Shop Balancing Machines vs Field balancing

There are three considerations with respect to mass balancing. These are --

1. The stand that supports the rotor and drives it
2. The instruments that measure motion
3. The methods, or procedures

This article was initially intended to cover the differences between “soft-bearing” and “hard-bearing” balancing machines. After some contemplation, it was realized that the instruments and methods are intertwined with the machines for shop balancing. And then there is field balancing of a machine in it’s permanently installed condition, under load and at speed. There is also flexible rotor balancing. Finally, there are the devilish reasons for why balancing does not always achieve satisfactory results. This article will address all of these subjects.

Why Balance?

The simple answer is to reduce vibration. The assumption with that answer is that a correction weight strategically placed will reduce that vibration. Fine and dandy if unbalance is the root cause. If something else is the reason for the perceived vibration, then adding a weight may not be entirely successful, or could even make it worse.

From a broader perspective, mass balancing is done in three general settings --

- As a final step in manufacturing to correct for less-than-perfect fabrication or assembly. This is production balancing on machines and using methods that produce fast cycle times.
- At a repair facility. A machine with problems is dis-assembled, modified, and then re-balanced to restore it’s center-of-gravity position. This is also done on a balancing stand.
- Adding weight, or removing some material, to a rotor in-place. This is field balancing. This is done at high speed, usually at it’s final service speed. This is the most dangerous and difficult, but delivers the

smoothest results when it works. No stand, or balancing machine, is used. It is supported in it’s own bearings, driven by it’s own prime mover.

The Stand

There are three kinds of balancing machines for general shop use. These are – gravity, soft-bearing, and hard-bearing stands.

Gravity balancing is simple and safe. It is suspending the part in manner such that the gravity force works on the heavy spot to swing it down. The part can be suspended on a string, as in figure 1.

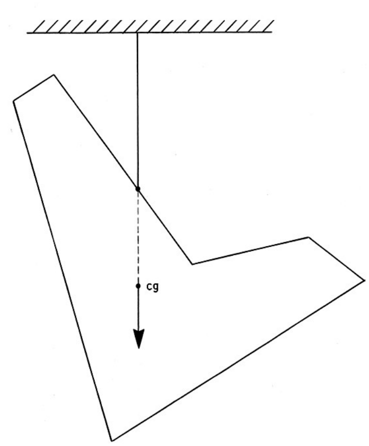


Figure 1. Any shape can be suspended on a string or wire

When suspended from a single point, the attraction to the Earth will force the center-of-gravity point to rotate to be under the point of suspension. The extension of that string will pass through the c.g. location. When suspended from a second point, then the intersection of the two imaginary extensions will define the c.g. point.

Another type of gravity balancing setup is mounting the part on a sharp and hard edge, figure 2.

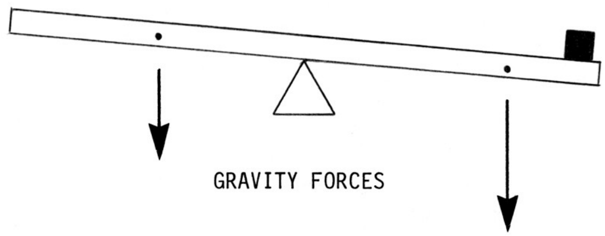


Figure 2. Part to be balanced is mounted on an edge or point.

The part geometry defines whether we use an edge or a point. A round disk would be placed on a point. A long bar would be on an edge. Gravity again commands the heavy side to rotate down toward toward the center of the Earth. The rotation amount and location is usually sensed optically with a liquid bubble.

A third setup is to mount a shaft on twin rollers, figure 3.

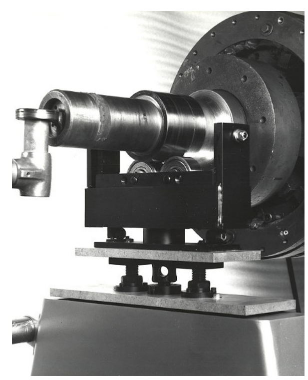


Figure 3a. Twin rollers supporting a shaft.

Figure 3b. Commercially available roller supports.

