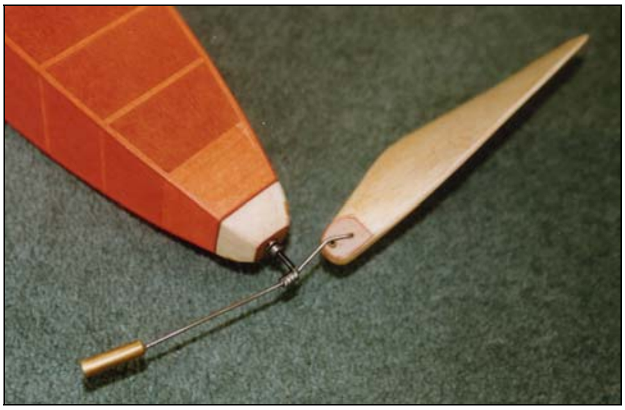
SINGLE BLADE PROPELLERS
THE BALANCING TRICK

By Martyn Pressnell



You may love or hate single blade propellers. To some they represent simplicity, easier to make and offering a smarter climb, to others they are less efficient or difficult to balance. The perception of their performance relates much to how well they are balanced, because lack of balance leads to inefficiency. A smart climb, although pleasurable to watch, is not necessarily the most efficient either. Simplicity of construction has an appeal if you want to save time, but perhaps you actually derive enjoyment from the construction process.

The modern F1B has the most efficient climb of all rubber model types, seen from the height gained on such little rubber. Apart from its aerodynamic shape, this efficiency has much to do with the relative freedom from vibration of the propeller. The motor is tight within the motor tube which itself prevents any undue whirling of the motor. However the single blade propeller need not vibrate unduly, and indeed the Wakefield Trophy itself has been won on three or more occasions by models with single bladed propellers. For the vintage modeller the challenge remains to master the single blade propeller, in order to successfully fly the splendid lightweights of yesteryear, or indeed Wakefields such as Korda’s or Earl Stahl’s Gypsy from the USA.

It is standard practice to statically balance all propellers. For twin blade propellers it is often only necessary to tweak the alignment of the blades, but for the single blade type one must carefully form and trim the counterbalance weight to achieve static balance. This balancing is intended to place the centre of gravity of the propeller assembly at the shaft axis, and to this end the propeller is required to achieve balance at any point without a tendency to rotate. This is much the same as when a car wheel is balanced. In addition however the counterweight arm is usually bent backwards by a centimetre or two, this feature being clearly shown on the plans of vintage lightweight rubber models. This is clear recognition that the propeller is more complicated than the wheel, and that it is not only the rotating masses which require balancing.

This raises questions, such as to what extent does static balancing meet the need for dynamic balancing, and what forces, other than inertia forces, have the potential to cause imbalance. Any unbalanced cyclic force or moment acting at the propeller shaft axis can cause imbalance. Of course we are acutely aware of unbalanced centrifugal force, but equally any rotating aerodynamic force will cause vibration unless steps are taken to balance it. Additionally, propellers produce a rotation of air in their wake, with tip vortices which can impinge on the wing and tail unit of the model. These later effects will be present with all propellers and can probably not be avoided.
My interest in this subject was aroused upon building a *RAFF V* recently, a 1942 lightweight rubber model designed by *Norman Marcus*. Taking my time in building it, I came to question why the single bladed

propeller was shown with counterbalance trail and to think about the particular aspects of balancing it. The arguments and calculations given here are all based upon this model. It proved to trim easily to a pleasing performance, but was lost in a very strong thermal unfortunately, on its first outing at Middle Wallop.

Static and Dynamic Balance

To make this as clear as I can it is necessary to adopt a technical explanation, but do bear with me as I will explain each point with a diagram, and a few example calculations as we proceed.

