100%	5 %
Climb	100%	100%	100%	20%
Fast Cruise	90%	86%	90%%	20%
Cruise	80%	82%	85%%	53%
Aerobatics	100%	100%	100%	2 %

For each scenario in the load model of Figure-1, the designer will calculate the gears, the bearings and shafts loads. Then he will calculate the cooling/lubrication requirements. The designer will verify that the housing will contain the displacements within the required limits. Finally, the hot stress point of the housing will be kept under the maximum allowed for fatigue life. A normal general aviation aircraft will face a very different load model (Table-2).

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Table-2. General aviation loads.

Operation	Power	Load	RPM	Time
Take Off	100%	100%	100%	0.1%
Climb	78%	100%	92%	1%
Cruise	51%	75%	80%	78%

In Table-2, it is possible to see that the total of the time is not 100%. In fact, for the remaining part of the flight the engine is throttled back. Just for an example, the automotive load model has a maximum rated load during only 5% to 10% of the design life, and 75% or more of the design life is at less than 25% of maximum output. Sports car are even less loaded with maximum power never reached in the whole life of a car. In fact, a car only takes between 30 and 60 HP to move 100km/h. Of course, more power is required for acceleration and hill-climbing, but most of the operational time in the vehicle is spent in some form of cruise.

General aviation PRSU normally has theoretically infinite life in the load model for critical components (shafts and housings) and a minimum of 2,000-hour life for replaceable components (bearings, gears and seals).

If a PSRU designed for the load model of Table-2 is used for aerobatics, the more-severe loads would reduce the TBO. The same happens also for the engine as it does with a certified aerobatics engine such as the Lycoming AEIO-540. However, the life should be adequate considering the maintenance which racing and aerobatic aircraft normally receive. Unfortunately, this assertion is not true for roller bearings, whose life can be reduced do nihil by higher loads as we will see in the following paragraphs.

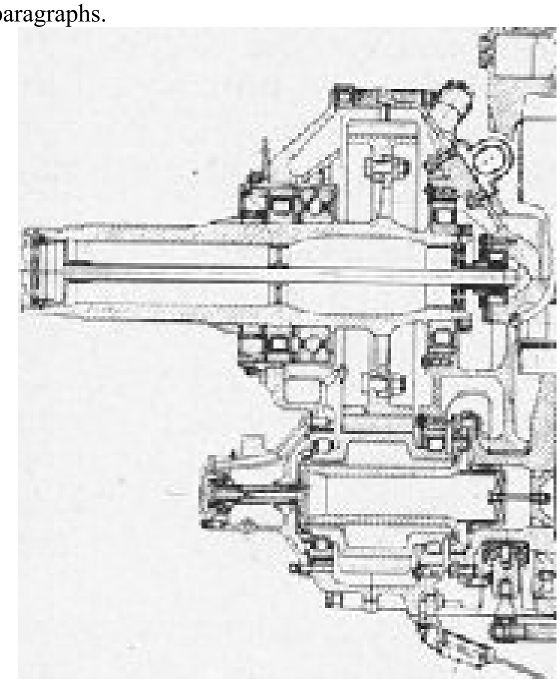

Figure-3. PRSU of WWII RR Merlin.

PSRU shafts, bearings and housing loads

The loadings imposed on the shafts in a PSRU come from cyclic bending loads imposed by propeller gyroscopic moments. This is the highest load on propeller shaft, bearings and housings. Cyclic bending loads imposed by the gear forces. Torsional loads are imposed by the engine torque[6]. Tensile and compressive loads are due to the propeller thrust. Cyclic bending loads are given by the overhung moment of propeller weight. In addition, the PSRU housing is attached to the engine (or is integral to the engine crankcase) and supports the PSRU and propeller weight (with additional G-loads) as well as (usually) a substantial portion of the engine weight (with additional G-loads).

The propeller imposes a cantilevered load on the nose of the propeller shaft. This load produces a bending moment with fully-reversing tensile and compressive stresses on the propeller shaft as the shaft rotates. The magnitude of those loads is a function of the distance from the propeller CG (Centre of Gravity) to the PSRU front bearing, and the mass of the propeller itself.

Gyroscopic moments impose extreme loads on the propeller shaft, bearings and PSRU housing. FAR Part 23 specifies design yaw and pitch rates to determine gyroscopic loads on engine mounts. Those loads can occur from gust loads and severe turbulence. Unfortunately, the gyroscopic loads generated by aerobatic maneuvers (snapping and tumbling maneuvers, the transition from level flight into a high G pull-up, etc.) can exceed the FAR spec loads by a factor more than 1.6. This is problematic especially for roller bearings. In any case, these maximum loads are instantaneous and occur for a very limited part of the life of the PRSU. Since these aerobatic loads are imposed by the propeller, “heavy” aluminum alloy, plywood and glass fiber reinforced propeller should be avoided in aerobatic aircrafts.

