The Science of Balancing

Balancing is a vital part of the manufacturing process for virtually all rotating machine components. Unfortunately, its importance is too often underestimated. Not having a thorough understanding of basic balancing principles, and an appreciation for the importance of the process can result in severe manufacturing difficulties.

This paper looks beyond what is often described as “smoke and mirrors” and focuses on the science. An understanding of basic balancing principles will ensure that more informed decisions are made, and potentially serious problems avoided.

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Balancing

Balancing is the process of evenly distributing a rotor's mass, or the mass of an assemblage of rotors, such that it is equally distributed about the intended spin axis. The term "unbalance" refers to the net amount of mass not uniformly distributed.

Unbalance is expressed in units of mass at some radius, i.e., ounce-inches (oz-in), gram-millimeters (g-mm), milligram-millimeters (mg-mm), and such. For reasons not essential to this paper, the International Standards Organization (ISO) has adopted the mixed metric and imperial units of gram-inches (g-in) as the default units for their recommended balancing tolerances, as outlined in the document ISO1940-1.

A rotor allowed to spin unrestrained will inherently spin about an axis that satisfies a balanced condition. In other words, a rotor will adopt a spin axis that ensures its mass is evenly distributed. This "natural" spin axis passes through the rotor's center-of-gravity (CG) and is referred to as the rotor's *Principal Axis of Inertia* (PAI). Vibration results when the forces generated by an unbalance attempt to make the rotor spin about its PAI but are restrained from doing so by whatever locates the rotor in the machine, e.g., bearings. It should be noted that, while unbalance, being a mass at some radius, itself does not change with speed. The force generated by an unbalance increases/decreases with the square of the speed.

Eccentricity

The effect an unbalance has on a given rotor depends on the mass of the rotor, its speed and, the amount of the unbalance. It should be evident that a given unbalance will have a much more significant effect on a small rotor, one you might hold in your hand, compared with say a steam turbine weighing several hundred thousand pounds. Therefore, to speak strictly in terms of a rotor's unbalance can be misleading. As we will see below, it is better to think of the effect an unbalance has on a given rotor.

Balancing can be thought of as the process of aligning a rotor's PAI with its intended spin axis. If the two were perfectly aligned, there would be no unbalance. Perfect alignment is, however, never possible, so parts are balanced to an acceptable CG displacement or, "eccentricity." An allowable eccentricity corresponds directly with the unbalance tolerance for the part. This relationship between CG displacement and unbalance is explained as follows:

The relationship between a rotor's unbalance, and the resulting eccentricity can be expressed as follows:

$$\mathbf{e = U/W} \quad \text{or,} \quad \mathbf{U = eW} \quad \text{or,} \quad \mathbf{W = U/e}$$

where;

e = eccentricity	(displacement of the PAI from the defined spin axis)
U = unbalance	(in units of mass at a radius)
W = weight	(of the rotor)

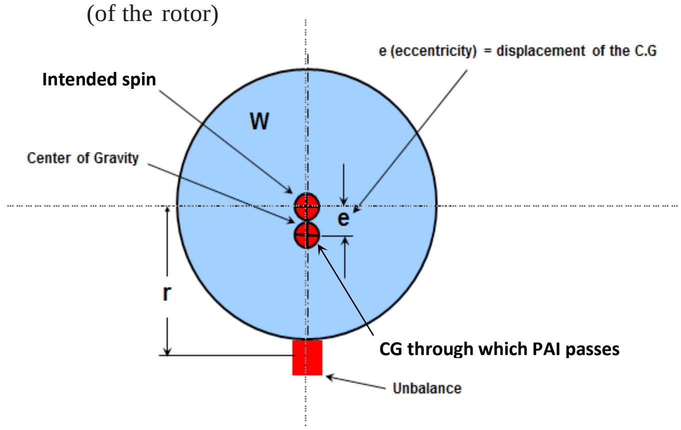

Fig.1 Effect of an unbalance on the CG of a disk-shaped rotor.

As illustrated in Fig.1 the eccentricity (CG displacement) is dependent on both the rotor's mass (weight), and unbalance.

Example: Assume the above rotor weighs 99 oz and its unbalance mass is 1 oz at a radius of 10 in. What is the associated CG displacement?

Total weight of the rotor = 99 oz + 1 oz = 100 oz

Unbalance = 1 oz at a radius of 10 inches or, 10 oz at a 1-inch radius = 10 oz-in

e = U/W or, 10 oz-in / 100 oz = **0.1 inches**

This means that this unbalance, on this weight rotor, represents an eccentricity of 0.1 inches.

Fig.2, below, again shows that eccentricity of the PAI is a function of both the unbalance and the rotor's mass. It should be evident that two rotors having identical unbalances but different weights will have different eccentricities. For a given unbalance the lighter rotor will have a greater eccentricity.