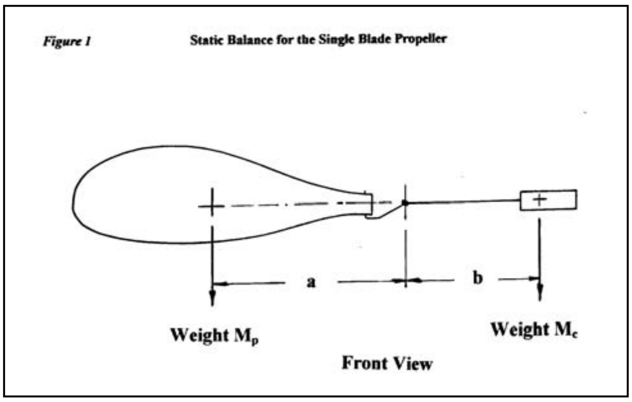
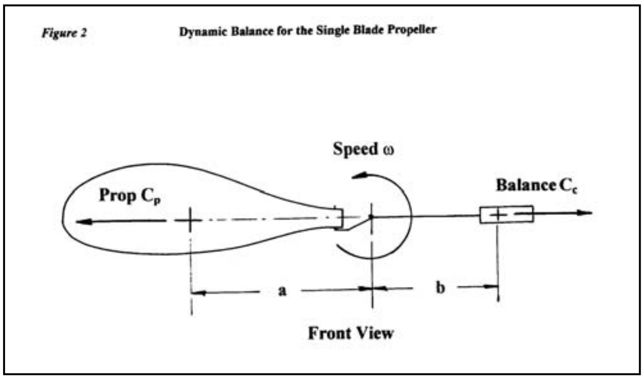


Figure 1 shows the front view of the single bladed propeller sitting horizontally. When this is statically balanced a condition of equilibrium is achieved in which the moment of the propeller blade weight **(M_p)** about the shaft axis is equal and opposite in direction to the moment of the counterbalance weight **(M_c)** about the shaft. That is to say the moments exactly cancel each other, leaving no residual out of balance moment.

Equilibrium is expressed by: $\mathbf{M_p\, a = M_c\, b}$ with **'a'** and **'b'** as the respective moment arms.

If a line drawn through the propeller blade and counterbalance centres of gravity intersects the propeller shaft exactly, the overall centre of gravity is at the shaft axis and static balance will be achieved in any position of the propeller.



If considering now the dynamic balance of the propeller, we look at the radial or centrifugal forces acting on the propeller blade **(C_p)** and counterbalance **(C_c)** masses, as shown in *Figure 2*. These are due to the rotation of the propeller, more particularly the radial acceleration of those masses. Thus taking the angular speed of rotation as **'ω'** (radians per second) the established principles of mechanics enables us to write:
$\mathbf{C_p = M_p\, (\omega^2 / g)\, a}$ and $\mathbf{C_c = M_c\, (\omega^2 / g)\, b}$

Then for equilibrium $\mathbf{C_p}$ and $\mathbf{C_c}$ are equated, and this results in the following:
$\mathbf{M_p\ (\omega^2 / g)\ a = M_c\ (\omega^2 / g)\ b}$ where $\mathbf{g = 9.81\ m / sec^2}$ due to gravity

The term $\mathbf{\omega^2 / g}$ occurring on both sides may be removed, and the expression remaining is found to be the same as the condition for static balance. Thus by satisfying static balance we are able to achieve this aspect of dynamic balance automatically, which is very convenient.

Centrifugal Force

For the *RAFF V*, some figures are available to calculate the centrifugal force on the propeller blade.

Propeller blade weight	$\mathbf{M_b = 6\ g}$	Counterbalance weight	$\mathbf{M_c = 6.4\ g}$
Blade c.g. position	**a = 80 mm**	Counterbalance c.g.	**b = 75 mm**

This satisfies the condition for static balance and taking an average propeller speed of **1300 rpm**:
Angular speed $\mathbf{\omega = 2\pi \times 1300 / 60 = 136.14\ rads / sec}$

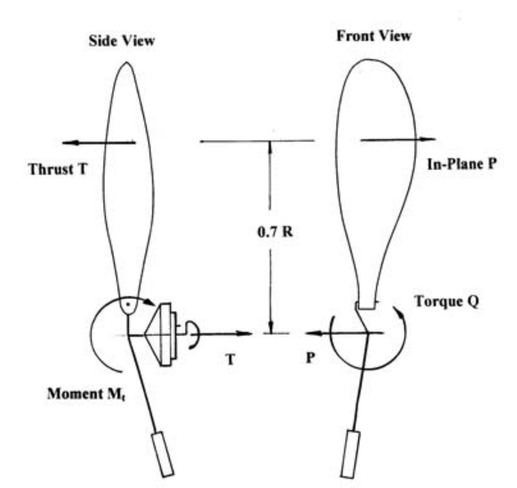
The average centrifugal force on the blade or counterbalance becomes:
$\mathbf{M_p\ (\omega^2 / g)\ a = 6 \times (136.14^2 / 9.81) \times (80 / 1000)}$
$\mathbf{C_p = 906.9\ g}$

So it is found that the average centrifugal force on the propeller blade is about 150 times the blade weight, no wonder it is important to balance it properly. The maximum value could be twice as much.