Figure 3a. Shows two rollers on one end of the shaft. There is another set of twin rollers on the other end of the shaft. The rollers must be precision ball bearings with minimum friction. The shaft surface must also be smooth and round, preferably precision ground. These factors determine the sensitivity of this setup on precision twin rollers, which is capable of achieving balance quality grade G2.5.

This type of twin roller balancing can also be done in-place on a machine at it's final operating location. Friction needs to be reduced to a minimum by removing the belts and uncoupling it from other machines. Gravity is what makes the heavy side swing down and friction is what impedes it. Sometimes, light tapping on the bearings helps overcome static friction to assist gravity.

These gravity methods are only for single plane balancing. They cannot sense, nor correct for, moment unbalance, or couple forces. For that, the rotor must be spun at some speed to detect the couple forces as the rotor wobbles. This is dynamic spin balancing on a machine capable of doing two-plane balancing. There are generally two types – hard-bearing and soft-bearing machines.

Hard vs Soft

The difference is in the natural frequency of the work supports. Imagine an electric motor with an unbalance. If this motor is hard bolted to a concrete floor, then it will have a high natural frequency, typically 50 to 200 Hertz (3,000 to 12,000 rpm). This will be a hard-bearing setup. If it operates at only 1800 rpm, then the motion will be perceivable, but not scary. If this same motor is mounted on coil springs, then it will have a low natural frequency, typically 3 to 5 Hertz (180 to 300 rpm). This will be a soft-bearing setup. It will then have more motion with the same unbalance. The electric motor may have rigid rolling element bearings in both situations. The hard or soft descriptions refer to the structural supports under the motor and are characterized by the natural frequency of the system. The system being the combination of the mass and the spring. The mass being the rotor to be balanced and the spring being the flexibility of the supports.

The hard-bearing machine will have balancing operations taking place at speeds far below it’s natural frequency, figure 4.

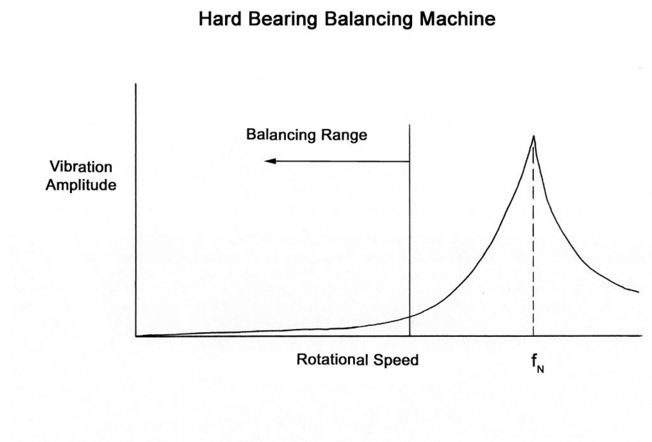


Figure 4. Hard-bearing machine speeds for balancing operations.

This has advantages for cycle time and calculations. This makes it ideal for production balancing. The cycle time is fast because the work supports are rigid and a robotic arm can place the rotor to be balanced onto the supports with good registration. The work supports do not wiggle. The part to be balanced is quickly engaged with a drive motor. The calculation for the correction weight is done in one step after the first spin up. This is because the measurements of motion are made during the linear portion of the resonance curve. In that region, the oscillatory motion is directly correlated to the phase reference on the rotor, being an optical tape or keyphasor. There is little delay between the heavy spot passage and it’s detection. Mechanical lag is a minimum. There is still electronic timing delay, or lag, in the filter and amplifier circuits, but this electronic lag is compensated for in the calibration of the machine.

Some simple scale measurements of the radius and axial locations of the proposed correction weights to the vibration sensors allow leverage ratio mathematics to directly calculate the amount of the correction weight and the circumferential location from the phase reference. After the first spin up, the correction weights are immediately displayed. There is no need for test weights. Tire balancing machines are hard-bearing.

