Balancing: Smoke and Mirrors No Longer

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By virtue of collected anecdotal accounts, equations and problem solving, balancing is discussed as more math and common sense, and less smoke and mirrors.

Introduction

In the late 1970s a balancing machine salesman visited a customer who had just purchased a new balancer from the salesman's competitor. The plant manager said they were very happy with their automatic balancing machine and offered to show it to the salesman. The manager walked the salesman out on the floor and the two of them watched the operator and balancer in action.

The operator placed a part on the balancer and closed the door. The balancer spun the part; stopped; welded on a weight; spun up again; stopped; and displayed "good part." The operator removed the balanced part, put in a new part, and closed the door. The balancer spun up the part; stopped; welded on a weight; spun up again; stopped; and displayed "good part." This scenario was repeated several more times as the salesman and the manager watched.

The manager commented, "We just love our new machine. All day long it balances parts by welding on weights and puts out good parts." The salesman suggested having the operator place a "bal-anced part" back in the balancer again—just to see what would happen. So the operator placed the previously balanced part back in the balancer again and closed the door. The balancer spun up the part; stopped; welded on a second weight; spun up again; stopped; and displayed "good part." The manager had the operator take another previously "balanced part" and put it into the balancer again. Again, the balancer spun up the part; welded on another weight; spun up again; and displayed "good part." Suddenly the manager was not so happy with his balancing machine. It had become clear: this machine was not balancing the parts at all. What they in fact actually had was an expensive welding machine to weld weights on their parts.

Balancing: Shedding Some Light

Production managers who have just added a new balancer to their shop or production line often ask, "How do I know if my part is balanced?" This question is usually asked after the person has had some basic training in balancing and has started balancing some parts. They quickly realize that, visually, there is no measurable difference between a "balanced" part and an "imbalanced" part. They can see that the "balanced" part has some holes (or other correction) and the "imbalanced" part has no holes (or other correction.) The balancing machine says, "good part," but they still feel a need to ask, "How do I know if the part is *really* balanced; and, "What if the balancer is wrong?" I will attempt to answer these questions in the pages that follow, such that "If you can fog a mirror, you can probably understand balancing."

Basic Balancing Principals

The simplest form of imbalance is called "force imbalance," "static imbalance" or "single-plane imbalance." These are all words for the same thing. If you take an imbalanced gear, mount it on a shaft and set it between two knife edges, the heavy spot will roll to the bottom. When this part is spun up and the heavy spot is spinning around, the forces generated by that heavy spot pull the gear in the same direction, similar to spinning a stone on a string. The forces caused by the imbalance increase or decrease as the square of the change in the rotational speed. Imbalance is usually measured and specified in units of ounce–inches, gram–centimeters or gram–millimeters. Roughly, $1\,oz–in = 72$ g–cm, or $720\,g–mm$ (Figs. 1 and 2).

Single-plane imbalance. The equation for calculating the amount of single plane imbalance is:

$$imbalance = mass\ (or\ weight) \times radius$$

This is the mass of the heavy spot multiplied by the gear radius to the center of the heavy spot.
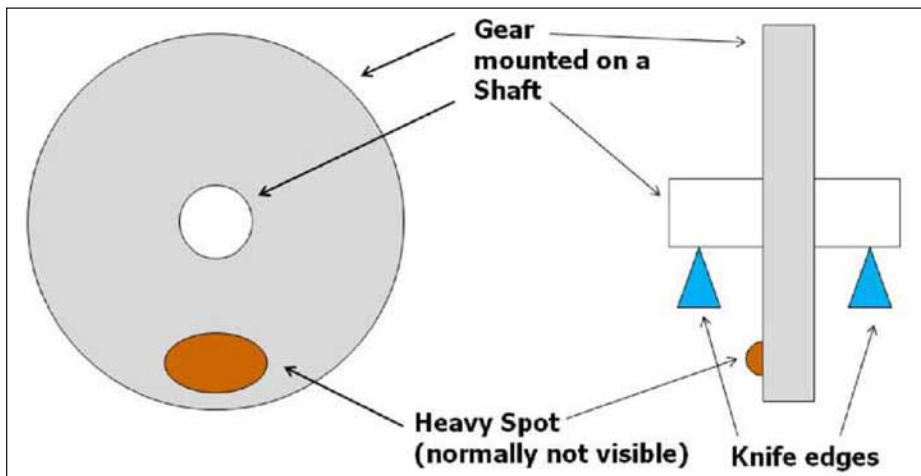

Figure 1   Part with imbalance.

