THE PISTONS POUND, THE GEARBOX PERISHES

Caught between the hammer and the anvil: a small gearbox tooth.

How to look after your gearbox teeth: the influence of propeller inertia.

Jérémie BUIATTI

Designer of E-PROPS propellers

Tooth 1: "THAT'S IT, I'VE HAD ENOUGH! IT'S ALWAYS THE SAME ONES WHO TAKE THE HIT! WE NEED TO CHANGE THE RPM RANGE!"

— "OUCH!" — "WHACK!"

Tooth 2: "THAT ONE ALWAYS HAS TO COMPLAIN! SHE'S SUCH A DOWNER…"

(@Sébastien EXTIER)

THE PISTONS POUND, THE GEARBOX PERISHES.

Caught between the hammer and the anvil: a small gearbox tooth.

How to look after your gearbox teeth: the influence of propeller inertia.

1. Why use a reduction gearbox?

On a direct-drive engine (Figure 1), there is no reduction gearbox :-)

Because it's absent, the gearbox causes no problems, weighs nothing, and costs nothing…

But generally, on this type of engine, the propeller turns too fast and/or the engine turns too slowly.

- either the engine is slow (approx. 2600 rpm): large displacement, significant mass, noisy engine.
- or the engine is faster (3300, even 3600 rpm), but in that case the propeller diameter is limited[1], so its efficiency is poor, especially on takeoff; it is also noisy.

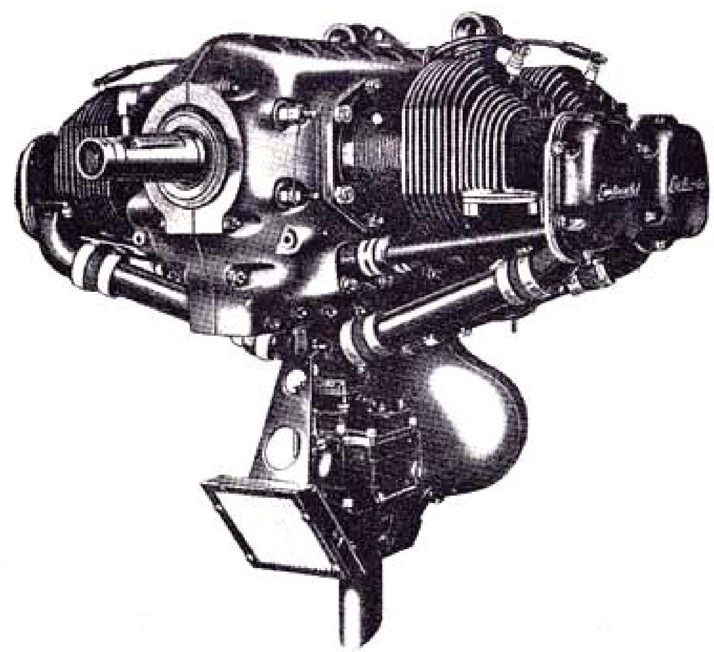


Figure 1: Continental A65 engine (@Continental)

On an engine fitted with a reduction gearbox, the engine speed and the propeller speed can be matched independently. A better engine and propeller efficiency can be achieved, mainly on takeoff, which greatly shortens the takeoff distance while limiting noise.

But developing a reduction gearbox is complex… mainly because of the ripple in engine torque (Figure 3), caused by the acceleration of the pistons and connecting rods, as well as by the pressure differences between the piston faces.

