You may have watched new tyres being fitted to your car and seen the wheels being balanced in the tyre bay on a machine that spins them at about 300rpm. The display panel shows the operator where to attach a lead weight to the rim of the wheel to dynamically balance the rotating mass as a whole. Sometimes a couple of weights are used. Most of us though, have never considered the possibility of dynamically balancing our propellers.

The ‘norm’ is an occasional static as opposed to dynamic balancing when we have made a few repairs or given the prop a repaint. All propellers gradually acquire that well-used look. There may be minor damage from rain or perhaps small stones... and rebalancing is required after any remedial work. A serviceable propeller, almost by definition, will have been statically balanced, hopefully in the not-too-distant past.

But static balance by no means guarantees flight with low levels of propeller-induced vibration. There can be many contributory causes. Apart from the propeller itself, the spinner may run slightly eccentrically, to say nothing of the occasional unmatched spinner-attachment screw, or maybe a riveted plate. Although identical propeller blade geometries are the ideal, there are bound to be differences due to manufacturing tolerances and material properties (especially for wooden and some composite blades). It is quite unlikely that the mass distribution along one blade from root to tip will be absolutely identical to another. Furthermore, there can be very small variations in propeller hub details, such as the locations of the torque dowels (if fitted) or in the alignment of drillings. As a result, even a new, well-made and statically-balanced propeller may exhibit less than perfect dynamic balance.

Excessive and avoidable in-flight vibration tends to crack exhaust systems and cooling baffles, and also the attach brackets for engine accessories such as pumps and alternators, and leads to excessive wear of engine components themselves. Cowl attachments may fret more and engine mountings deteriorate faster. Objectionable vibration can also spoil the pleasure of passengers and crew, increasing fatigue and discomfort especially when touring. Some owners seldom fly other types than their own. They may then drift into assuming that the vibration levels to which they have become accustomed in their own aircraft are ‘normal’ and may not notice any gradual deterioration. But even the simplest dynamic balancing system provides an objective measurement of propeller-induced vibration.

Establishing a baseline for a nearly new propeller would be helpful when monitoring developments in future years. Digital electronics has lowered the price of dynamic balancing systems to the point where they are cost-effective purchases for maintenance organisations or specialist propeller-balancing businesses – and a few owners take the long view and buy one for their own use. In fact, there is growing recognition that dynamic propeller balancing can be cost-effective.

**THE SYSTEMS**

A dynamic balancing system will include one or more small accelerometers mounted to a stiff bracket fastened to the engine, fairly close to the propeller. There will also be a small optical device; this senses the passage of a small strip of reflective tape, bonded to the rear face of one of the propeller blades near the root.

The software uses the data from these two sources to calculate the peak shaking velocity experienced by the accelerometer. Expect an American system to display the peak velocity as inches per second (IPS). The display will include the calculated position where weight should be added (or removed) from the propeller-spinner combination.

Some systems have an ‘averaging button’ that instructs the software to perform a repeated set of calculations over a period of a few seconds before an averaged value is displayed. This is quite helpful because it can remove small external influences, like a light breeze. Then again, wildly fluctuating results
suggest that there is something that needs attention before any attempt to dynamically balance the propeller.

The FAA has assessed the practical significance of peak shaking velocities as shown in Fig 1 (right).

The first measurements on my own aircraft showed maximum static rpm to be very close to the rpm for economic cruise on my engine, and I was none too pleased to record an average value of 0.42 IPS. Had I been unknowingly operating my engine in a way that could exacerbate long-term wear?

A quick search on the Internet soon reassured me that 0.42 IPS was more or less typical for propellers that had not been dynamically balanced. For example, a US mechanic summarised his experience as follows: “I counted up the initial balance readings on a sample of 650 aircraft of all makes and models... fixed-pitch, constant-speed. The breakdown is about 15% with 0.2 IPS or less, another 20% in the range 0.2 to 0.4 IPS, 25% in the range 0.4 to 0.6 IPS, 15% with 0.6-0.8 IPS and the rest above.” So at least 0.4 IPS was observed in two-thirds of his ‘before balance’ tests. So it seemed my own 0.42 IPS was unexceptional.