Using oil-based modeling clay, shape and weigh a one-gram piece. Add the one-gram mass of clay to a balanced gear so the clay is located at a radius of 200 mm. The gear now has an imbalance of:

$$\text{imbalance} = 1\,g \times 200\,mm = 200\,g\text{–}mm;$$
$$(0.035\,oz \times 8\,in = 0.28\,oz\text{–}in)$$

Reflecting on Balancing Machines

The following is a very brief synopsis of balancing machines, past and present:

Balancing ways. A gear assembly (or a gear mounted on a shaft) is placed on two knife edges. The heavy side rolls to the bottom to show the imbalance.

Bubble balancers. The axis of the part is held vertically and loosely. The part does not rotate and a bubble is used to show the location of the imbalance or heavy spot.

Soft-suspension balancing machines. Hold the part suspended on a fine wire. The part is spun at high speeds (above the resonant frequency of the suspension) and the machine measures the displacement.

Parts of different weights require a different calibration; parts with large initial imbalance must be balanced in steps at gradually increasing speeds.

Hard-suspension balancing machines. Hold the part on a stiff suspension; the part is spun at relatively low speeds (below the resonant frequency) and the machine measures the force caused by the imbalance. Calibration is the same for the full range of part weights. This suspension readily allows for on-machine correction; even parts with large amounts of imbalance can be balanced on the first spin. Non-rotating balancing machines with a hard suspension use what is called a stiff pivot.

Forces generated by the imbalance — smokescreen. To calculate the amount of force caused by imbalance in a rotating object, use the following equation:

$$F_{unb} = 1.77 \text{ (rpm/1,000) 2 (oz–in)}$$
or,
$$F_{unb} = 127.41(\text{rpm/1,000}) \, 2 \times (g\text{–}cm)$$

where:

F_{unb} is the centrifugal force generated by imbalance in a rotating object—in pounds

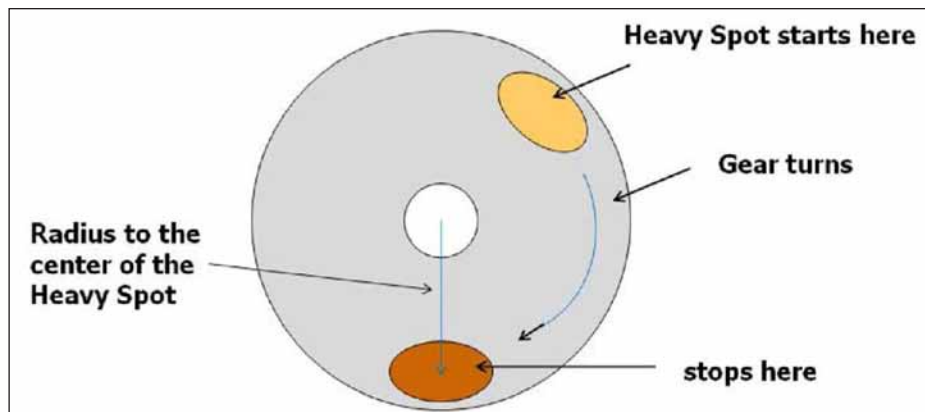oz–in is the amount of imbalance in the residual heavy spot—in ounce–inches
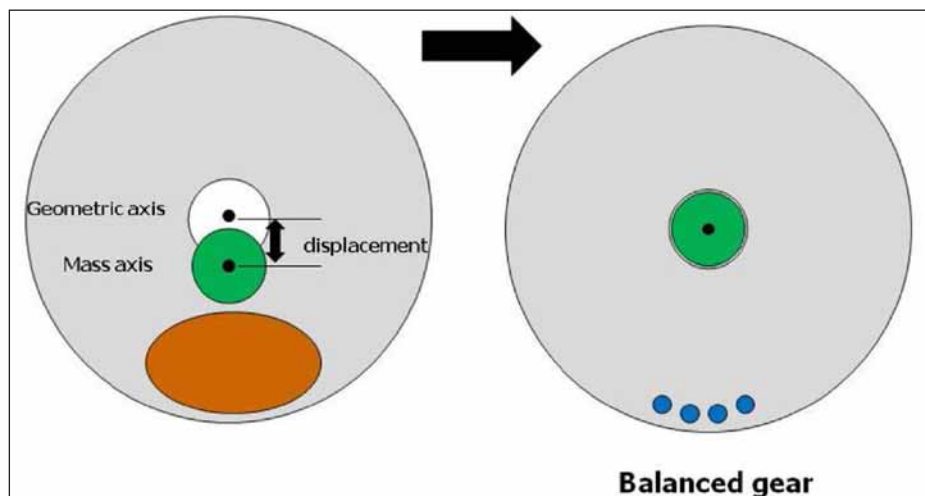