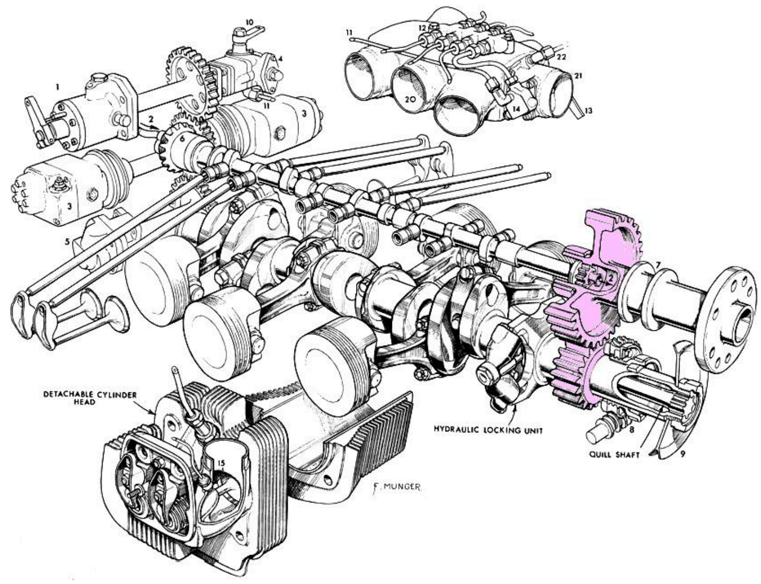


Figure 2: Gear-type reduction drive on a Continental Tiara engine
(@Flight)

---

[1] So as not to exceed the speed of sound at the blade tip. Reminder: $V = \omega \cdot R < 340$ m/s, with ω: rotational speed [rad/s] and R: blade radius [m].

2. The propeller/gearbox matching problem

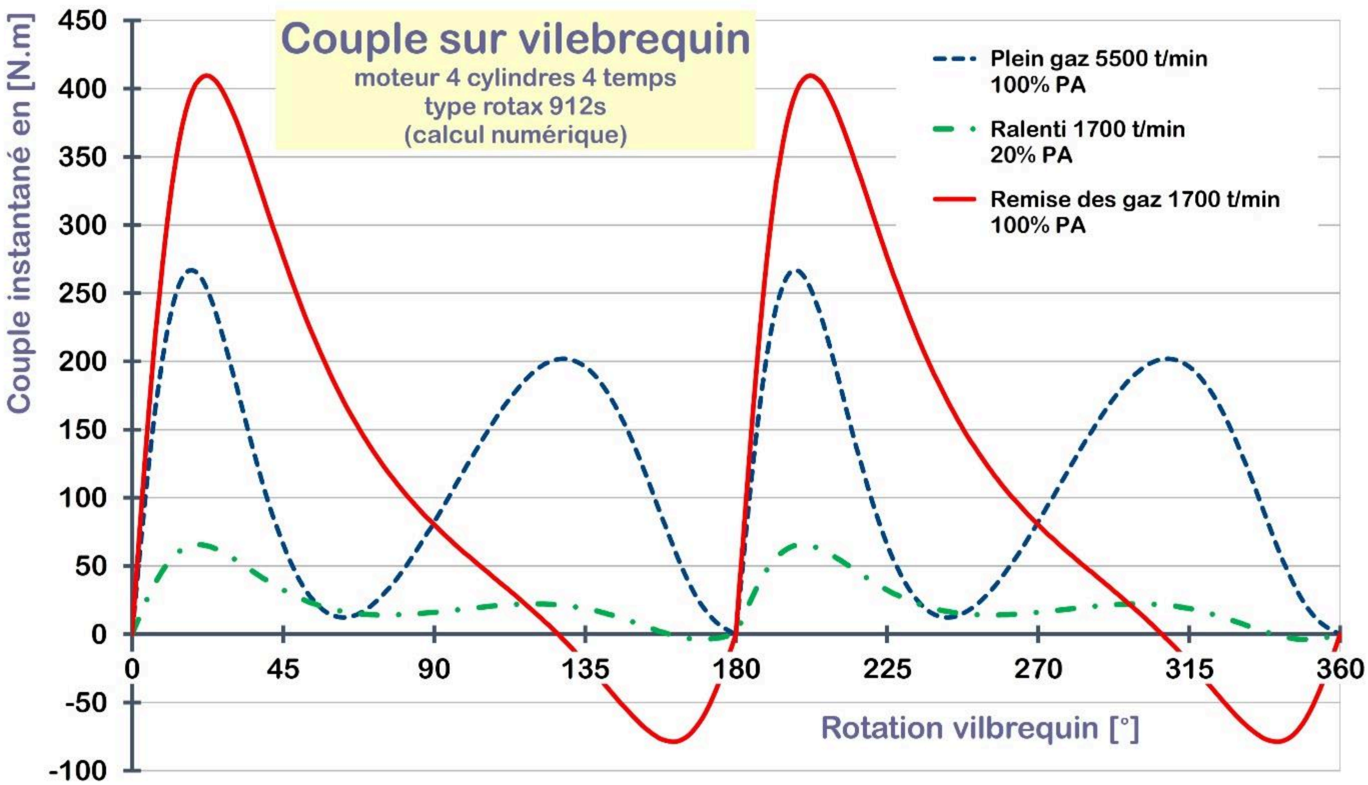


Figure 3: Torque ripple on the crankshaft of a 4-cylinder, 4-stroke engine (Rotax 912S, 2.43 reduction ratio). To reduce the risk of error, all rotational speeds and torques are expressed on the crankshaft side.