Although the thrust loads can be significant, the stresses are typically low on a propeller shaft, which is adequately designed to withstand the other propeller shaft loadings. FAR 23.371 requires that an engine mount structure carries, without any damage, the loads applied by the worst-possible combination of: a yaw velocity of 2.5 radians per second, a pitch velocity of 1.0 radian per second, a downward vertical load of 2.5 g, with maximum continuous thrust at 1.25 times the engine torque at maximum continuous power. The housing should also carry in addition the internal loads generated by the power transmission mechanism.

Bearings

Historically, many PSRUs use rolling element bearings (ball, roller) to support the shafts. During WWII, a few Allied aircrafts used a coupled ball and roller bearing instead of the 4 contact ball bearing of Figure-1 (Figure-3). As part of the design process, it is strictly necessary to calculate the expected life of each bearing in the context of the PSRU.

A good way to make this calculation is to verify existing designs. The Authors were lucky enough to examine a RR Merlin from a SAAF De Havilland DH.98

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Mosquito PR Mk XVI, which crashed into a hill in bad visibility (Coriano, San Marino, November 27th, 1944). Two Rolls-Royce Merlin 76/77 piston engines powered this aircraft. It was therefore possible to calculate approximately the life of the most loaded bearing, the one on the propeller side. It is a combined roller+ballbearing (Figure-3). For the calculations, the author assumed that is was an "off-the-shelf" top quality commercial unit of a well-known bearing manufacturer. The standard ArvidPalmgren method was used (1)

$$L_{10h} = \frac{10^6}{60n}\left(\frac{C}{P}\right)^p \quad (1)$$

In the RR Merlin, the propeller speed n is 1,260 rpm. In fact, the Merlin 76 had a gear ratio of 2.38 and the crankshaft runs at 3,000 rpm maximum. Due to stiffness considerations, the cylindrical roller bearing bears the entire radial load. This combined bearing lasted only $L_{10hMerlin}$=30h with FAR 23.371 loads. This life is at 10% failure probability. During service, Merlin propeller bearings usually outlasted the engine TBO. Civil variants of the RR Merlin used the same bearings and the TBO was about TBO_{Merlin}=600h. Therefore, it is possible to say that, assuming the correct dimensioning of the RR designers, for a general aircraft TBO_{GA}= 2,000h, you need a L_{10h}=100h (2).

$$L_{10h} = \frac{TBO_{GA}}{TBO_{Merlin}} L_{10hMerlin} = 100 \quad (2)$$

This very low endurance is because the worst combined load case is faced for a very limited part of the aircraft life. A completely different problem is to design a PRSU for an aerobatic aircraft. The prediction of the expected life of a rolling element bearing in a specific application involves more analysis than simply applying ArvidPalmgren's equation (1). The dynamic load rating C listed in bearing catalogs is defined as the load at which 90% of a large population of identical bearings will operate satisfactorily at full load and constant speed for one million cycles. Many rolling element bearing manufacturers publish detailed life-load analysis procedures. These procedures enable a designer to predict how many hours a desired percentage of apparently identical bearings will survive with a specified load at a specified RPM.

The bearing life calculations, which the manufacturers publish, take into account factors as lubrication, contamination and temperature data. The above-mentioned calculations of the life of rolling bearings are based on the presumption that the bearing operate under constant operational conditions. In aircraft applications where the modulus and direction of the load, the speed, the temperature, the conditions of lubrication and the level of contaminations varies with time, it is not possible to determine the bearing life directly. In such cases, it is necessary to define the "Load History". Therefore, the bearing working cycle is divided into several time-periods in which the operational conditions are approximately constant. To average parameters C_m and n_m are then calculated (3) and (4).

$$n_m = \frac{\sum_{i=1}^{n} t_i n_i}{T} \quad (3)$$

$$P_m = \sqrt[p]{\frac{\sum_{i=1}^{n} P_i^p t_i n_i}{n_m T}} \quad (4)$$

A more reliable, but less rapid methods, uses the Locati's approach. The bearing life is calculated with the residual life concept. For each load level Ci, that lasts t_i(hours) the total life available $L_{10h\text{-}i}$ is calculated. The bearing is verified if condition (5) is fulfilled.

$$\sum_{i=1}^{n} \frac{t_i}{L_{10h_i}} \le 1 \quad (5)$$

Statistical data of linear acceleration and angular velocity are available from measurement experienced by aerobatic pilots at head level for medical purposes. The accelerometers were fixed on the headrest with the x parallel to the propeller axis and positive toward the propeller (tractor propeller). The y axis is pointed upward (toward the sky when taxiing).

