Where's the Heavy Spot?

The Fundamental problem with <u>all</u> balancing is not knowing the axial location of the "heavy spot". The heavy spot is a term used during mass balancing to visualize, with a vector, the results of timing measurements. It is an imaginary concept. There is no real heavy spot, but creating one on paper or computer allows us to place a correction weight to reduce vibration. Figure 1 illustrates the idea.

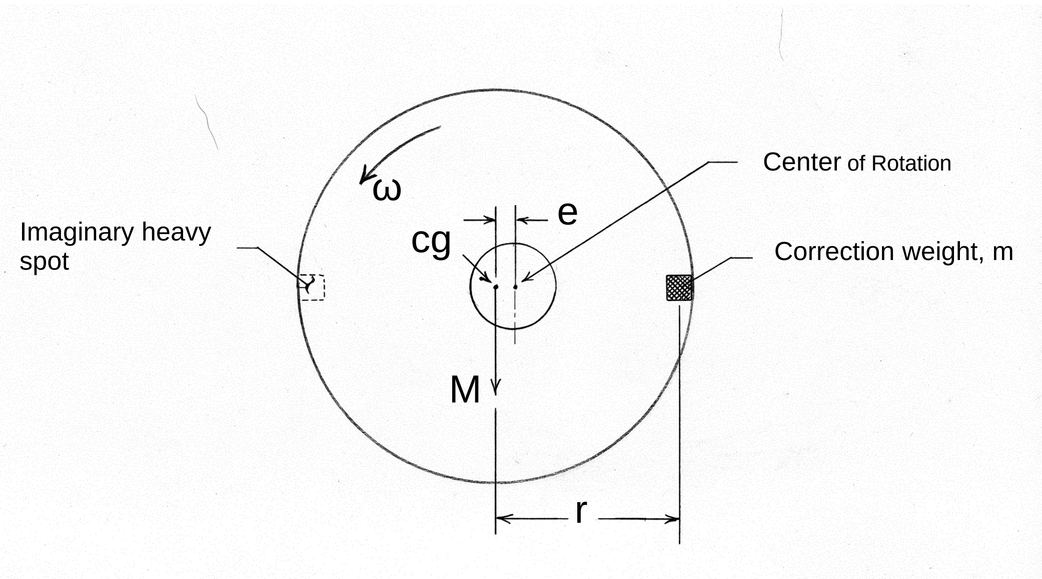

Figure 1. A hole bored off center for the shaft and bearings.

In Figure 1, the hole bored for the shaft and bearings is offset and not concentric with the outside diameter of the rotating disk. That creates an eccentricity, e, where the center of rotation is displaced laterally from the center of gravity, c.g. The result is a vibration synchronous with the rotating speed, which we call an unbalance. Vibration that is synchronous with the rotating speed can be caused by other manufacturing defects, such as non-uniform mass density, material buildup or erosion, assembly hardware not weighing the same, welding slag, non straight shafts, rough bearings that do not repeat the rotating center, misalignment, attached parts like pulleys or couplings that shift the rotating center, and others. Figure 1 is just one manufacturing defect that illustrates some of the fundamental concepts of mass balancing. The main point is that the heavy spot is imaginary. The correction weight, 180 degrees on the opposite side, is what compensates for these defects.

There are only two principal equations in mass balancing. One is the centrifugal force equation:

$F_c = mr\omega^2$ where F_c = centrifugal force
m = correction weight
r = radius of correction weight
ω = speed of rotation in radians per second

The other is the balance standard equation, Me = mr

where M = total mass of rotor
e = eccentricity
m = correction weight
r = radius of correction weight

This balance standard equation is typically re-arranged as e = mr/M to define the specific unbalance, which when multiplied by the speed, ω, produces the balance quality grades G1 through G40. The eccentricity is created by "less-than-perfect" manufacturing or assembly. These defects are made good by adding a correction weight at the proper location. This shows that manufacturing and balancing are connected and dependent processes.

The objective of balance measurements is to find the amount and location of the imaginary heavy spot. There are instruments and procedures for doing this which are based on timing measurements between a trigger sensor and a vibration transducer, plus the application of a test weight to calibrate the timing measurements. It is a well established technology, but does not always work as advertised. The symptoms for not working are when the addition of the correction weight does not quickly converge to a smooth running solution and may even diverge. This is particularly troublesome for flexible rotors, but can be a problem for any rotor.

It would be nice to have an imaging system, like an infrared scope, that can "see" the heavy spot. Unfortunately, none exists yet, so we must infer the heavy spot location and amount from indirect measurements. We measure vibration at both bearings, or both ends of the machine, on stationary parts.

We assume that the heavy spot is close to where the highest vibration is measured, but cross-effect can confuse that assumption.