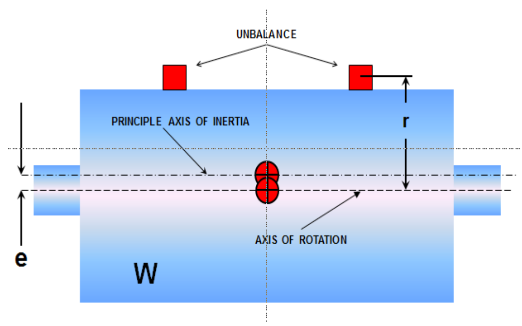

Fig.2 Effect of unbalance on the spin axis of a symmetrical rotor.

As mentioned balancing is the process of evenly distributing a rotor's mass, or the mass of an assemblage of rotors, such that the mass is uniformly distributed about the intended spin axis. The balancing process can be thought of as aligning the PAI with the rotor's designed spin axis. As the unbalance is reduced so is the associated eccentricity. The balancing tolerance defines the allowable eccentricity.

Having established the connection between a rotor's unbalance and the resulting eccentricity leads us to the discussion of balancing tolerances. A balancing tolerance defines more than just the allowable residual unbalance, it defines the maximum permissible eccentricity for a rotor.

Repeatability

It is essential to understand that, unless a balance tolerance can be repeated, there is no verification that it has been met. **Repeatability in balancing is everything**. To verify that a rotor has been balanced to its specified tolerance it must repeat this tolerance after having been removed from the machine, disassembled, reassembled and, placed back in the machine. As a matter of fact, to ensure a part's tolerance has been achieved the SAE's EG-1A Balance Committee's document ARP4163 (Tooling Design Criteria) recommends the entire balancing process repeat to 20% of the specified tolerance.

Many factors affect repeatability. As illustrated in Fig.3, these include such things as datum tolerances, runouts mechanical repeatability of the rotor assembly itself, error from mounting the rotor in its final installation, tooling unbalance (which, in most cases, can be compensated for), growth or shifting of the rotor's components, and so forth.

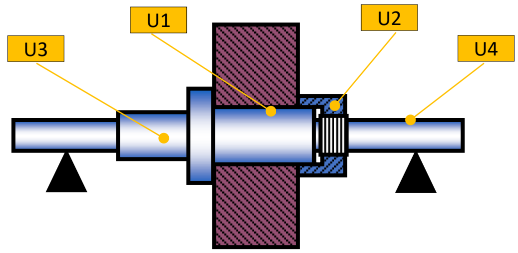

Fig.3 Effect of unbalance on the spin axis of a symmetrical rotor.

Unbalance:

U1: Due to arbor runout and rotor fit clearance.

U2: due nut's pilot and thread clearance.

U3: residual unbalance of the arbor.

U4: datum runout variations.

Tolerance

Unlike a machining tolerance, where an allowable range is specified, an unbalance tolerance defines a specific threshold. A balancing tolerance specifies a part's maximum allowable residual unbalance. A residual unbalance below this tolerance is fine but, may be overkill. A residual unbalance above this level is unacceptable.

When one thinks of everything in today's world that spins, most requiring balancing to some degree, the number is staggering. Although each type of rotor may require a different tolerance, the importance of that tolerance to each is equal. Be it a dental turbine, jet engine component, or child's toy, each has a tolerance appropriate for the rotor's intended use.

At one time, when balancing machines had comparatively little sensitivity, the widespread practice was to balance to the limit of what the machine could detect. As balancing technology improved, it became possible to balance well below what was necessary for the part. The practice of balancing to "zero" was then no longer cost-effective, and manufacturers began to set standards. There are any number of ways in which these tolerances can be determined. One method is to calculate the maximum worst-case repeatability based on the errors outlined in Fig.3 (a tolerance is only valid if the part itself can repeat this tolerance). A manufacturer can also set a part's tolerance empirically, i.e., based on what was found to be acceptable through experience. This, however, may not be possible with a new part. Different organizations, such as API or military, may also define tolerances in a variety of ways. Finally, and probably the most common method is to consult a recommended balancing tolerance chart such as ISO1940-1, published by the International Standards Organization. This document groups types of "like" rotors together into recommended quality grades. Once a quality grade is determined the user need only input the rotor's weight and maximum service speed into a chart to determine what balancing tolerance is recommended.

It is essential to understand balancing speeds. As said, a part's tolerance is based on its application, weight and, maximum service speed. Very often a customer will specify a tolerance, then ask to have the part balanced at its service speed. Some of these service speeds can be so high that running the part at this speed, in a balancing machine, would be extremely dangerous without a bunker. It is also not necessary. Remembering that a part's unbalance does not change with speed, and its tolerance is already based on its service conditions, it is not necessary to specify a balancing speed. Instead, since the force generated by the unbalance is a function of speed, it is only necessary for the operator to run the part at a speed where the machine has the sensitivity to identify the tolerance unbalance. Balancing can often be done at a fraction of the speed the part sees in service.

Balancing Machines

Balancing machines come in a variety of designs and sizes. Some identity unbalance based on a calibrated measure of displacement (soft-bearing machines) while others utilize a dynamometer system to measure force (hard-bearing machines). While not the only designs, soft- and hard-bearing machines are today by far the most common types. Each design has pros and cons but, both can accomplish the task if the underlying design principles are understood and the machine properly operated.