Graph legend — "Torque on crankshaft", 4-cylinder 4-stroke engine, Rotax 912S type (numerical calculation). Y-axis: Instantaneous torque [N·m]. X-axis: Crankshaft rotation [°]. Dashed blue: Full throttle, 5500 rpm, 100% MAP (manifold pressure). Dash-dot green: Idle, 1700 rpm, 20% MAP. Solid red: Throttle burst (go-around), 1700 rpm, 100% MAP.

Engine torque is far from constant (Figure 3). The propeller's aerodynamic torque, on the other hand, remains constant[2] for a given RPM (Figure 4).

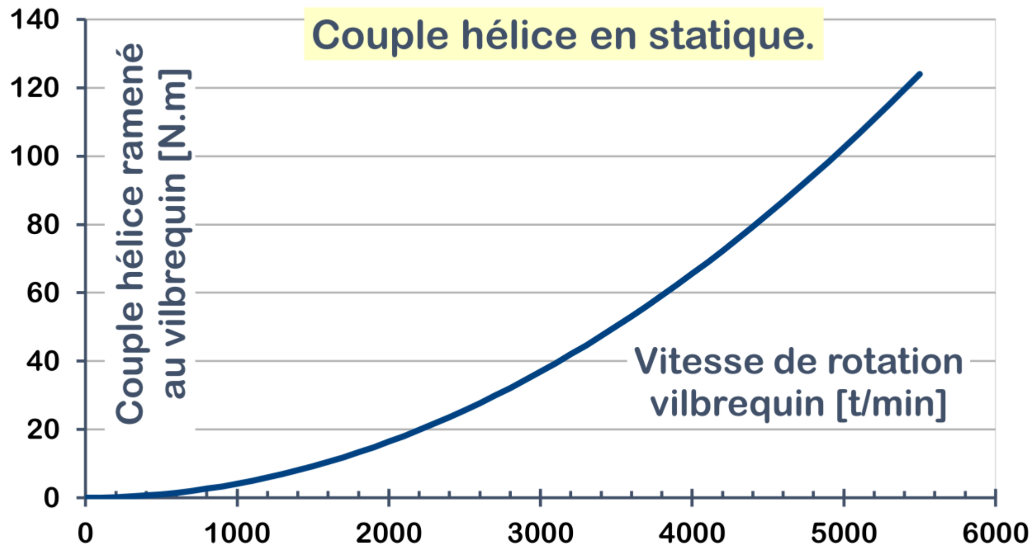


Figure 4: Propeller torque vs. RPM.

Graph — "Propeller torque, static condition." Y-axis: Propeller torque referred to the crankshaft [N·m]. X-axis: Crankshaft rotational speed [rpm].

---

[2] At least when the propeller-shaft angle of attack is zero.

It is therefore the inertia of the rotating parts (crankshaft, flywheel, gearbox, and propeller) that absorbs the engine torque ripple, and supplies torque during the non-driving phases (piston acceleration, gas compression).

A quick reminder: when a mass is subjected to a force, it undergoes a translational acceleration: A = F / m. When a shaft is subjected to a torque, it undergoes a rotational acceleration, given by:

Table 1 — Acceleration of a solid body of moment of inertia I_{gx} under a torque C.

$$\ddot{\theta} = C / I_{gx}$$

Quantity	Symbol	Unit
Rotational acceleration	$\ddot{\theta}$	[rad/s²]
Engine torque	C	[N·m]
Moment of inertia about the rotation axis x	I_{gx}	[kg·m²]

The moment of inertia is to rotation what mass is to translation. It represents the way mass is distributed around the rotation axis (gx), and reflects the shaft's "reluctance" to speed up or slow down in rotation. The moment of inertia (I_{gx}) has the dimensions of a mass times a distance-to-the-axis squared [kg·m²]. The appendix at the end of the article gives a method for experimentally determining this moment of inertia about an axis.