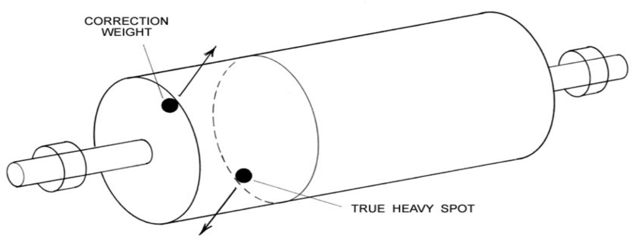

Figure 2. A long rotor where the heavy spot is at some arbitrary and unknown axial location.

In figure 2, the heavy spot is nearer the left bearing. If cross-effect is not terribly active, then the measured vibration will be greater at the left bearing and less at the right bearing. I may be tempted to keep it simple and do only single plane balancing by placing a correction weight at the left end of this long rotor where it is convenient. Remember, the heavy spot is invisible. The correction weight, along with the heavy spot, creates a couple. The vibration may improve, but not good enough. I may continue with trim balancing. Further trim correction weights on the left plane may just make it worse.

If cross-effect was active to where the vibration was higher at the right plane, then single plane balancing by adding correction weights at the right plane would be a frustrating and futile exercise. Doing two plane balancing on a rigid rotor using the influence-coefficient method has the potential to make this rotor operate well. It requires, however, linearity in the mathematical algorithm, a well conditioned matrix, stable measurements of amplitude, phase & speed, and no other mechanical abnormalities corrupting the measurements. Two plane balancing on rigid rotors bypasses this problem of unknown axial location of the heavy spot by compensating for static and couple conditions and cross-effect, all simultaneously. If the rotor is flexible, then good luck. For flexible rotors, the axial location of the true heavy spot in inferred from bending mode simulations, or actual measurements of the bending. That is considerably more complicated.

It would seem that a thin disk would simplify this problem because the heavy spot must be somewhere on the disk, right? It should be an easy single plane balance job. Not so fast. If the disk is skewed, or crooked, to where it is not perpendicular to the shaft axis, then that creates a virtual couple. In figure 3, the centrifugal forces acting on each half of the rotor are displaced axially by an offset distance, d. That creates a wobble. The vibration that it creates can be reduced with two correction weights.

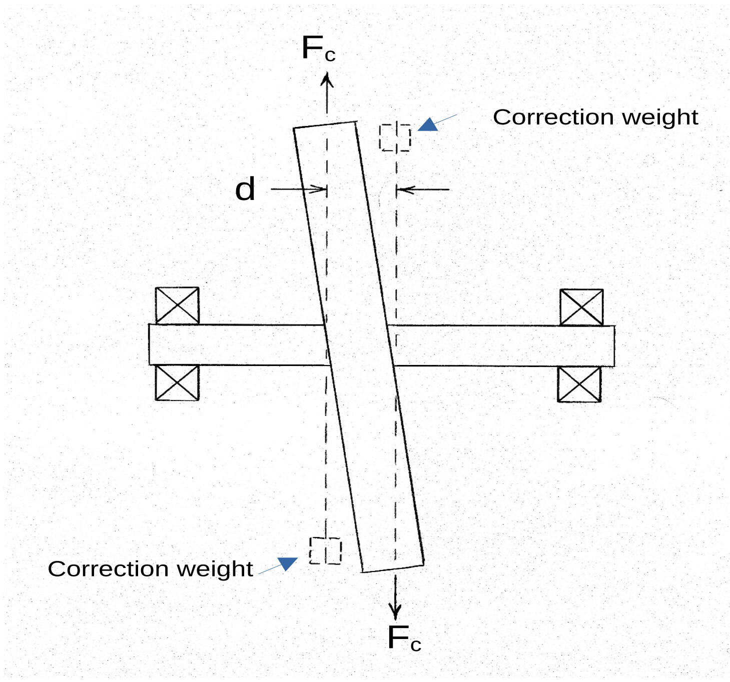

Figure3. A skewed rotor, not perpendicular to the shaft axis.

The imaginary heavy spot now becomes two heavy spots, displaced axially, that the centrifugal force acts on. The correction weights to fix this would be outside the disk in empty air space. Since they would be very close with a short axial spacing, that means that they would be very large correction weights. This skewed disk will statically balance very well, but dynamically it is unbalanceable. The only real solution is to square up the disk to remove the skew.

So how do we deal with this problem of not knowing the axial location of the heavy spot? First, recognize it as a possibility when balancing is not quickly converging to a solution. There are several strategies.

1. Distribute the correction weight along the length of the rotor. There is potential for at least some of the weight correction to be in a favorable plane.