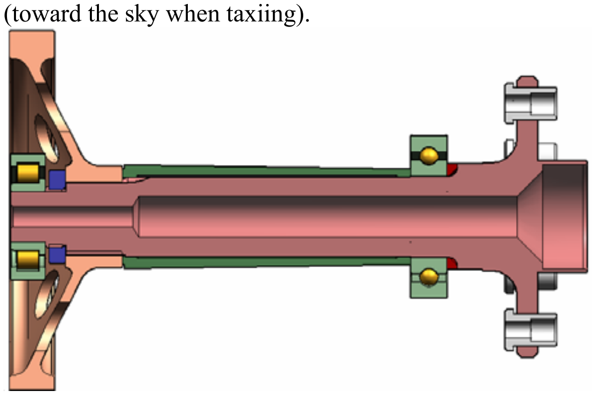

Figure-4. Propeller shaft example.

Table-3 summarizes the maximum measured accelerations and angular velocities.

Table-3. Experimental aerobatics data.

Axis	Acc.
+x (g)	8.24
-x (g)	-7.86
+y (g)	10.44
-y (g)	-9.82

+z (g)	13.96
-z (g)	-19.4
+θx (deg/s)	460.66
-θx (deg/s)	-425.64
+θy (deg/s)	190.46
-θy (deg/s	-185.68
+θz (deg/s	154.1
-θz (deg/s)	-137.

Typically, engine TBO is reduced to 1/3 when the aircraft is used for aerobatics only. So an aerobatic TBO of 2,000/3≈650h can be considered satisfactory also for the bearings. FAR 23.371 requires for mounts a yaw velocity of 2.5 radians per second, a pitch velocity of 1.0 radian per second, a downward vertical load of 2.5 g, with maximum continuous thrust at 1.25 times the engine torque at maximum continuous power. Therefore, the maximum rotation vector modulus is 2.69 rad/s (6).

$$\dot{\vartheta}_{GA} = \sqrt{\dot{\vartheta}_y^2 + \dot{\vartheta}_z^2} = \sqrt{2.5^2 + 1^2} = 2.69 \qquad (6)$$

From Table-3 the maximum yaw velocity is 154 deg/s (2.7 rad/s); the maximum pitch velocity is 190.5 deg/s (3.3 rad/s). Therefore, the rotation vector modulus of table 3 is 4.3 rad/s (7).

$$\dot{\vartheta}_{aerob} = \sqrt{\dot{\vartheta}_y^2 + \dot{\vartheta}_z^2} = \sqrt{2.7^2 + 3.3^2} = 4.3 \qquad (7)$$

The increase in angular velocity of the aerobatic aircraft is about 60%. The vertical g acceleration (z direction) is much higher -19g vs -2.5g of the FAR. However, as we will see in the following part of this paper; this condition is not so severe for the PRSU as the angular velocity gyroscopic loads. On this basis, the life of the ball bearing on propeller side will be reduced with be reduced from TBOg=2,000h to 500h (equation 8). This is also approximately the life of the original RR Merlin engine.

$$TBO_{aerob} = \left(\frac{\dot{\vartheta}_{GA}}{\dot{\vartheta}_{aerob}} \right)^p TBOg = 500h \qquad (8)$$

In addition, the bearings of the aerobatic aircraft should withstand the new peak load for a life of about 30h (as the Mosquito RR Merlin engine). In the aerobatic case, the loads are not from FAR but from Table-3. The hydrodynamic bearing technology is also used for input and propeller shafts. This is the same type of bearings that support most of the crankshafts assemblies. For example, this technology is used in the Continental GTSIO-520 gearbox. These pressure-lubricated hydrodynamic bearings provide significantly greater capacity than comparably sized rolling element bearings. Unfortunately, they are highly intolerant to misalignments. For this reason, they require extremely stiff shafts and housing. While, this result is possible in PRSUs integrated in the engine crankcase, the weight penalty for "added" PRSU, like the automotive conversion ones, may be prohibitive.