Torque variations translate into acceleration variations, and therefore into speed variations. During each engine cycle, the moving parts accelerate and decelerate.

2.1 The effect of speed variations

In reduction gearboxes that use a positive-engagement (obstacle-type) reduction — toothed belt, gear, or chain — the practical implementation of such gearboxes very often includes a certain amount of functional backlash[3].

If the torque stays positive (energy flowing from the engine to the propeller), the teeth stay "engaged" and the backlash has no effect on how the system behaves.

If the torque reverses (the propeller feeds energy back to the engine), torque is transmitted through the other flank of the teeth.

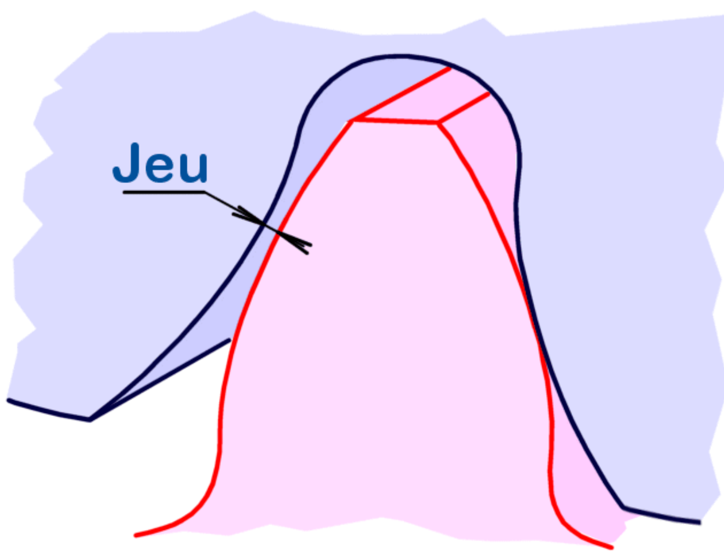


Figure 5: Operating backlash
(label in figure: "Jeu" = Backlash)

---

[3] The range of angle over which there is no contact, and therefore no torque transmission, between engine and propeller. It's also worth recalling that "Backlash is the soul of mechanics"!

But when the torque switches from positive to negative on every engine cycle, during the time it takes to cross the backlash, the two rotational speeds are no longer linked. A speed difference can therefore build up.

This difference in rotational speed between the propeller and the crankshaft has to be absorbed when the teeth make contact again (presumably through impact and elastic deformation of the components, particularly the teeth). We will call this mode of operation: *operation with backlash* (backlash mode).

Operating the system in this mode generates impacts — and therefore, probably, undesirable effects (ageing, breakage, etc.). And in the event of resonance (mass-spring effect), these effects will show up quickly and violently.

2.2 How to reduce the risk of backlash-mode operation

The condition is that the torque transmitted from the engine to the propeller must not change sign on every engine cycle. In power (driving) mode, this requires that **the gear wheel connected to the propeller must always be able to decelerate more strongly than the one connected to the crankshaft**.

In other words: for the gearbox tooth to stay engaged, the aerodynamic torque must be able to slow the propeller down more strongly than the compression torque slows down the crankshaft.

In "engine braking" mode (descent at reduced throttle), this requires that the gear wheel connected to the propeller must always be able to accelerate more strongly than the one connected to the crankshaft.

Power is presumably reduced in "engine braking" mode, so we'll set this operating mode aside. But the designer of a reduction gearbox should also give thought to the case that is "presumably not sizing," because, as we all know, the devil is in the details…

The aerodynamic torque is taken to be equal to the mean torque (constant RPM).

The propeller's maximum deceleration is given by:	$\ddot{\theta}_{propeller} = R^2 \cdot C_{propeller} / I_{gx,propeller}$
The crankshaft's deceleration is given by:	$\ddot{\theta}_{crank} = C_{neg} / I_{gx,engine}$
Reduction ratio $R = \omega_{engine} / \omega_{propeller}$	**R** [–]
Negative engine torque	$\mathbf{C_{neg}}$: [N·m]
Propeller torque referred to the crankshaft	$\mathbf{C_{propeller}}$: [N·m]
Condition for backlash-free operation:	$\ddot{\theta}_{propeller} \geq \ddot{\theta}_{crank}$

Speeds, accelerations, and torques are expressed on the crankshaft side.

