The Importance of Balancing Tooling

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All too often, when faced with the challenge of balancing a new rotor, thoughts will go to the balancing machine, the operator, the correction method, and what tooling will be needed to mount the rotor in the machine, usually in that order. Properly addressing these variables will result in a good, repeatable balancing process. Unfortunately, the balancing machine is often given the highest priority, while tooling becomes little more than an afterthought. This paper will attempt to emphasize that, without proper tooling, the balancing process cannot work, regardless of how capable the balancing machine is. Underestimating the importance of balancing tooling is a common mistake that has led to countless problems and, in some cases, parts that are worse after balancing.

Let’s contextualize some facts about balancing so that we can truly appreciate the process's criticality and understand what’s required of both the machine and the tooling.

When thinking about balancing a new rotor, customers will almost always think about the balancing machine first. Many customers only think about the machine. If the machine can do the job, what more do I need? So, let’s start with that. I have a new part, a “rotor,” that I need to balance. What’s the big deal? I only need a machine with enough sensitivity to see the residual unbalance that represents my tolerance. I'm done if I balance the part to where the displayed residual unbalance is equal to, or less than, my tolerance. Correct? Well, not necessarily.

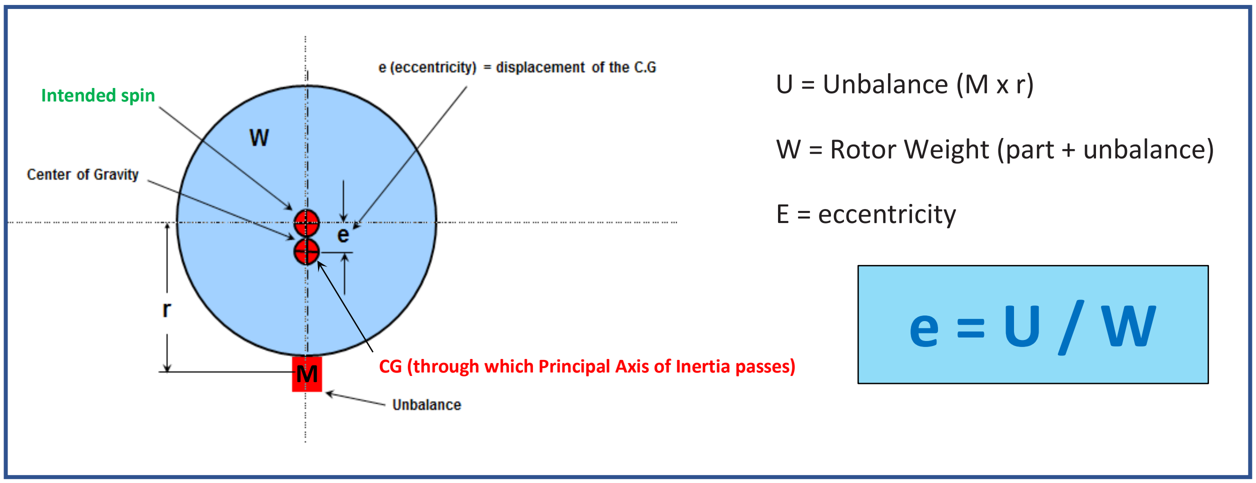
First, we’ll need to mount the rotor in the balancing machine. If the rotor has no journals, tooling will be required. Tooling is defined as the hardware necessary to mount a rotor in the appropriate balancing machine. On horizontal-type balancers, this might be an arbor, stub-shaft(s), or cradle—anything that allows the rotor to spin about its designed spin axis. On vertical-type balancers, tooling is defined as the interface between the machine's spindle and the rotor.

Assume the part we’re talking about is a disc-shaped impeller weighing 20 lbs. It’s a disk that will be mounted on a shaft through its bore. Based on the ISO21940-1 tolerance guideline, this part falls under a G-2.5 quality grade description. In service, this 20 lb. (9,080 gram) impeller will be driven by a 3,600-rpm motor. According to the ISO guideline, the recommended tolerance for such a rotor weighing 20 lbs., with a maximum service speed of 3,600 rpm, is 3.5 gram-inches (standard ISO tolerances are given in mixed units of grams and inches). This means that an acceptable amount of residual unbalance (post-balancing) is 3.5 grams at a radius of 1 inch. No problem, my machine has the sensitivity to see this residual unbalance.

Let's back up a bit to when the part was first designed. One of the first orders of business for the design engineer was the establishment of the part's spin axis. Once defined, the engineer designed the rotor around this axis.

On paper, the rotor can be considered perfect, with all its mass evenly distributed about the axis of rotation; therefore, the rotor is "perfectly" balanced. Designing a rotor and manufacturing one are two different things, though. It's easy to make a balanced rotor on paper. Building one is a different matter. Manufacturing errors such as run-outs, variations in material density, manufacturing tolerances, thermal changes, and, in the case of rotors comprised of multiple parts, fit errors. A rotor, or an assembly of multiple rotors, that looked perfect on paper can have significant unbalance after manufacturing.