Propeller derived load on bearings

Figure-4 shows a propeller shaft of a PRSU for a diesel engine. On the left hand side, the spur gear wheel insists on a small cylindrical roller bearing. On the right the 4 contacts ball bearings supports the propeller flange. Table-4 summarizes the engine propeller and shaft data.

Table-4. Engine Propeller and shaft data.

Engine Max Power	210	HP	Pmax
Propeller max speed	2500	rpm	ω
max polar moment of inertia propeller	0.7	kgm^2	J
propeller mass	18	kg	M
Pitch rotation velocity	π/3	rad/s	B_y
Yaw rotation velocity	2.5	rad/s	B_z
Propeller cantilever arm	32.6	mm	a
Bearings center distance	163	mm	b

For normal general aviation use, a plywood propeller from a major manufacturer is considered. This propeller has blades made by high compressed thin layered laminated beech wood reinforced by layers of epoxy fiberglass/aramid/carbon. The propeller mass of 18 kg includes a hydraulic variable pitch hub.

The axial load is traditionally considered 20N for every HP. This is a maximum value for an aircraft. In our case the engine maximum power is 210HP. The maximum thrust is therefore 4200N. The FAR 23.371for engine mounts requires an increment of 25%. Therefore, the design load 4250N. An airframe yaw velocity or 2.5 rad/s outputs a torque on the x-y plane (of Table 3) calculated by equation (9).

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$$M_{xy} = J \cdot B_z \cdot \omega = 0.7 \cdot 2.5 \cdot \frac{2500\pi}{30} = 458 \qquad (9)$$

The vertical acceleration of a_y=-2.5g gives a vertical load F_y =-442N (10):

$$F_y = Ma_y = 18 \times -2.5g = -442 \qquad (10)$$

Therefore, the reaction (load) R_{by} on the propeller 4 contacts ball bearing is 3340 N (11).

$$R_{by} = \left|\frac{Ma_y}{b}\right| + \left|F_y \frac{a+b}{b}\right| = 2810 + 529 = 3340 \qquad (11)$$

The reaction (load) R_{bz} on the propeller 4 contacts ball bearing is 2810 N (12).

$$R_{bz} = \left|\frac{B_y J\omega}{b}\right| = 2810 \qquad (12)$$

The total load R_b on the 4 contact ball bearing of Figure-4 is 4,365 N. If the aerobatics loads are considered (Table-3), R_b becomes 7,013N with an increment of 60%. If a lighter CFRP-fixed pitch propeller is used for aerobatics with J=0.55 kgm^2 and M=7 kg, the Load on the four contacts ball bearing is only 4,790N (10% increment vs. general aviation loads).

CONCLUSIONS

Propeller induced, gyroscopic and inertia loads are extremely important for bearing selection and life evaluation. Engine power becomes easily a secondary factor for bearings and housing design. For this reason, it is important to select the best bearing assembly for the specific application with the required propeller. A very simplified method for bearing life calculation is introduced in this paper. It is based on similar proven and extremely successful design of existing PRSUs. This method compares the life of these design with the new design. Aerobatics and general aviation loads are also compared. It is demonstrated that the selection of a CFRP fixed pitch propeller for aerobatics use keeps the load approximately to the same level of a general aviation aircraft with a plywood-reinforced off-the-shelf propeller. A numerical example validates the design method.

SYMBOLS

Description	Value	Unit	Symbol
Bearing life	-	h	L_{10h}
Bearing life at load P_i	-	h	L_{10h-i}
Bearing rot. velocity	-	rpm	n
Average rot. velocity	-	rpm	n_m
n for a load step	-	rpm	n_i
Bearing ultimate load 1,000,000 cycles 10% failure probability	-	N	C
Equivalent dynamic load	-	N	P
Dynamic load of step	-	N	P_i
Average dynamic load	-	N	P_m
Duration of a load step	-	h	t_i
Total duration of the load cycle	-	h	T
Bearing life RR Merlin	30	n	$L_{10hMerlin}$
Exp. Palmgren eq.	-	3,4/3	p
Time Between Overhaul general aviation aircraft	-	h	TBO_{GA}
TBO RR Merlin	600	h	TBO_{Merlin}
Aircraft rotation vector General Aviation	-	rad/s	Θ'_{GA}
Θ' aerobatics	-	rad/s	Θ'_{aerob}
Yaw rot. velocity	2.5	rad/s	B_z
Propeller cantilever arm	32.6	mm	a
Bearings center distance	163	mm	b
propeller mass	18	kg	M
Propeller cantilever arm	32.6	mm	a
Bearings center distance	163	mm	b

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