Figure 2   Part with imbalance.

Figure 3   Balancing is alignment: mass axis to geometric axis.

In a gear assembly operating at 1,500 rpm with 1 oz–in of imbalance:

$$F_{unb} = 1.77 \text{ (rpm/1,000) 2 (oz–in)} = 1.77 \times (1,500/1,000) \, 2 \times 1\,oz\text{–}in = 4 \text{ lb force}$$

In a gear assembly with 4× the amount of imbalance, the force is 4× larger:

$$F_{unb} = 1.77 \text{ (rpm/1,000) 2 (oz–in)} = 1.77 \times (1,500/1,000) \, 2 \times 4\,oz\text{–}in = 16 \text{ lb force}$$

In the first gear assembly, operating at 4× the original speed, the force is 16× larger:

$$F_{unb} = 1.77 \text{ (rpm/1,000) 2 (oz–in)} = 1.77 \times (6,000/1,000) \, 2 \times 1\,oz\text{–}in = 64 \text{ lb force}$$

The problems caused by the imbalance are relative to the overall weight, age and use of the gear assembly.

Displacement = distance between geometric axis and mass axis. On a balanced gear the geometric axis and mass axis are the same. The geometric axis is the axis determined during manufacture; it is the center of the shaft that the gear is mounted upon. The mass axis is the line or axis that the gear will naturally rotate around if it is tossed up into the air and spun (Fig. 3).

If you add some mass to the gear on one side, the center of mass—or mass axis of the gear—shifts in the direction of the added mass. The distance between the mass axis and the geometric axis is called "displacement."

displacement = amount of imbalance/total mass (or weight)

To calculate the displacement, take the amount of imbalance, i.e.: 200 g–mm, and divide it by the total mass of the gear or gear assembly, i.e.: 50 kg or 50,000 g.