After giving the equation a good shake, the condition becomes:

$$I_{propeller} \leq R^2 \cdot (C_{propeller} / C_{neg}) \cdot I_{gx,engine}$$

Numerical application for our Rotax 912S engine, reduction ratio 2.43:

Looking at the graph (Figure 3), the worst case of negative torque is a throttle burst (an almost instantaneous transition from full idle to full throttle).

In this case (1700 rpm, 100% intake), the torque reaches a negative value of 80 N·m.

At this speed, the propeller's aerodynamic torque $C_{propeller}$ is on the order of 12 N·m.

Engine/propeller reduction ratio	$R = \omega_{engine}/\omega_{propeller}$	2.43 [–]
Negative engine torque	C_{neg}	80 [N·m]
Propeller torque referred to the crankshaft	$C_{propeller}$	12 [N·m]
Condition for backlash-free operation	$I_{propeller} \leq R^2 \cdot (C_{propeller}/C_{neg}) \cdot I_{gx,engine}$	

Our equation becomes: $I_{propeller} < I_{engine} \times 2.43^2 \times (12/80) \Rightarrow$ **$I_{propeller} < I_{engine} \times 0.9$**

Rotax's specification is: $I_{propeller}$ (max) = **0.6 kg·m²**

$\Rightarrow I_{engine}$ should therefore be greater than 0.6 / 0.9 = **0.68 kg·m²**

$C_{propeller} = R \cdot C_{engine}$ and $\dot{\theta}_{propeller} = \dot{\theta}_{engine} / R$

Propeller side: $\ddot{\theta}_{propeller} = C_{propeller} / I_{gx,propeller}$

Referred to the engine side: $\ddot{\theta}_{propeller} = R^2 \cdot C_{propeller} / I_{gx,propeller}$

$\ddot{\theta}_{engine} = C_{neg} / I_{gx,engine}$

Condition: $\ddot{\theta}_{propeller} \geq \ddot{\theta}_{engine} \Rightarrow R^2 \cdot C_{propeller}/I_{gx,propeller} \geq C_{neg}/I_{gx,engine}$

$\Rightarrow I_{gx,propeller} \leq R^2 \cdot (C_{propeller}/C_{neg}) \cdot I_{gx,engine}$

That's the moment of inertia of a 136 kg disc, 20 cm in diameter. Since that's just about double the engine's total mass, under these conditions an instantaneous throttle burst *will* cause backlash-mode operation. Assuming the crankshaft's moment of inertia is on the order of 0.1 kg·m², the propeller's moment of inertia would need to stay below 0.09 kg·m² to avoid backlash operation. But the lightest propellers for this engine are on the order of 0.25 kg·m².

Fortunately, the Rotax 912's reduction gearbox is fitted with a dog-clutch system that can absorb the torque spikes within the gearbox.

Observation:

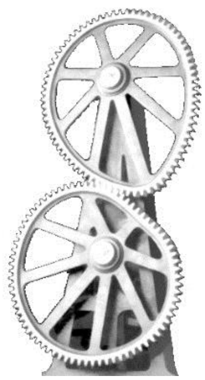
In the presence of negative torque, if the mean torque is very low or zero, the condition cannot be met. Given that, at constant RPM and with no airspeed, the propeller's mean torque is proportional to the square of the rotational speed and can be expressed as ($k \cdot \omega^2$):

There is therefore a minimum rotational speed ω below which it is impossible to satisfy the condition.

If this speed range is used — for example, at idle during "warm-up" — beware: DANGER.

How to favor this backlash-free operating condition to avoid problems — in other words, how to avoid sticking your finger in the ever-diverging spiral gear of knocks and costs?

- Keep the propeller's moment of inertia $I_{propeller}$ small.
- Keep the engine's moment of inertia I_{engine} large (an engine flywheel — but that's heavy).
- Use a fast-turning engine, so that the reduction ratio R is large.
- Avoid operating at low mean torque: avoid use at low RPM.
- Reduce negative torque peaks by increasing the number of cylinders: an engine with more cylinders (but that's more expensive).
- Use a clutch, so as to disconnect the propeller at low RPM (centrifugal clutch).



