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. Admittedly, all these variables share the responsibility of delivering a good, repeatable, balancing process. Unfortunately, the balancing machine is many times given the highest priority, while tooling becomes little more than an afterthought. This paper will attempt to emphasize the fact that, without proper tooling, the balancing process cannot work, regardless of how good a machine is being used. Underestimating the importance of balancing tooling is a common mistake, one that has led to countless problems and, is some cases parts that are worse after balancing than before.

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

When thinking about having to balance a new rotor, customers will almost always think about the balancing machine first. As a matter of fact, many customers never think about anything other than 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? All I need is a machine with enough sensitivity to see the residual unbalance that represents my tolerance. If I balance the part to where the displayed residual unbalance is equal to, or less than, my tolerance, all will be good with the world, and I'm done. Correct? Well, not necessarily.

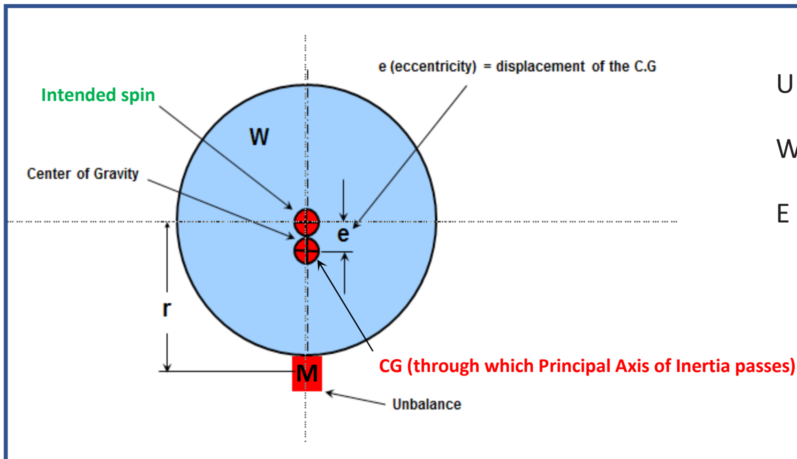
First, we'll need to mount the rotor in the balancing machine. If the rotor has no journals of its own, tooling will be needed. Tooling will be defined as the hardware necessary to mount a rotor in the appropriate balancing machine. On horizontal-type balancers, this might be an arbor, stub-shaft, cradle, 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 pump impeller that weighs 20 lbs. It's essentially a disk that will mount on a shaft through its bore. Based on the ISO1940-1 standard this part falls under a G-2.5 quality grade description (which includes small pump impellers and turbo-compressors). In service this 20 lb. (9,080 gram) impeller will be driven by a 3,600-rpm motor. According to the ISO standard 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 tolerance units are 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 designing 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 thought of as perfect; all its mass being evenly distributed about the axis of rotation and, therefore the rotor is "perfectly" balanced. Designing a rotor and making one are two different things though. It's easy to make a balanced rotor on paper. Building one is a different matter. Because of manufacturing errors such as run-outs, components, variation in material density, manufacturing tolerances, thermal changes and, in the case of rotors comprised of multiple parts, fit errors, a rotor that looked perfect on paper can have a significant amount of unbalance after its made.

A rotor will always attempt to rotate about its mass axis, what is commonly referred to as its Principal Axis of Inertia (PAI). This 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 is really nothing more than aligning this PAI with the defined spin axis. Think of it like this; if the axis the rotor wants to rotate about is the same as that which you intended it to rotate about, there is no unbalance, hence no forces to cause vibration. The closer the two are aligned the better balanced the rotor. Conversely, the greater the distance between the two, the greater the forces must be resulting from the unbalance. As we will see, there is a direct correlation between a rotor's unbalance and the distance, "eccentricity", between its PAI and the defined (intended) spin axis.



U = Unbalance (M x r)

W = Rotor Weight (part + unbalance)

E = eccentricity

e = U / W

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. pump impeller when running at 3,600 rpm? First off, it should be clear that the unbalance represents an uneven distribution of mass about the axis that the designing engineer intended, i.e., the bearing axis. The impeller wants to spin about its PAI that is separated by some eccentricity from the bearing 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, my tolerance is equivalent to an eccentricity of 0.0004". What does this mean to me? Most important it means that I need a balancing process; machine, operator, tooling, and part, where 0.0004" can be reliably measured. But, not only measured, ***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?

This repeatability portion of the process is what many people overlook. 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 to through a bore by hand easily, it can be said that one needs a clearance of roughly 0.002". 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 run-outs become measurable in the tenths of thousands, the process can become a bit trickier. The requirement to build 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're talking about a jet engine turbo-compressor rotor. Like the pump impeller, it weighs 20 lbs., shares much of its geometry with the pump impeller, and is also balanced to a G-2.5 tolerance. Unlike our pump impeller though, this rotor has a maximum service speed of 20,000 rpm. According to ISO1940, this rotor has a recommended tolerance of 0.35 g-in, ten times tighter than our pump impeller'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 an unbalance 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, a challenge that needs to be overcome if the rotor's tolerance requires it.

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 rest of the balancing process, tooling will often be required to repeat a residual unbalance equal 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 and, ***if your balancing process does not repeat, you haven't balanced a thing.***

For any rotor requiring it, tooling is an integral and critical part of the balancing process. No more important than the machine's ability to measure the required tolerance but, no less either.

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