The hard-bearing machine, while being favored for production balancing, has additional factors to be considered. First, the piece to be rotated is typically coupled to a drive motor. This is called end drive. It could be a belt drive over the periphery, but for speed of engaging and disengaging the method of spin up, the end drive is favored for production. This means that the drive motor and coupling are rotating at the same speed as the part to be balanced. It is not possible to filter out, electronically, the vibration coming from the drive setup. The drive motor and coupling must be extraordinarily well balanced below the expected level to be achieved on the production part. In addition, the connection to the part must not introduce any “fit” defects that would corrupt the measurements, such as eccentricities or misalignment.

Second, the hard-bearing machine is rigidly connected to the foundation block, which usually must be very massive. The block, or pedestal, then becomes part of the machine. The hard-bearing machine is calibrated in-place along with it’s foundation. If it is moved, then it should be re-calibrated to maintain this one-run balancing capability.

Third, the hard-bearing machine is sensitive to nearby background activity because it is not isolated from the surrounding environment. External vibrations can be transmitted to the sensors at the work supports. Much of this can be electronically filtered out, but vibrations synchronous with the balancing speed cannot.

Fourth, the balancing speed usually must be faster. Since there is little motion at the rigid work supports, where the sensors are, the rotor must be spun faster just to get a decent amplitude reading. This makes it less safe to operate in an open shop. If it jumps off of the work supports and rolls along the shop floor, then it poses a safety hazard.

Fifth, the hard-bearing machine requires more sophisticated electronics to amplify the weak signals and to filter out external noise.

Sixth, the hand feel calibration is lost. Since there is so little motion, it is difficult for the operator to judge the residual unbalance condition by just laying hands on the work supports. The operator must rely entirely on the display instruments to judge the balance condition. This is like flying blind in the clouds without seeing the ground. He/she must read and understand the instruction manual and trust that the calibration is valid.

The soft-bearing balancing machine may look similar to the hard-bearing machine from a distance. The best way to determine which is to push on the work supports. The soft-bearing work supports should easily move about 1/2-inch with a light hand push, if the supports are not locked.

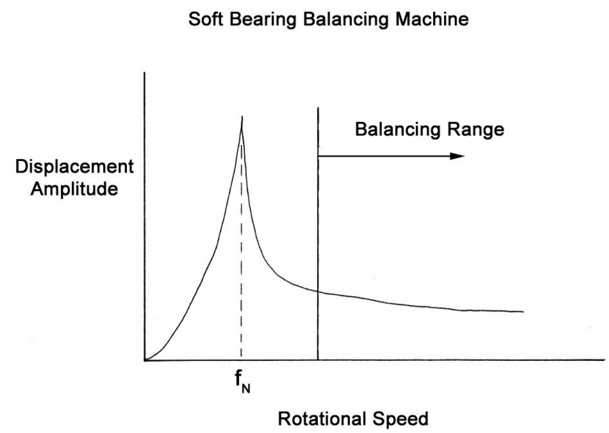
The soft-bearing machine is almost always belt driven. It may be air-driven, but not end driven. It would be difficult to engage the part with an end drive if the support wiggles. Being belt driven means that the drive system will not introduce synchronous vibrations to the balance measurements. The motor, belt, and pulleys will most likely be spinning at other speeds that can easily be filtered out. This simplifies the electronics. In addition, the drive belt may be dis-engaged as it is on some machines. Then the only thing spinning is the part to be balanced and the twin rollers that it is riding on. It is possible that a 1Xrpm motion can be created if the shaft journal is not round (which is not unbalance), but that can be a problem with all balancing – hard-bearing machines and field balancing also.

The soft-bearing machine can be moved around. It does not need a rigid and massive foundation. It can even be placed on dirt. This makes it more flexible in a repair environment. It is calibrated on each size rotor with a test weight. The test weight trial run adds a little time, but that time for an additional trial run is negligible in light of the total time for the repair.

The soft-bearing machine is not sensitive to nearby activity. The soft work supports function as isolation barriers. This means that nearby motion, grinding, drilling, or turning operations may not bother the measurements. Nearby foot and vehicular traffic can even be tolerated. This makes the soft-bearing balancing machine more suitable in a repair shop.

The soft-bearing machine produces excellent balance results at low speed, typically less than 500 rpm. This is because of it’s very low natural frequency, figure 5.