Cyclic Aerodynamic Forces and Moments

A single bladed propeller produces three forces at the shaft, thrust **(T)**, centrifugal **($\mathbf{C_p}$)** as above and a force **(P)** in the plane of rotation. The associated moments are **($\mathbf{M_t}$)** due to thrust and the torque **(Q)** about the shaft, due to the in-plane force. These are shown in *Figure 3*.

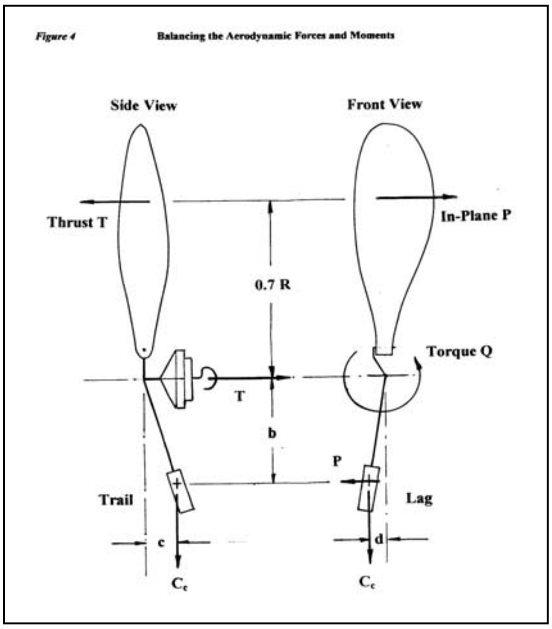
Figure 3 Cyclic Aerodynamic Forces and Moments



For a double blade propeller these three forces and moments are counter balancing because of symmetry, leaving simply the total thrust and torque at the shaft. Thrust and torque are not cyclic however, because they act along and about the shaft axis respectively, passing through the nose block to the rubber motor. The model itself receives the thrust and torque from the motor at the rear motor peg.

For the single blade propeller however, we have remaining the three cyclic forces and moments **(C_p)**, **(P)**, and **(M_t)**. The term 'cyclic' refers to those forces and moments that rotate with the propeller and therefore require balancing if vibration is to be avoided. We have discussed **(C_p)** and shown how it is balanced statically and dynamically above. Thus we have remaining the propeller aerodynamic in-plane force **(P)** and the thrust moment **(M_t)**.

Balancing the Aerodynamic Forces



Balancing the thrust moment is taken care of by moving the counterweight backwards, that is to say by bending the arm of the counterbalance aft. This is common practice, but so that it can be quantified let us define the position achieved as the **'trail'** dimension **(c)**. The balance can be achieved by shifting the centrifugal force of the counterbalance, which must be done maintaining the arm dimension 'b' so that dynamic balance is not disturbed, see *Figure 4*. The position of the thrust force **(T)** is taken here to act at 70% of the blade radius **(0.7R)**, which is reasonably close for practical purposes. Then to achieve equilibrium:

The trail dimension: $\mathbf{c = 0.7R\ T / C_p}$

However, we need to evaluate a propeller thrust figure in order to get at the trail dimension, and that will be done in a moment. But now let us turn to the in-plane force **(P)**. Again we will assume that the drag force acts at 70% of the blade radius, with the thrust force. This is directly related to the torque **(Q)** such that:

In-plane force: $\mathbf{P = Q / 0.7R}$

Now to balance this force it is again necessary to bend the counterbalance arm, this time backwards in the plane of rotation to create what is called here the **'lag'** dimension **(d)** see *Figure 4* again. This introduces a component of the counterbalance centrifugal force to equilibrate the in-plane propeller force. For balance:

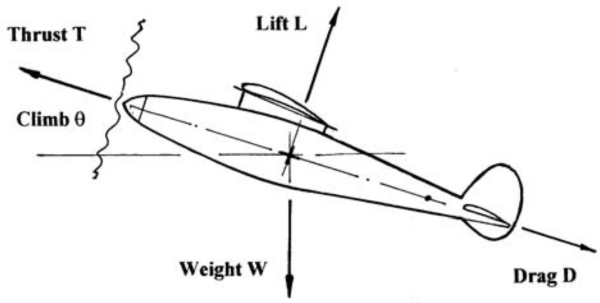
The lag dimension: $\mathbf{d = (P\ b) / C_c = Q\ b / 0.7R\ C_p}$

Thus to find the lag dimension it is necessary to evaluate the torque. The conclusion reached is that the balance of a single blade propeller depends on the thrust and torque, as well as the rotational speed, at any point in time. This is possibly the first occasion these relationships have been formerly expressed in the modelling literature.