displacement = 200 g–mm/50,000 g = 0.004 mm of displacement

0.28 oz–in /1,764 oz = 0.00016" (1.6×10^{-4}) of displacement

Balancing = adalignment of geometric axis and mass axis. Gears may be balanced by adding weight 180° from the heavy spot; by welding; riveting; adding epoxy putty; etc. (Fig. 4). When we balance the gear from the above example, we remove material at the angle of the heavy spot—either by drilling, milling or grind-
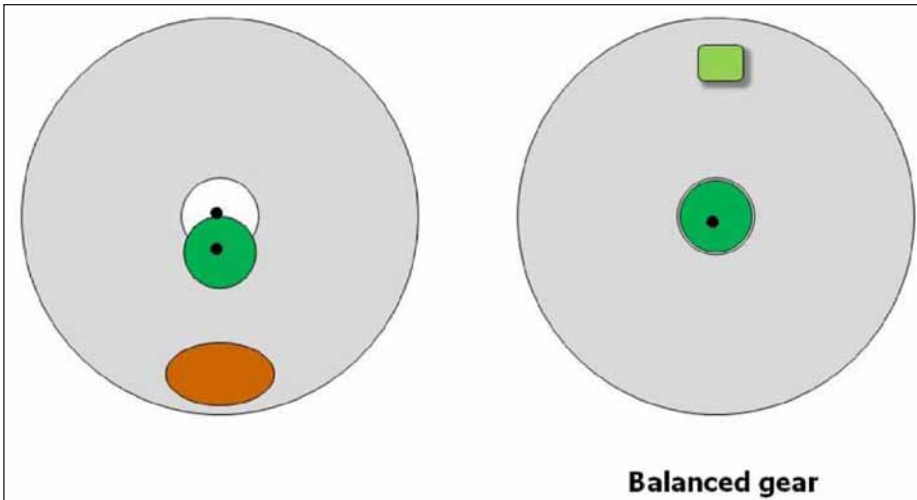
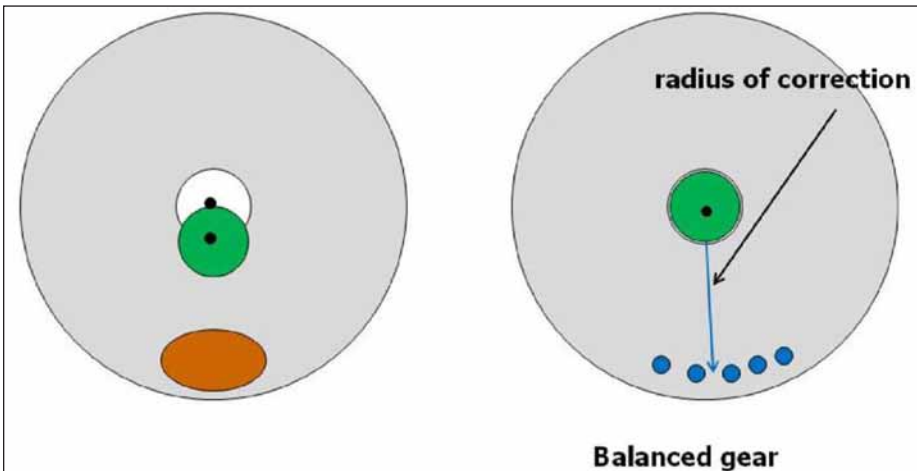**Figure 4   Welding on a weight to correct imbalance.**

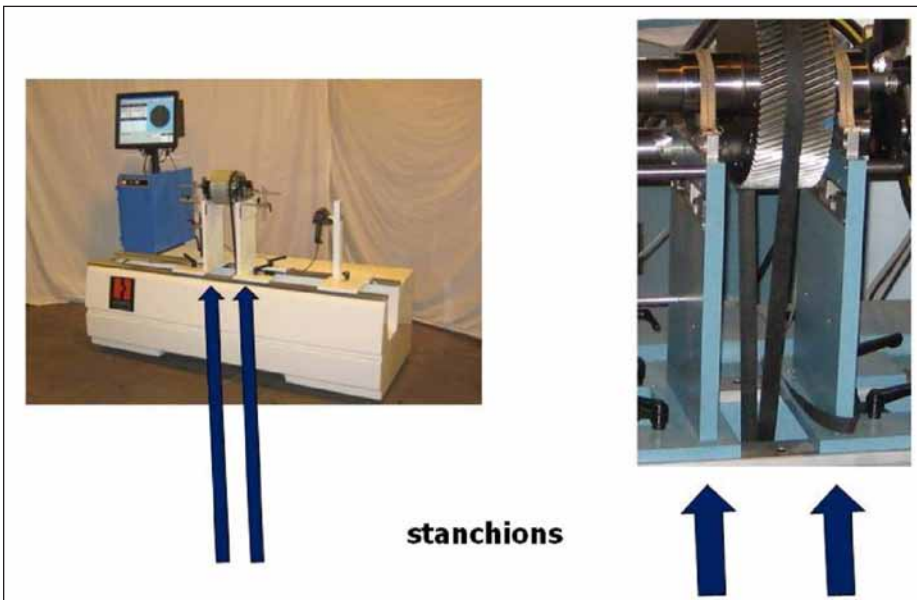**Figure 5   Drilling holes to correct imbalance.**