A rotor will always attempt to rotate about its mass axis, commonly called its Principal Axis of Inertia (PAI). The PAI is the axis it "wants" to rotate about. Unrestrained by such things as bearings, say, rotating in outer space, a rotor will spin about its PAI. The balancing process involves aligning the PAI with the defined spin axis. Think of it like this: if the axis the rotor wants to spin about is the same as that which you intended it to spin about, then there is no unbalance, and hence, there are no forces to cause vibration. The closer the two are aligned, the better the balance of the rotor. Conversely, the greater the distance between the two, the larger the unbalance is and the greater the forces that act on the structure, resulting in stress and vibration. As we will see, a direct correlation exists between a rotor's unbalance and the distance, "eccentricity," between its PAI and the defined (intended) spin axis.



The above illustration shows a disk-shaped part, e.g., flywheel, gear, pump impeller, fan, etc. The mass **M**, at radius **r**, results in an unbalance **U**. Dividing the unbalance **U** by the weight **W** (rotor plus unbalance mass) gives us the eccentricity **e** (how far the rotor's mass center is displaced from the intended spin axis).

So, what effect does an unbalance of 3.5 grams at a one-inch radius have on the above-outlined 20 lb. impeller when running at 3,600 rpm? First, it should be clear that the unbalance represents an uneven mass distribution about the designed spin axis. The impeller wants to spin about its PAI, separated by some eccentricity (distance) from the intended spin axis. What is this eccentricity, though? The relationship e=U/M allows one to calculate this. An unbalance tolerance of 3.5 gram-inches for a rotor weighing 9,080 grams (20 lb.) is equivalent to an allowable eccentricity of 0.00039 inches. In other words, the unbalance tolerance allows for approximately 0.0004" between the PAI and the intended spin axis.

So, the tolerance is equivalent to an eccentricity of 0.0004". What does this mean to me? Most importantly, it means that I need a balancing process: machine, operator, tooling, and part, where 0.0004" can be reliably measured, and ***REPEATED***. In the world of balancing, *repeatability is everything*. Measuring unbalance is one thing, repeating the measurement is everything. If I can't repeat my unbalance measurement how will I know I've corrected it?

Many people overlook this repeatability portion of the process. The balancing machine's capability cannot be utilized unless the entire system can define the axis of rotation accurately enough. Since we're measuring the distance between the PAI and the spin axis, the spin axis must be well-defined. If not, the balancing process becomes one of trying to hit a moving target.

Just as important to the balancing process as the machine's ability to measure the unbalance is the tooling's ability to repeatedly define the axis of rotation.

In the machining world, tolerances on the order of 0.002" are not considered tight. For example, for one to pass a shaft through a bore by hand easily, it can be said that a clearance of roughly 0.002" is needed. When this clearance gets to, say, 0.001", passing the same shaft through the bore by hand requires a bit of concentration and care. As the clearance and runouts become measurable in the tenths of thousands, the process can become a bit trickier. Building tooling that will repeat an axis to within tenths of thousandths of inches requires attention to detail but, is not uncommon.

Now, let's look at another rotor. This time, we are considering a jet engine turbo-compressor rotor. Like the previous impeller, it weighs 20 lbs. and is also balanced to a G-2.5 tolerance. This rotor, however, has a maximum service speed of 20,000 rpm, unlike the last impeller disc. According to ISO1940, this rotor has a recommended tolerance of 0.35 g-in, ten times tighter than our first rotor's tolerance. Can the balancing machine read this amount? Yes, the machine can detect 0.35 g-in. But what does this mean in terms of eccentricity? Remembering that e=U/M, for a tolerance of 0.35 g-in and a rotor weight of 9,080 grams, the allowable eccentricity is now 0.000039 inches, roughly 0.00004" (40 millionths of an inch!). The question now is not so much can the machine detect this incredibly small eccentricity; it can, but rather, can the tooling and the process as a whole repeat it? Building tooling to repeat a spin axis within millionths of inches when machining to such tolerances is difficult, if not impossible, becomes a challenge, but one that must be overcome for the rotor's tolerance to be repeated.

It should also be mentioned that it is often not enough to design tooling that will repeat a rotor's tolerance. To allow for some error in the remaining balancing process, tooling will frequently be required to repeat to 20% of the actual rotor tolerance (see SAE ARP4163).

By now, it should be evident that measuring a tight tolerance is one thing; repeating it is another. **If your balancing process does not repeat, you haven't balanced anything.**

For any rotor requiring it, tooling is an integral and critical part of the balancing process.

EXAMPLE:

Rotor Weight, W = 20 lb. (9,072 g) disc.
Maximum Service Speed: 20,000 rpm.
Tolerance: G-2.5 quality grade (in accordance with ISO21940-1

Recommended Tolerance: 0.35 gram-inches (g-in).
Eccentricity, e = $U_{tolerance}$ / W: 0.35 g-in / 9,072 g. = 0.00004 in (40 micro-inches)

Conclusion: The balance tooling and the fit in the final installation must all repeat within 40 micro-inches for this balancing process to be valid.

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