Figure 5. Balancing operations for a soft-bearing machine are above it’s natural frequency.



The soft-bearing machine will go through a motion excursion as it passes through the low natural frequency on both runup and coastdown. That is why locks are used to control that excitement when spinning up. After it passes through the natural frequency oscillation, then the work supports are unlocked. Beyond that, the amplitude of motion, in displacement, does not change much as the speed increases. That is because the additional generated centrifugal force is absorbed by the inertia of the mass of the part plus parasitic mass of the supports. The frequency terms cancel and the energies are equivalent – the energy of rotation (centrifugal force) and the energy of oscillation (work inertia). This physical principle allows good balancing to take place at low speed. There is no reason to go much faster beyond the natural frequency of approximately 200 rpm if the unbalance does not produce more motion. This makes the soft-bearing balancing machine much safer in an open shop.

The soft-bearing machine employs simpler electronics. Because balancing takes place at low speed, the velocity sensor is the preferred detector of motion. In addition to being more sensitive at low speed, it also produces a healthy voltage output – about 10X more amplitude than an accelerometer at that low speed. That means that it needs only simple filtering electronics to produce a usable signal at 1Xrpm. It also means that it is capable of balancing to finer levels, not only due to the good signal to noise ratio, but also because of the flexible work supports that amplify the residual unbalance.

Finally, the soft-bearing balancing machine retains good hand feel calibration. If I can still feel oscillation at the work supports, then I know that the balance is not good enough. I do not need to understand the instructions, nor do I need to rely on electronic calibration. The instruction manual can be written in Chinese and I do not even need to read it. I can still balance.

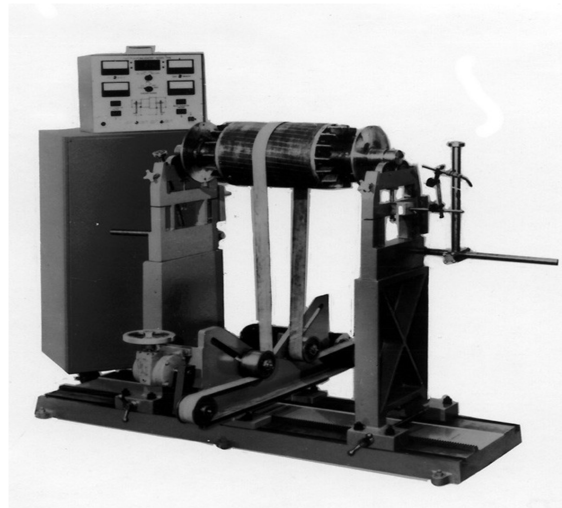


Figure 6. A soft-bearing, belt driven balancing machine.

Field Balancing

Shop balancing is better at measuring for the heavy spot and for correcting the unbalance. It can achieve a fine residual unbalance condition of G2.5 or G1.0. Field balancing is better at reducing vibration on site. These seem like contradictory statements. Let me explain.

Shop balancing, on a balancing machine with consistent structural behavior and known electronic delays, is a calibrated situation. Within the weight limitations of the machine, the amplitude and phase response is predictable. A hard-bearing machine is calibrated at it’s location on it’s pedestal and can produce a calculated correction weight in two planes after a single spin up and some linear tape measurements. A soft-bearing machine can also do one-run balancing after successfully balancing a sample rotor of similar geometry and mass. The sensitivity vectors are stored. Every subsequent rotor of the same configuration can be spun up once, the influence coefficients recalled (the sensitivity vectors), and the correction weights promptly generated.

Field balancing, in contrast, is an uncalibrated situation. Every machine balanced in-place is a new problem. The speeds are different. The structural support system is variable, being flexible, rigid, or even resonant. The motion sensors can be accelerometers, velocity transducers, or even proximity probes for displacement. They are placed at variable orientation, horizontal, vertical, or 45°, and possibly different axial distances. The phase sensors, optical or keyphasor, are also oriented where most appropriate. Finally, the signal conditioners, being filters and amplifiers, have capacitors and inductors in the electronic circuits that create their own timing delays dependent on frequency. Given all this unknown variability, the location and amount of the heavy spot is uncertain just from initial readings. The calculation of the correction weight cannot be deduced from this initial run (except if identical machines are being balanced with identical sensors used setup at identical positions and the same influence coefficients are recalled from memory from a previous successful balance).