At this point I did the static balance, after some careful settling of the aluminum protective leading-edge and rescaling the end grain against moisture ingress. It was rebalanced with spray paint and remounted on the engine with the spinner bracket. But I decided not to replace the skull cap spinner as observers to the first test run had commented on an apparent small eccentricity. The tracking check was satisfactory.

The second test run produced an improved 0.31 IPS average peak velocity. The static rebalance, and leaving off the spinner, had moved the propeller from the ‘pretty rough running’ category into the ‘slightly rough’. This was objective evidence of improvement. However, I couldn’t swear to any real improvement in ‘ride quality’ on the basis of a flight test.

PRACTICAL BALANCING

Correcting dynamic imbalance requires some means of safely attaching balance weights. One can read accounts on the web of how individuals choose to do this. Furthermore, PDFs of the instruction manuals for the commonly available balancing systems are often to be found on the web, complete with illustrations or recommended approaches.

For example, the starter ring gear of some Lycoming engines has drillings every 30°. A single bolt with washers to make up the required balance weight may be fastened through a hole, or if necessary a second bolt may be added in an adjacent hole. Here ‘small’ balance weights are applied at some ‘large’ radius from the thrust line. In other cases, trial weights such as extra washers are attached under the spinner attach screws. After the required orientation of the balance weights has been established, they are removed. A hole is then drilled in the spinner back plate for a permanently installed balance weight at the same angular position. Since this will be at a smaller radius from the thrust line, the balance weight is increased pro-rata to the radius of installation.

The simpler dynamic balance systems do not tell the operator how much balance weight is required. If only it was that simple! Instead, the system will usually indicate the angular position for the unspecified balance weight in terms of the number of degrees – in the direction of propeller rotation – beyond the datum given by the reflective tape on the back face of the propeller. In essence, you will be searching for the size of the balance weight and its angular location that together exactly compensate for the original dynamic imbalance. But searching for two unknowns simultaneously can be a deeply frustrating experience!

Fortunately, there is a practical and systematic iterative approach. You first identify the optimum angular location for balance weights in Stage 1. Then you find the optimal weight per se, in Stage 2.

I shall use my own experience to illustrate the workings of the method. The initial data is summarised in the Fig 2 (above). Since my balancing system displays the angle where weight is to be removed, shown in the penultimate column, a final column shows the diametrically opposite orientation for adding balance weight.

Ideally, a large enough weight would be installed at an angular position 47° in the direction of propeller rotation from the datum through the reflective tape. Instead, the nearest propeller attach bolt to this

<table>
<thead>
<tr>
<th>FIG 1</th>
<th>Peak velocity IPS</th>
<th>Assessment</th>
<th>Action required &amp; summary description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25</td>
<td>Dangerous</td>
<td>Propeller should be removed and a static balance performed</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>Very rough</td>
<td>Operation at this vibration level could cause damage. Propeller can be dynamically balanced but a large amount of corrective weight will be required.</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>Rough</td>
<td>Long-term operation at this level could cause excessive wear. Propeller definitely requires dynamic balancing.</td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td>Slightly rough</td>
<td>Dynamic balance will improve passenger comfort.</td>
<td></td>
</tr>
<tr>
<td>0.15</td>
<td>Fair</td>
<td>This is the maximum acceptable level after dynamic balancing.</td>
<td></td>
</tr>
<tr>
<td>0.07</td>
<td>Good</td>
<td>Vibration levels less than this will not be detected by pilot or passengers.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FIG 2</th>
<th>Run</th>
<th>Balance weights</th>
<th>IPS</th>
<th>Remove at</th>
<th>Add at</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>After propeller static balance</td>
<td>0.31</td>
<td>227°</td>
<td>47°</td>
<td></td>
</tr>
</tbody>
</table>
location was identified and labelled ‘bolt 0’. A lead washer and penny washer weighing a fairly arbitrary 40g were installed under the head of this bolt. Then all the propeller bolts were retorqued, propeller tracking was rechecked and locking wire reinstalled. A second run gave the results in Fig 3 (right).

Some real progress had been made. The dynamic imbalance was now in the ‘fair’ category and actually less than the FAA threshold for dynamic balance. So matters could have been left there. But I wanted to know how to further reduce the imbalance. The final column of the table calls up a second balance weight 107° beyond the datum. This was, by a numerical coincidence, 60° further on in the direction of propeller rotation than previously. A fairly arbitrary 10g weight was installed on ‘bolt 1’, next to ‘bolt 0’ in the direction of rotation. The IPS in Run 3 (fig 4, right) took the state of balance into the FAA ‘good balance’ category.