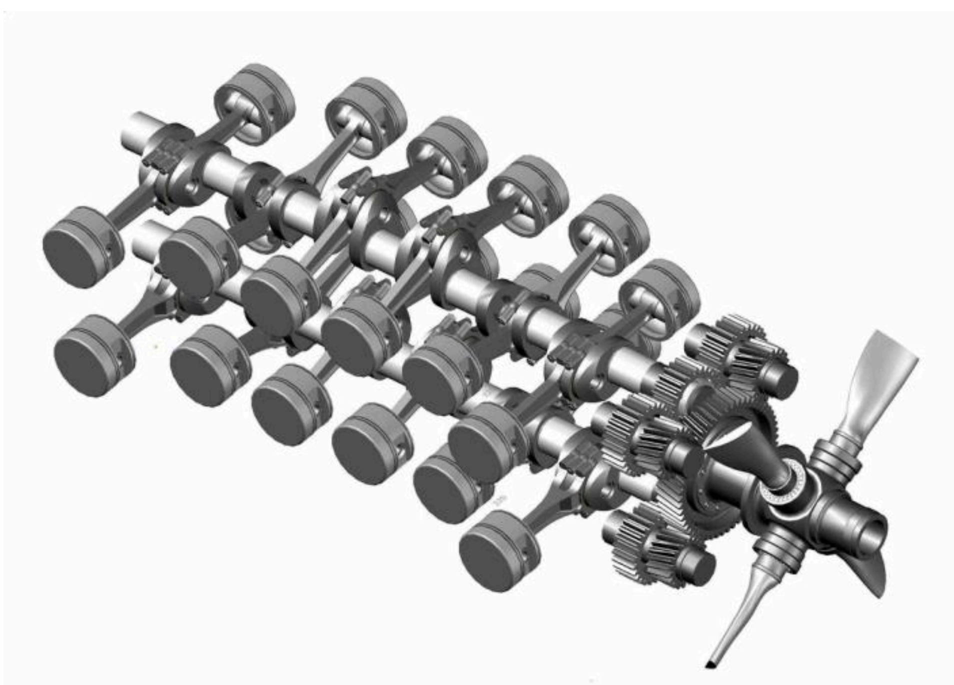


Figure 6: Increasing the number of cylinders to reduce torque ripple.

2.3 How to create problems for yourself (to entertain investors, or stave off boredom)

An optimist's reminder: a system works for as long as it has no reason to fail.

- Build a low-ratio gearbox, for example to gear down a slow engine (diesel, R < 1.8).
- Gear down a single- or twin-cylinder engine (several geared V-twins are currently under development — worth watching with interest…).
- Lighten the engine's rotating parts (thereby reducing engine inertia).
- Choose a heavy propeller with a large moment of inertia (and no, it will *not* "run smoother"!).
- Let the engine idle at very low RPM on the ground.
- Have large load imbalances between cylinders at idle (carburetor balancing, ignition problems…).

Figure 7: a big propeller!!
(@ Musée de l'Air)

It isn't always possible to avoid backlash-mode operation across the whole operating range. How can the consequences be reduced?

- Torque limiter (careful: friction = wear and heat).
- A flexible coupling between the crankshaft and the gearbox, flector-type (careful: ageing and heat).
- A large-diameter flywheel (no wear, no heat build-up, and perhaps no heavier than a complex system with a high probability of failure).

Exotic solution:

- Fit a variable-pitch propeller with a control system synchronized to the engine cycles, so as to generate a suitably variable propeller torque (an idea for wealthy investors only)!
- Use a propeller with blade lead-lag (drag) hinges, which amounts to using centrifugal force to store energy. In that case, expect a variety of resonance issues across the whole RPM range.

Note: with toothed belts, a small amount of torque can still be transmitted by friction while crossing the backlash, which reduces the risk by dissipating energy in the event of resonance.

2.4 What about friction drives (Poly-V belt, V-belt)?

The belt also acts as a torque limiter. The risk of resonance is very low. On the other hand, if the belt is undersized, slip can reach significant values (measured up to 8% on a single-cylinder paramotor), which shortens the belt's service life. And it's worth remembering that with 8% slip, the propeller will, at best, only see 92% of the power[4].