To solve this problem in field balancing, the instrumentation is calibrated on-site with test weights. The test weight, of known amount, is placed on the rotor at a declared location. The machine is spun up to a stable speed. The vibration change is noted in both amplitude and phase (timing delay). This trial run, along with the original vibration with no test weight on-board allows the machine response to be estimated. The estimated correction weight can then be calculated after these two runs for single plane balancing. The requirement is that both runs be at the same speed and the numbers stable i.e. not drifting or changing too much. Two plane balancing requires test weights to be placed separately in both planes and three runs are needed to calculate the first set of correction weights.

Field balancing should be done at as low a speed as practical to obtain stable readings. After welding on the rotor, or any other major alterations, static balancing should be first observed to remove the gross unbalance to make that first spin up less exciting. The final vibration, after some corrections, should be done at the maximum service speed.

Methods

What has been described above is only one of the 12 different methods of balancing. A partial list is in table 1 below.

Table 1. Known methods of balancing.

Method	Instrument requirements	Planes	Advantages	Disadvantages
Trial and error	Minimum None to simple filtered amplitude	As many as desired	Potential for producing fine levels of balance	Time consuming.
Four run without phase	Filtered amplitude	One at a time	Quickly converges Always works Simple graphical calculations	Requires four starts and stops.
Seven run without phase	Filtered amplitude Computer	Two	Compensates for cross-effect Quickly converges	Requires seven starts and stops.
Single plane	Filtered amplitude plus phase	One at a time	Fast balancing when it works Best for thin disks Applicable when phase is nearly the same at both bearings Graphical calculations	Cannot compensate for cross-effect. Does not work well near resonances, faulty foundations, instabilities, nonlinearities, or when other root causes exist.
Two plane	Filtered amplitude plus phase Computer	Two	Compensates for cross-effect Applicable when phase is more than 30° different at both bearings	Same difficulties as above for single plane when phase is not reliable. Requires computer to calculate correction weights.
Static couple	Filtered amplitude plus phase	Three	Graphical calculations using single-plane vectors Useful when three planes are available	Requires more runs than two-plane method on rigid rotors. Limited to first and second flexural modes on flexible rotors.
Modal	Filtered amplitude plus phase	As many as necessary	For flexible rotors	Requires knowledge of bending modes.
Multiplane Multispeed	Filtered amplitude plus phase Computer	Many	For flexible rotors No previous knowledge of bending modes needed	Many runs. It is a mechanical method—physical insight is lost.
Manufacturing tolerance control	Precision metrology tools	Many	Potentially smoothest machines Can make field balancing unnecessary	Most costly.
Cleaning	None	All	Fast, cheap	None—cleaning is always recommended for a dirty rotor.

Two additional methods of balancing, not typically used, are “timed oscillation” and “phase only” balancing. For a more complete description of each method, refer to my balancing text in the bibliography.

Balancing involves four separate tasks. The first is some analysis to convince yourself that unbalance is the root cause problem before launching into the job. This includes a visual and mechanical inspection of the machine, initial vibration measurements, and some discussion with people close to it like when did this start and any recent maintenance.

The second task is the measurements. We want to measure the original vibration “as found” and the change with a test weight on-board. This is the easy part, albeit with some risk to be described in the next section under “hazards”. The amplitude is a direct output from the vibration sensor after some filtering to operating speed. It is straightforward if the calibration constant for the sensor is properly set. The phase is a timing measurement between the two sensors – optical pickup and vibration sensor. We can measure time very precisely, but the phase is the more difficult number to acquire because of speed variations, ambient light, the time response of the optic sensor in relation to the visible “on time” of the tape, the angle of view, and distance of stand off.