One could just continue to ‘cut and try’ the balance weights on bolts ‘0’ and ‘1’ until the ‘angle to remove weight’ which is currently 301° became the 47° shown in Run 1 as the angle to add weight. Stage 1 would then be complete. But there is a better way.

Specifically, we want to know how much to move the centre of mass from its current position of 60° x 10/(40+10) = 12° beyond ‘bolt 0’ in the direction of ‘bolt 1’. The following polar diagram takes away most of the guessing. Run 1 is represented by the line at 47° to the datum and with scaled length for 0.31 IPS. Run 3 is represented by the line at 121° to the datum with scaled length 0.04 IPS. The red line is the ‘correction vector’ contributed by the existing balance weights. This is at 7° to the original imbalance vector. It was therefore decided to use 35g on ‘bolt 0’ and 15g on ‘bolt 1’ because the centre of mass is then 60° x 15/(35+15) = 18° beyond ‘bolt 0’. That is to say, that the centre of mass will have rotated by 18°-12° = 6° in the direction of propeller rotation, very close to the 7° predicted requirement from the polar diagram (right).

Run 4 (fig 5) was more or less spot on! The 53° angle to remove weight almost exactly matches the 47° angle to add weight to improve dynamic balance. In my own aircraft, we removed the upper engine cowl and mounted the accelerometer near the rear face of the propeller. Then the optical sender was installed and reflective tape attached to the rear face of the propeller. It wasn’t possible to replace the upper engine cowl because of the need to route the connecting wires from the sender units to the processing equipment in the cockpit. With chocks under the wheels, I carefully warmed up the engine and then carried out a full power check, noting that the displayed rpm cross-checked quite closely with the tachometer in the panel. After pressing the ‘averaging function’ on the control box it was necessary to extend the full-power run for a few more seconds. Then the engine rpm was reduced gradually and carefully to ground idle, so as not to cause undue thermal stress.
balance found in Run 1. This means that the two balance weights now combine to provide a ‘correction vector’ that to all practical purposes is oriented opposite the original ‘out-of-balance vector’ in Run 1. Bingo! Stage 1 was complete.

The IPS may have increased from Run 3 to Run 4 but that is of no consequence because reducing the IPS as much as possible is now the goal of Stage 2. This was done by factoring the weights by the magnitude of the two vectors. New balance weight on bolt 0 is $35g \times \frac{0.31}{0.31+0.07} = 35g \times 0.82 = 29g$. New balance weight on ‘bolt 1’ is $15g \times \frac{0.31}{0.31+0.07} = 15g \times 0.82 = 12g$.

Clearly the dynamic balance was now as good as it was going to get! A zero angle shown on the instrument suggests that no further discrimination was available from my equipment. The final run had given the results in Fig 6 (right).

The outcome was better than I had dared to hope and I don’t think it was just beginner’s luck. How long a wooden propeller will retain its state of balance over the coming months and years remains to be seen. And I would expect to have to check the dynamic balance if my propeller were removed and reinstalled for whatever reason. The time and effort is not that great. But I do worry in my blacker moments about whether ground-running the engine at full power without the upper engine cowl could itself be damaging. In the meantime, I have almost convinced myself that the performance and fuel economy have improved, if only slightly, during a recent ‘Round the coast of Britain’ trip. Certainly it gave a more relaxed ride and I felt no fatigue even after some long legs of around four hours. Friends are queuing up to borrow the equipment and that perhaps speaks for itself.

Dynamic Balancing equipment really is very useful. For example, if the results of testing are not consistent this will frustrate your balancing intentions but you have real evidence to suggest that there is a potentially major problem that requires your urgent attention. Is the engine mount cracked perhaps, or is some ancillary equipment improperly fastened to the engine? Worse yet, has some internal engine component suffered incipient failure?

Advanced dynamic balancing equipment in the hands of the experienced professional becomes a powerful diagnostic and non-invasive tool for assessing the state of the engine itself. Sophisticated analytical techniques are brought to bear on the data collected by several accelerometers and this may be done periodically as a means of monitoring the engine life and for triggering overhaul decisions.