2.5 And without a reduction gearbox?

Without a reduction gearbox, the backlash between propeller and crankshaft is, in principle, zero (proper maintenance = a joint tightened to the correct torque). The rotational speeds are therefore equal. The inertia of the propeller and of the engine thus share the torque ripple in proportion to their respective values.

The instantaneous torque split between propeller and engine becomes:

$$C_{ripple,propeller} = C_{ripple,engine} \times I_{propeller} / (I_{propeller} + I_{engine})$$

A low propeller moment of inertia will reduce the torque peaks experienced by the propeller and its connection to the engine. This is why direct-drive engines specify a maximum propeller moment of inertia (0.3 kg·m² for the Jabiru 2200). On the other hand, since the total moment of inertia is lower, idle speed will tend to be less stable — but a slight increase in RPM is enough to restore smooth running.

 Graphic design and layout: Matthieu BARREAU

---

[4] The 8% that's lost represents about 1 kW of heating! Luckily, the small pulley — the one that heats up — is mounted on the crankshaft. On two-stroke engines, the crankshaft is cooled by the intake air. Heating of the intake air reduces power, which in turn reduces slip. Phew!

Appendix: Experimental determination of the moment of inertia

The moment of inertia of a solid body is easily measured using the pendulum method.

The principle is to measure the period of a vertical-axis pendulum whose restoring action is provided by the weight of the solid, by means of the chosen fixture.

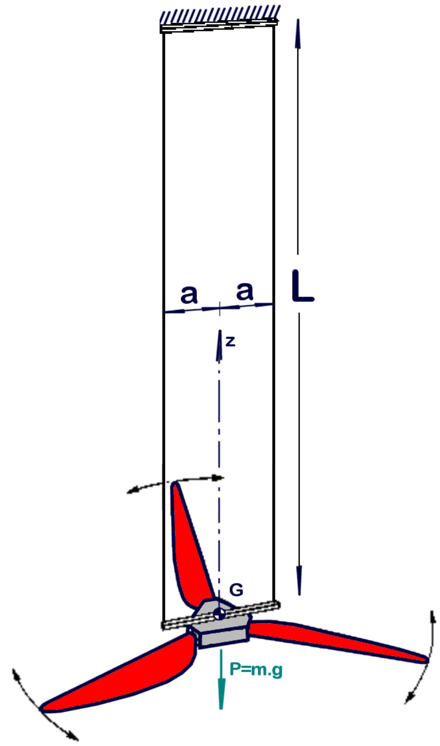
Equipment needed:

- Some cord.
- A stopwatch (Breguet, Dodane, Mathey-Tissot type 12, or similar ☺).
- A scale with a measuring range compatible with the mass of the solid.

Setup:

The solid is hung from a pendulum made of long lengths of cord (L). The spacing between the two attachment points (2a) must be small compared with the length (L) of the cords (L/(2a) > 6).

Axis Z must coincide with the axis about which you want to know the moment of inertia.



Pendulum test rig: attachment spacing a–a, cord length L, axis Z, center of gravity G, weight P = m·g.

Measurement:

- First determine the mass of the solid (m) by weighing it.
- Then hang it from your rig and let it settle. Rotate the solid about its own axis by at most a quarter turn, and… let go while starting your stopwatch.
- Count the time taken for the solid to complete 30 oscillations. One oscillation is counted from the position where you released the solid to its nearest return to that position.
- From this, work out the time taken for one oscillation (called the oscillation's period T). Don't hesitate to take several measurements of the period to make your data more reliable.

Calculation:

The value of the moment of inertia is obtained with the following formula, where:

$$I_{OZ} = (m \cdot g \cdot T^2 \cdot a^2) / (4 \cdot L \cdot \pi^2)$$

Symbol	Quantity	Unit
I_{OZ}	Moment of inertia about the z-axis	[kg·m²]
m	Mass of the solid	[kg]
g	Acceleration due to gravity, $g = 9.81\ m/s^2$	[m/s²]
T	Oscillation period	[s]
a	Distance from the axis to the attachment points	[m]
L	Length of the cords	[m]