The third task is the calculations. Balancing involves some sophisticated mathematics. The measurements are vectors with both amplitude and phase. The phase is a time converted to an angle derived from the tachometer pulse. These vectors are loaded into a matrix along with the test weight. The calculation for the correction weight is vector matrix math using the influence coefficient method. This is not trivial. The matrix must be well conditioned to render a successful calculation. The balancer cannot know beforehand if the matrix is ill conditioned. One possible indicator is little change in the phase angle during the trial run. Another indicator is a ridiculously large correction weight result. The good news is that the balancer does not need to know how to do vector matrix calculations. The mathematical algorithm is now public domain and it can be downloaded from the internet.

There is also some algebra that may be needed to adjust the correction weight. Some other balancing methods require geometry and trigonometry. Most modern digital balancing instruments take care of all of this mathematics internally, but that makes the balancer totally dependent on that instrument and it’s batteries. The only fall back option if the instrument poops out is possibly “trial and error”.

The fourth task is to apply the permanent correction weight. In my experience, this is the most difficult. Every machine is different. The balancer must think on his/her feet and be creative. There are many options to add weight – welding, hardware, epoxy, clips, tape, wire, solder, clamps, or adhesives. There are also options for removing weight 180° opposite – drilling, grinding, milling pockets, sanding, nipping sheet metal, and removing previous existing weights that someone else applied.

Hazards in the Field

Mass balancing can be a dangerous business, but no more than driving a car. We are modifying a rotor that spins at high speed. Too much weight can bend the shaft. Test weights can fly off. We are putting hands on the rotor and it must be prevented from starting during this time. That means de-energizing the controls for my safety. Tools can be left inside to get into trouble when re-started. Clothing and cables can get entangled. There is a temptation to touch the rotor when it is coasting down. It can backspin, even if de-energized, due to airflow. There can be another source of power from an emergency generator. Some other person may attempt to cut your lock off. The controls can be mis-wired. My advise is to get a good nights sleep, stay sober, and look after yourself.

Another hazard is damaging the machine system during a start. Every start stresses the machine, electrically, thermally, and mechanically. If there is some pre-existing defect in the system, like a weak electrical ground isolation, loose coupling hardware, or cracked welds, then it could fail during one loaded start. For these reasons, it is advisable to stand outside “the line of fire”, and caution others to do so. In addition, each start should be in an unloaded condition with dampers closed or slow speed from a VFD (variable speed drive). After successful balancing, then the machine can be placed in it’s normal operating condition to check for any changes from unloaded to loaded.

A more subtle hazard is affecting the plant operations by shutting down the utility service. That may be unintentional. It can happen if balancing a machine that is in parallel with a sister machine that is supplying service while the one is being balanced. They may be supplied by a common electrical feed, or controls can be intertwined. Every start and stop must be coordinated with operations to re-position dampers or valves, modulate speeds and maintain flow. There may be pre-existing defects in the controls or some other electrical connection that the balancer has no knowledge of. A subsequent start can trigger a sequence of failures that affects the service to the factory. For this reason, it is advisable to not operate any plant controls. A technician or engineer familiar with the plant systems and the coordination required should be asked to do all starts and stops.

Flexible Rotor Balancing

Most common utility & service machines i.e. motors, pumps, and fans can be considered “rigid rotors” when bolted to a concrete foundation and operating below 5,000 rpm. When these conditions are not satisfied, on springs or upper platforms and at higher speeds, then rigid rotor balancing may not work well. The rotor is considered flexible. Flexible rotor balancing is not for the novice or the inexperienced.