2. Move to another correction plane with a fresh trial weight and a new balance job.

3. Do two plane balancing and hope that the rotor is rigid.

4. Transition to the four-run method. This will confirm or disprove if you are in the right plane. This method avoids measurement anomalies. If any weight in that plane can make an improvement, then the four-run method will find it.

5. Rather than add correction weights, try the alternate method of balancing by reducing the eccentricity. This means moving the rotating center to better coincide with the center of gravity. This may require some re-machining.

What if the shaft is not straight on this thin disk? I can offer some real examples, figure 4.

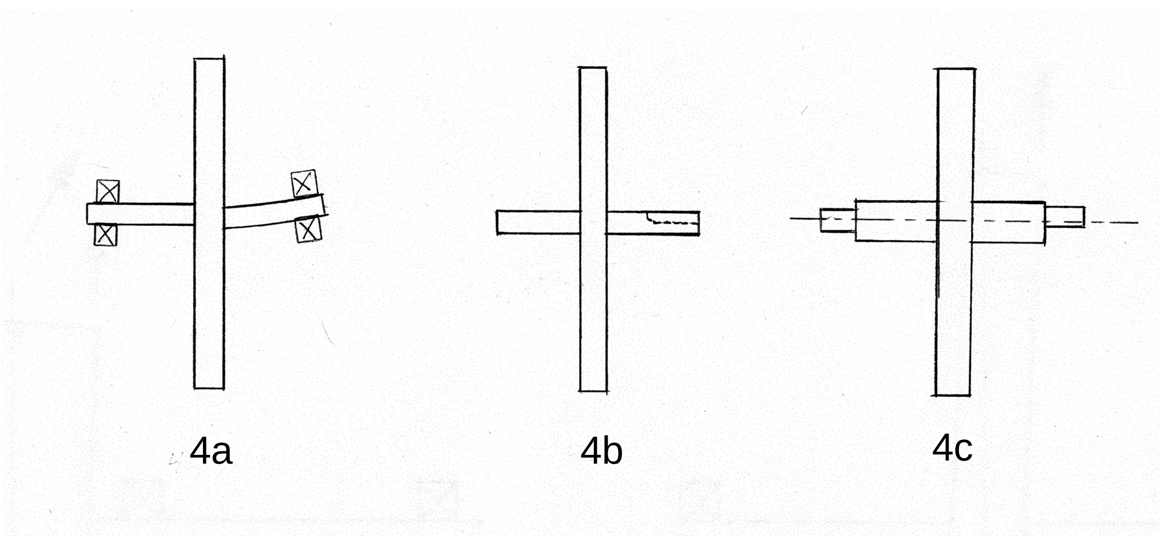

Figure 4. Three conditions where the heavy spot is not in the plane of the disk.

One is a bent shaft where the bend is beyond the disk plane, figure 4a). This condition is only somewhat correctable with weight if the correction weight is placed at an axial location where the developed centrifugal force at speed will tend to draw it straighter. A dial indicator measurement of runout would be useful here to locate the correction plane.

Another condition is where a keyway is cut into the shaft, figure 4b). The unused keyway, or an inappropriate length of key, produces an immediate unbalance.. Balance weights placed in the plane of the disk will do no good. The correction weights need to be in the plane of the keyway. This should be obvious from a visual inspection of the machine, but the temptation is to do single plane balancing at the disk. After some less-than-successful balance efforts, then the prudent strategy is to abandon the disk and move trial weights to a different axial plane.

A third condition is where the bearing journals are not co-axial, figure 4c). This condition is actually easy to create on a lathe when both ends of the shaft are machined in separate setups. The machinist will chuck up the shaft to turn the diameters along most of it's length, but he/she cannot cut metal into the chuck area. So he/she will unchuck it, turn it around 180 degrees, and finish machining the other end in a separate setup. The two bearing journals will not be on the same shaft centerline. The amount of departure depends on the lathe bearings and the precision of the chuck. The bad news is that the balancer has no prior knowledge of this pre-existing condition. Mass placement at any axial location other than the off center journal will be fruitless. The defect was created during manufacturing. The balance effort on the rotor will not correct this defect because the imaginary heavy spot is not where expected.

The gist of this article is that mass balancing is not a mature technology that guarantees successful results on every job, even if instruments and procedures are working correctly. It is still part science and part art. The art is recognizing when things are not converging to a smoother machine. It is time to disengage and do something different. The different thing could be to adjust the procedure, abandon the procedure and transition to another type of balancing procedure (there are 13 known method of balancing), or quit balancing and begin diagnosis for some other mechanical abnormality. If quitting, then the balance effort was not a waste of time. It was useful in diagnosis as a process of elimination that unbalance is not the root cause of vibration.