The Manufacturer's World of Coupling Potential Unbalance

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Abstract

Coupling balance is important to vibration free operation of turbomachinery. Understanding how and what in a coupling affects vibration is the purpose of this paper. Discussed are the basics of balancing, why a coupling is balanced, what contributes to unbalance in a coupling, how to bring a coupling into balance, when to balance a coupling and to what level, coupling balance limits, the arbitrary balance criteria, and the various types of coupling balance.

Introduction

The subject of coupling balance or unbalance has confused and mystified many. In reality, however, it is rather simple once a basic understanding is achieved of what contributes to unbalance and how it affects a system. Once this understanding is obtained, the arbitrary balance limits can be put into perspective of a system's needs and from the manufacturer's view.

The Basics of Balancing

Units for Balance or Unbalance

The unbalance in a piece of rotating equipment is usually expressed in terms of unbalance weight (ounces) and its distance from the rotating centerline (inches). Thus, the unbalance (U) in a part is expressed in oz-in. Example: An unbalance weight of four oz is at a distance from the rotating centerline of two in (Figure 1). The unbalance (U) is therefore eight oz-in.

For couplings, it is more convenient to express unbalance in terms of mass displacement. This usually helps bring balance limits into perspective with tolerances, fits and the "real world".

Mass displacement is usually specified as micro-inches, mils or inches, (1000 μ-in= 1 mil = 0.001 in). Example: If a 50 lb part (800 oz) is displaced 0.001 in (1 mil or 1000 μ-in) from the centerline (Figure 2). then an 8 oz-in imbalance (800 oz × 0.001 in) would occur.

Unbalance = 2" × 4 oz = 8 oz-in.

Figure 1. Units for Unbalance

Displaced
.001 = 1 mil = 1000 microinches

W = 50 lbs
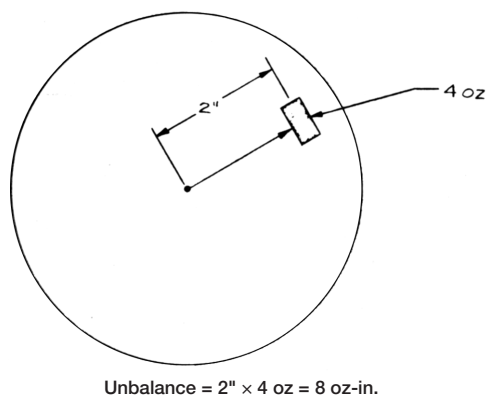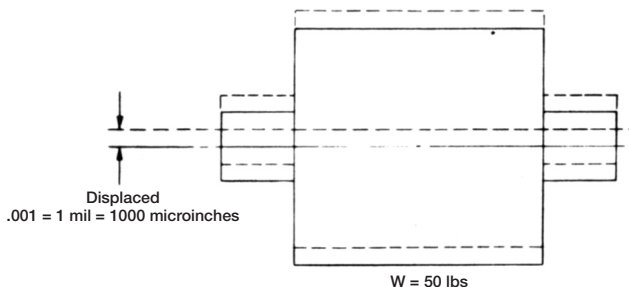
Figure 2. Unbalanced Mass Displacement

Balancing

Balancing is a procedure by which the mass distribution of a rotating part is checked and, if required, adjusted (usually by metal removal) so the unbalance force or the vibration of the equipment is reduced.

Types of Unbalance

Single-Plane Unbalance (sometimes called Static Balance)

This unbalance condition exists when the center of gravity of a rotating part does not lie on the axis of rotation (Figure 3). This part will not be in static equilibrium when placed at random positions about its axis. Single-plane balancing can be done without rotation (much like static balancing of an automobile wheel), but most couplings are balanced on a balancing machine which is more accurate. Single-plane balancing is usually limited to short parts, usually with a length less than 1.5 x D_O (depending on part configuration), where D_O is the outside diameter of the part being balanced.
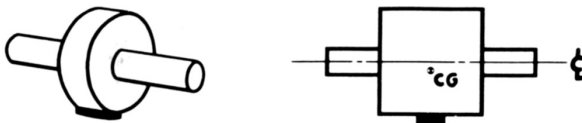