Figure 6   Cradle-style balancer with two stanchions to support the part.

ing. If we precisely remove one gram of mass, at a radius of 200 mm and at the angle of the heavy spot, the mass axis and geometric axis are realigned and the gear is "balanced" (Fig. 5). We could also remove two grams at a 100 mm radius or 20 grams at a 10 mm radius. The smallest corrections for imbalance are made as close to the outer diameter of the part as possible.

Balance tolerance. One method of setting a balance tolerance is using the API equation:

balance tolerance = 4W/N = 4 × weight-in-pounds-per-stanchion/rpm

Using a 50,000g (110 lb) gear assembly that rotates at 5,000 rpm in use:

4 × 55 lb/5,000 rpm = 0.044 oz–in / stanchion = 32 g–mm/stanchion

It is important to note that although the rpm is used in the equation to determine the amount of imbalance, this does not mean the part must be spun at 5,000 rpm to measure it. Some balancers do not spin at all; rather, they measure the weight on all sides of the geometric center of the part.

imbalance = (1 g × 32 mm)/stanchion × 2 stanchions = 64 g–mm = 0.088 oz–in.

The gear assembly will have 64 g–mm of imbalance, whether it is sitting still or spinning at 100 rpm, 3,500 rpm or 10,000 rpm. The forces caused by the imbalance will be vastly different, but the amount of imbalance remains the same. It is important to list the rpm assumed for a particular balance tolerance. The balance tolerance is often listed as 32 g–mm at 5,000 rpm. Again, the 5,000 rpm is specifying the *operating* speed—*not* the balancing speed. If in use the part spins faster or slower than 5,000 rpm, a different balance tolerance should be calculated.

The only reason to balance at the operating speed is if parts or components of the assembly swing out or shift at a higher speed. Many turbines and combines have blades or hammers that shift outward as the part is spun up to the operating speed, so they should be balanced at that speed. When components are shifting at different speeds, the imbalance is also changing. For ultra-precision balancing, replicating the operating temperature and pressure for the part in use should be considered (Fig. 6).

Two-plane imbalance. In the case of two gears mounted on a shaft, one gear may have imbalance—caused by a heavy spot at one angle—and the second gear may have a different amount of imbalance at a different angle. This is variously called "dynamic imbalance," "two-plane imbalance" or "a combination of couple imbalance and force imbalance." In this case the mass axis and geometric axis are no longer parallel, but skewed. To correct the imbalance, the heavy spot on each gear will need to be removed.

As the two correction planes are moved closer together, along the geometric axis, the amount of correction required increases to infinity. The smallest corrections are made closest to the part's outer diameter, with the correction planes the farthest apart (Fig. 7).

Importance—or not—of small variations. If a balanced gear with a mass of 50 Kg (110 lb) is mounted on a balanced shaft and the clearance, or eccentricity, is such that the gear is held off center by 0.00006" (or 6×10^{-5} inch), it will put the assembly in imbalance:

$$110\,\text{lb} \times 16\,\text{oz/lb} \times 6 \times 10^{-5} = 0.106\,\text{oz–in}\ (63\,\text{g–mm}),\ 0.053\,\text{oz–in/stanchion}$$

Compare this to our balance tolerance of 0.04 oz–in/stanchion. The assembly is out of tolerance—not because of any imbalance in the gear but because the gear is held off center in the assembly. The shaft may have run-out (TIR) or clearance of 0.00012" (1.2×10^{-4}) – or 0.003 mm.

Don't let your time spent balancing be wasted. It is inefficient to balance components to tight tolerances unless part dimensions, clearance and run-out are held to equally tight tolerances in the final assembly. Where possible, it is often best to balance the full assembly in its own bearings, either radial or preloaded axial (Figs. 8 and 9).