Amplitude measuring machines, referred to as “soft-bearing,” have been in use since the late 1800s while the newer force measuring, “hard-bearing,” machines first came into use in the 1950/60s. Both designs have proven themselves over many years. Interestingly, although there have been convenience and speed improvements over the years, the basic machines have changed little. The sensitivity of a 1960s vintage machine is essentially the same as a new one today. It can also be argued that yesteryears analog instrumentations had distinct advantages over new digital instrumentations for some applications requiring real-time data (flexible rotors). So why is it that balancing machine sensitivities have not improved over the last half-century? Thesimple fact is, they have not had to. Considering all the variables in a typical balancing process (tooling, operator, part, tolerance issues, etc.), the machine is least likely to be the problem. Take, for example, a 250-lb. capacity horizontal machine. Such a machine may be capable of measuring an eccentricity of 5 micro-inches (0.000005"). With a machine having a 5 micro-inch sensitivity, the problem becomes how to produce a part, and interface tool, that can repeat this eccentricity.

There are many variables in the balancing process which can influence the outcome. Aside from the machine, arguably the two most problematic are parts with unrealistic (non-repeatable) tolerances and, tooling.

All too often parts are specified with tolerances that cannot be repeated. This happens for several reasons; grand-fathering (using a tolerance that was ok for an older, similar yet still different part with a different service speed), choosing an ISO quality grade that is too tight or, picking a tolerance out of thin air. In each case, the person responsible did not understand that the tolerance represents an allowable eccentricity and that, unless the sum of all mechanical variables in the design of the part and tooling can repeat this, the tolerance is not valid.

Tooling

Tooling is another major issue, the importance of which is very often overlooked. Tooling is defined as the interface hardware between the rotor and machine's measuring system. Tooling can be as simple as the rollers upon which a part’s journals ride or, as elaborate as air bearing or interference fit tooling.

Because tooling is often deceptively simple in appearance, its importance to the balancing process is often underestimated. Tooling is as critical to the balancing process as the machine itself. Unless a tool can repeat a part's tolerance over many mounts and dismounts, it makes no difference how good a the machine being used is.

The issue of tooling is so critical, and so often overlooked, that a further comment is warranted. When purchasing a balancing machine, tooling is all too often not adequately considered. While the balancing machine may have the required sensitivity to achieve the tolerance, unless the tooling used can repeat this tolerance, the process will fail. It is therefore strongly advised that tooling be considered concurrent with the machine selection. Furthermore, while the balancing machine manufacturers know their machines, tooling may not be their forte. It is advisable to get several tooling source quotes. Regardless of the source, it is recommended that final acceptance of the tooling be subject to the supplier proving the tooling will repeat the rotor's tolerance. A useful source of tooling information is the SAE document ARP4163 (Balancing Machines: Tooling Design Criteria).

The best way to validate tooling for a specific process is, to begin with, a machine that has been certified in accordance with the SAE’s EG-1A Balancing Committee recommended practices (ISO has similar practices but, in the US the SAE’s guidelines are most commonly used). There are several recommended practices depending on whether you are using a soft- or hard-bearing machine and whether this machine is a horizontal or vertical type, single- or two-plane capable. These are as follows:

- Hard-bearing Horizontal:
  - Single Plane: N/A
  - Two-Plane: ARP4048
- Hard-bearing Vertical:
  - Single Plane: ARP 5323
  - Two Plane: ARP 4050
- Soft-bearing Horizontal: ARP 587
- Soft-bearing Vertical: ARP 588

<u>*Notes*</u>

1) *These tests require specialized proving rotors and weight sets in accordance with ARP4162A. These can be purchased but, unless they will be used regularly, renting is often a more cost-effective option.*
2) *While these are described as "Aerospace Recommended Practices (ARP), they can, and should, be applied to any balancing application considered as critical. These are also excellent acceptance criteria for new machines.*

Once the machine has proven it can achieve and repeat to a level at least equivalent to that required by the part's tolerance, the tooling can be tested. Different companies have difference tooling requirements, but they all boil down to the same idea; the tooling must repeat the part's tolerance (tested with an actual part) after repeated mounts and dismounts. To allow for other inevitable errors in the balancing process, the tooling should really repeat better than the part's tolerance (5X is recommended).

It is not uncommon for today's aerospace rotors to be specified with tolerance eccentricities on the order of millionths of inches. Rotors with an allowable mass eccentricity of 100 micro-inches (0.000100") barely raise an eyebrow. When a customer requires their tooling repeat to 1/5 of the rotor's tolerance (as recommended by SAE ARP4163), however, the tool needs to demonstrate a repeatability of 20 micro-inches. In many cases, especially with vertical machines, this is the machine's minimum achievable residual eccentricity (e_{mar}), i.e., the limit of what the machine can read.

We have now outlined what unbalance is the importance of proper tooling, repeatability and, some of the overall challenges involved with building a successful balancing process. This is a good beginning. We now need to get into the specifics of the distinct types of unbalance, their effects on a rotor and how to deal with them. This is addressed in the paper, *Unbalance Types and Their Effects.*

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