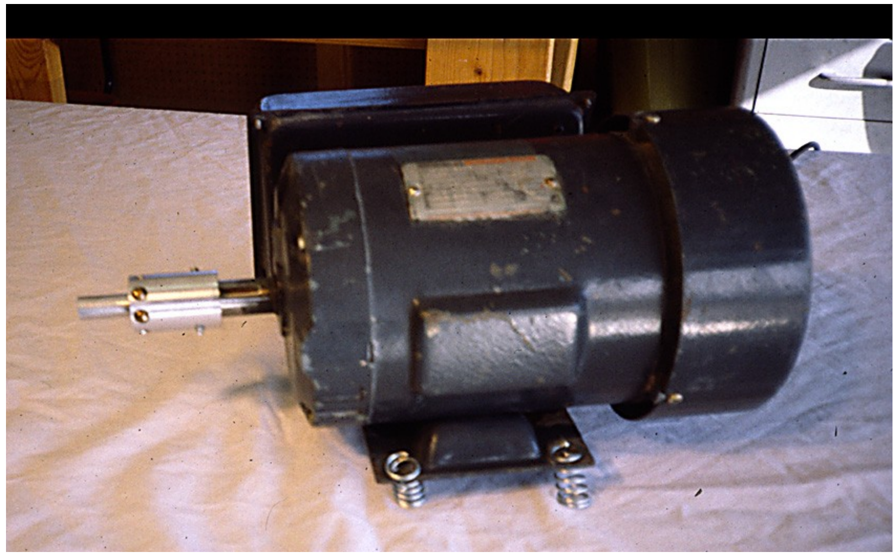
All balancing on a hard-bearing balancing machine is rigid rotor balancing. On a soft-bearing balancing machine rigid rotor balancing can also apply when sufficiently above the natural frequency of the work supports, typically 2x higher. Flexible rotor balancing applies when resonance is active either in the work supports or bending of the rotor at it’s critical speed. Flexible rotor balancing will not be covered here, only for the balancer to recognize it. The indications are unstable amplitude and phase. A further symptom is the first correction weight does not make a significant improvement. The vibration is not reduced to at least 1/2 of the original. The confirmation is an impact test to measure the natural frequencies.

Gas turbine engines, steam turbines, high speed compressors, and multistage pumps are flexible but are typically balanced as components using single-plane rigid rotor methods. The fully assembled rotor is treated as flexible, either in the shop or in the field. At that time, flexible rotor balancing methods are employed at multiple speeds with some knowledge of the bending modes and stiffness and damping in the plain bearings.

Make One

It is not difficult to put together a balancing setup in a shop or a garage. What is needed is an electric motor and an adapter, figure 7.

Figure 7. A home made balancing machine.



The motor is mounted on springs or pads to make it a soft-bearing setup. An adapter is machined that will mount onto the motor shaft with another diameter for the part to be balanced. The adapter is pre-drilled & tapped for balance weights. The adapter is attached to the electric motor, which is driven at it's normal speed or by a VFD. The motor has some internal residual unbalance. Portable vibration instruments for balancing are attached to the side of the motor. Screws are added to the adapter to make it operate as smooth as possible. The rotor to be balanced is then added onto the adapter. Any new vibration is assumed to be unbalance in the newly added part, and balancing of it can proceed normally.

It is also possible to build a complete balancing machine from parts or surplus purchases. The mechanical section of balancing machines has not changed much is 70 years. The major changes have been replacing the DC motors with AC motors and drives, and upgrading to digital electronics. So a surplus frame is a good purchase. Add upgraded electronics & displays, recondition the work supports, download the public domain calculation software, and you have a state-of-the-art soft-bearing balancing machine.

What Went Wrong ?

Mass balancing, especially in the field, does not always work as planned. Some of the reasons for less than satisfactory results could be instrument malfunctions or poor procedures, but there are also physical conditions on the machine that prevent success. One obvious reason is that there is another mechanical defect which weight placement cannot correct. In that case, balancing was a diagnostic step that eliminates unbalance as a cause. That should direct the balancer to cease balancing efforts and start some other diagnostics like measuring for distortion with a dial indicator, misalignments, resonance tests, hardware looseness, or others.

Besides other root causes, the influence coefficient method of calculation is not perfect. The algorithm depends on linearity for both amplitude and phase changes. Around resonances, neither can be expected to be linear. One strategy is to change speed. Another is to stop, do impact testing for natural frequencies, and proceed from there. A third strategy is to select another method of balancing that does not rely on a well conditioned vector matrix.

An often not mentioned reason for poor balancing results is the selection of the test weight and it’s location. A too small test weight will not display a change. A too large test weight will drive the vibration large into a non-linear response with harmonics. The influence coefficient method is also sensitive to the location of the test weight. It is not supposed to be, but it is. The strategy is to stop, move the test weight 90°, and start over with a fresh problem.

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