Problem solving: production line gears–mirror images. When balancing gears in a production environment it is important to continually monitor the final balanced product. Are they actually balanced? Is the machine still calibrated and set up correctly? And how do you know? To confirm that "balanced" gears are actually balanced, one should take five or 10 from each lot back to the balancer and run the following tests:
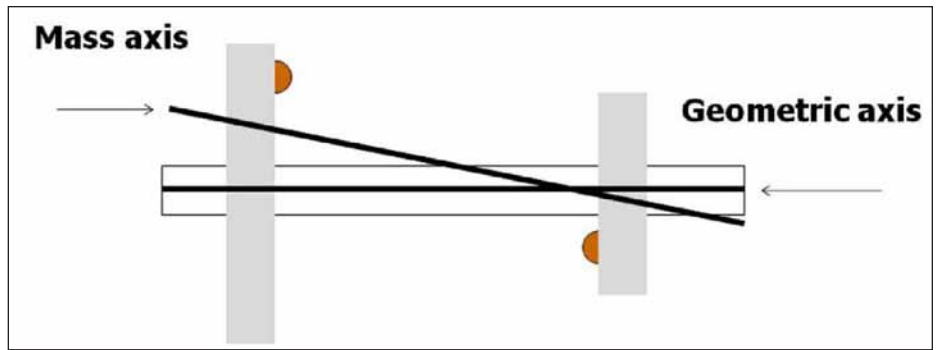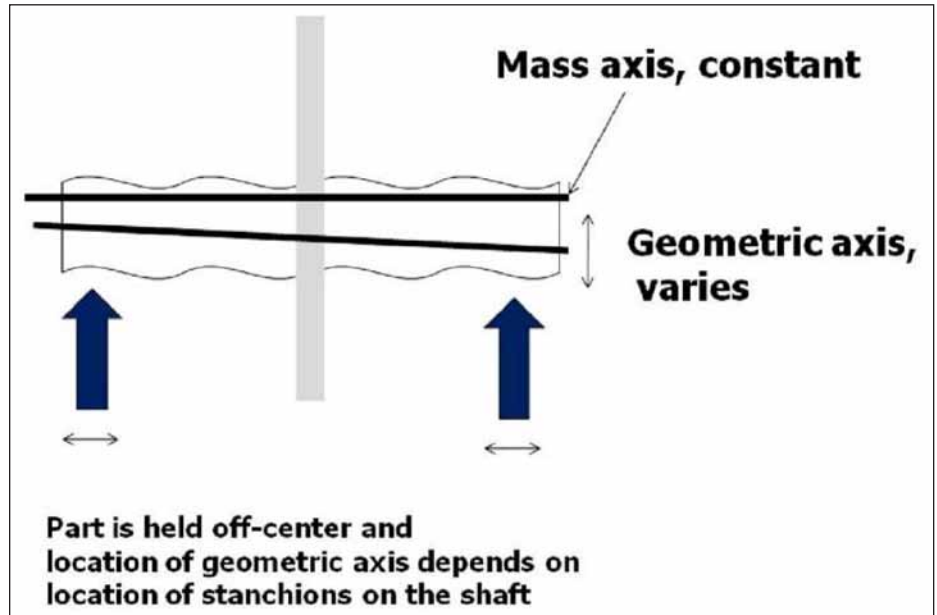

Figure 7   Two-plane imbalance.

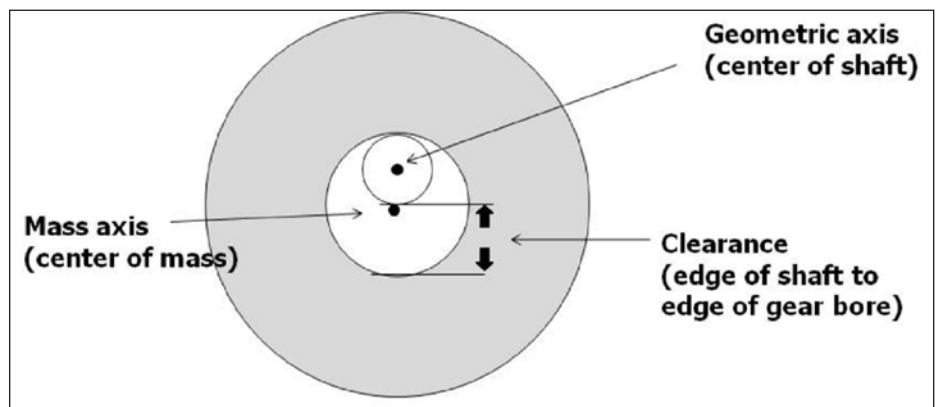Figure 8   Small variations (exaggerated view).