Evaluating Thrust and Torque

Because thrust, torque and rpm are reducing throughout the motor run, it is convenient simply to work with average figures. For the *RAFF V* a steady angle of climb of about 30 degrees to the horizontal was observed during most of the climb.

Figure 5 Lift, Weight, Thrust and Drag Related



(T/W) = (D/L) cos θ + sin θ

Referring now to *Figure 5*, where the model is shown climbing at an angle **'θ'** to the horizontal, a relationship between lift **(L)**, weight **(W)**, thrust **(T)** and drag **(D)** can be established:

(T/W) = (D/L) cos θ + sin θ

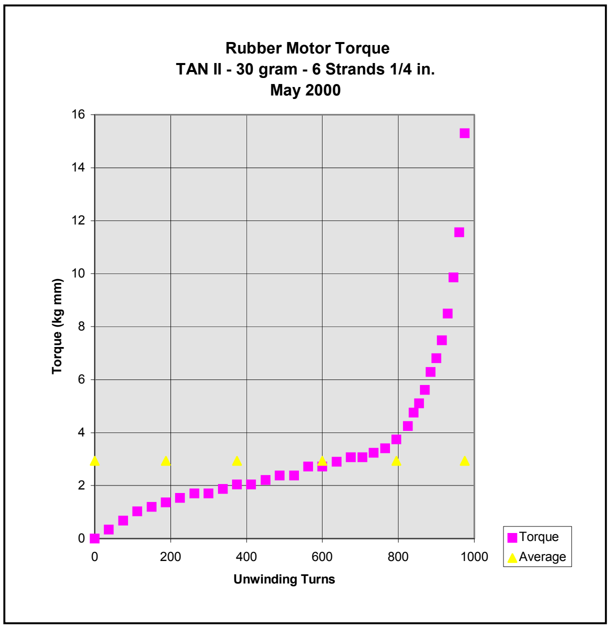
For the *RAFF V* we may reasonably assume a Lift to Drag ratio **(L/D) = 10:1** and taking the angle of climb to be **30 degrees**, we find that **T/W = 0.587**. With a model total weight of 100 grammes:

The average thrust is found to be **T = 58.7 g**

and then finding the required trail dimension:

c = (0.7 x 178 x 58.7) / 906.9 c = 8.06` mm

For the *RAFF V* the motor comprised of 30 g of Tan II rubber, in six strands taking 975 turns and unwinding in 45 seconds, giving therefore an average propeller speed of 1,300 rpm, as used to find the centrifugal force. The propeller of 14 in. diameter has a radius **(R**) of 178 mm.
The motor was tested to find its torque / turns characteristics whilst unwinding, enabling the average torque to be found, see below:



The average torque was found to be **Q = 2.93 kg mm**

So that the in-plane force is given by:
P = (2.93 x 1000) / (0.7 x 178) **P = 23.5 g**

and then the required lag dimension can be found
d = (2.93 x 1000 x 75) / (0.7 x 178 x 906.7) d = 1.95 mm

So it is found that the in-plane force is about **40 %** of the thrust, and the lag dimension is about **24 %** of the trail dimension, which in turn is about **11 %** of the counterbalance arm length. This could be regarded as a fairly general result for lightweight rubber models. The obvious difficulty of incorporating and maintaining the small lag dimension is a challenge to overcome, but there is a clear indication of the way in which the counterbalance arm should be tweaked.

Residual Out of Balance Forces

The example calculations given for the *RAFF V* are offered as an explanation of the general situation, and to illustrate that the question of balance is far from straightforward. It is not advocated that these calculations should be repeated for each and every model, rather that trail and lag should be incorporated for each propeller in the proportions suggested, as a starting point.

A further effect of incorporating counterbalance lag is that the centre of gravity of the whole propeller assembly is moved off the shaft axis by a very small amount. Although the centrifugal and aerodynamic forces remain in balance as explained, the effect is that the propeller mass is moved up and down by the propeller's rotation in the 1g field of Earth's gravity. The effect will probably not be noticed.

Remember that the calculations were made for average conditions alone, and imbalance could occur during other parts of the motor run, requiring further adjustment on a trial and error basis. Whilst centrifugal forces will remain in balance throughout the motor run, the effects of thrust and torque can be expected to vary. However there is a significant compensatory effect in that thrust, torque and (propeller speed)^2 remain approximately in the same proportion to each other, and hence the values of 'trail' and 'lag' found with average figures may well prove acceptable throughout the climb. No unacceptable vibrations were noticed during the *RAFF V's* short life span.

This article is dedicated to the happy memory of that little orange, yellow and blue *RAFF V*, I hope its purpose will be fulfilled in giving insight and satisfaction to all who read this.