Figure 9   Small variations (exaggerated view).

- Measure imbalance. Is it below tolerance?
- Turn the part 180° on the tooling and measure imbalance again. Is it still below tolerance?
- Measure each of the parts in this manner; if they are not all clearly below tolerance, you should run the entire lot through the balancer again. Lesson learned: check early and often until you gain confidence in the balancer.
- Add a test weight—to either the spindle or a master part. Is the balancer calibrated? Does the balancer display the amount of imbalance expected for the test weight?
- Check the rest of the set-up related to your part and correction method.

It is important to keep scrap parts from getting accidentally mixed in with the good parts. There are many standard balancing machine features available to help with this, including:

- Password required to remove scrap parts from the balancer
- Locked scrap bins
- Ink marking only good parts or only scrap parts
- Automatic transfer of parts to conveyors for good or scrap parts

Problem solving: gear assembly—blowing smoke. When balancing gears that will be assembled later, it makes sense to balance the assembly as well. Even though the individual gears and shaft are balanced, the final assembly may have imbalance due to clearance and run-out. (See "Importance—or not—of small variations" above) To test that the gears or assemblies are truly balanced you can use the list given in "production line gears" = measure, turn 180° to measure again, and test calibration.

Sometimes a gear assembly is balanced, the machine setup is changed, and another part or assembly is balanced; then the setup is changed again and the first assembly is put back into the balancer. The readings may be quite different; why? (See again, "Importance of Small Variations.") When you are reading fine levels of imbalance, small changes can make a big difference. If the balancer bearings locate in one location on the shaft one time and another location the next—and there is run-out in the shaft—the geometric centerline changes in turn as do the imbalance readings. For this reason it is often best to balance the

assembly in its own bearings—radial or preloaded axial.

Other causes of vibration: smoking guns. Sometime, even though an automobile or other assembly is "completely balanced," there is still vibration. Some possible causes are:

- Misalignment
- Reciprocating masses
- Worn bearings
- RPM is higher than expected and tolerances weren't set correctly
- Components were balanced but assemblies were not
- Components were balanced on surfaces that are "close" but not the actual mounting surfaces
- Resonance
- Vibration that is caused by imbalance always increases with an increase in the rotational speed. Thus any vibration that comes and goes as the rpm is increased is not caused by imbalance.

Conclusions

- Balancing is heavily math-based; when imbalance readings change or unexpected vibration occurs, get down to the basics of balancing and do the math.
- Most balancing machines can't tell if you have added weight to the part, changed parts, or if it is the same part; all they can do is measure and display the imbalance.
- There is a reason for the change and it can usually be calculated. ⚙

References

1. *Balance Information Guide*. Hines Industries, Inc., Ann Arbor, MI 2004.
2. "Balancing Requirements of Rigid Rotors." IRD Balancing, Louisville, KY, Rev. 2, March 2009.
3. *Basic Balancing Theory.* American Hofmann, Lynchburg, VA.
4. "Understanding Balance Tolerances." Schenck Trebel Corp, Deer Park, NY.

Working at her family-owned company—Ann Arbor, MI-based Hines Industries, Inc. *(www.hinesindustries.com)*— **Robin Hines Mifsud** has gained more than 17 years' experience in the parts balancing industry. Having earned BS and MBA degrees, Hines Mifsud has held a variety of positions at the company, including—machinist; assembling, calibrating and servicing equipment; managing a balancing service; and the marketing and selling of machinery for the last 11 years. She presented the preceding paper at last year's AGMA Technical Conference.