Figure 3. Single Plane Unbalance

Two-plane (Moment, Coupling or Dynamic) Unbalance

This type of unbalance is present when the unbalance existing in two planes is out of phase as shown in Figure 4, but not necessarily 180° out of phase. The principal inertia axis closest to the axis of rotation is displaced from the axis of rotation and these two axes are skewed with respect to each other. If not restrained by bearings, a rotating part with this type of unbalance will tend to rotate about its principal inertia axis closest to its geometric axis. If the moments are equal and opposite moments, they are referred to as a coupling unbalance.
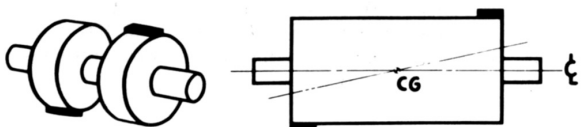

Figure 4. Two Plane Unbalance

Rigid Rotor

A rotor is considered rigid when it can be corrected in any two planes and, after the part is balanced, its unbalance does not significantly exceed the unbalance tolerance limit at any other speed up to the maximum operating speed with running conditions which closely approximate those of the final system. A flexible coupling is an assembly of several components that may have diametral clearances and eccentricities between pilot surfaces of its components. Therefore, it is not appropriate to apply standards and requirements that are written to apply to rigid rotors. Many coupling selectors and users attempt to do this in lieu of something more appropriate.

Axis of Rotation

The axis of rotation is a line about which a part rotates as determined by journals, fit or other locating surfaces.

Principal Inertia Axis Displacement

The displacement of the principal inertia axis is the movement of the inertia axis that is closest to the axis of rotation, with respect to the axis of rotation. In some special cases, these two axes may be parallel. In most cases, they are not parallel and are, therefore, at different distances from each other in the two usual balancing planes.

Amount of Unbalance

The amount of unbalance is the measure of unbalance in a part (or a specific plane), without relationship to its angular position.

Residual Unbalance

Residual unbalance is the amount of unbalance left after a part has been balanced. It is equal to or usually less than the balance limit tolerance for the part. *Note:* As a check to determine whether a part is balanced, remove the part from the balancing machine and then replace it. The residual unbalance will not necessarily be the same as the original reading. This is due to the potential differences in mounting and/or indicating surface runouts.

Potential Unbalance

The potential unbalance is the maximum amount of unbalance that might exist in a coupling assembly after balancing (if corrected), disassembly and reassembly.

Balance Limit Tolerance

The balance limit tolerance specifies a maximum value below which the state of unbalance of a coupling is considered acceptable. There are two types of balance limit tolerances:
  • Balance limit tolerance for residual unbalance.
  • Balance limit tolerance for potential unbalance

Mandrel

A shaft on which the coupling components or assembly is mounted for balancing purposes is called a mandrel (Figure 5).

Bushing Adapter A bushing adapter or adapter assembly is used to mount the coupling components or the coupling assembly on the mandrel (Figure 5).
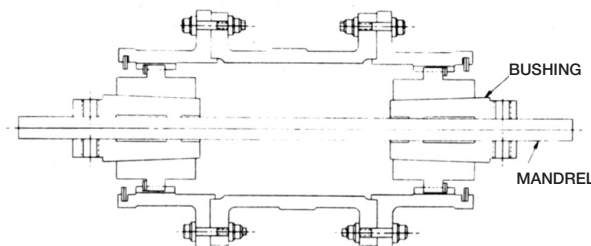

Figure 5. Assembly Balancing Mandrel for a Gear Coupling.

Mandrel Assembly

A mandrel assembly consisting of one or more bushings, used to support the part mounted on a mandrel (Figure 5).

Mounting Surface

A mounting surface is the surface of a mandrel, bushing, or mandrel assembly on which another part of the balancing tooling, a coupling component, or the coupling assembly is mounted. This surface determines the rotational axis of the part being balanced.

Mounting Fixtures

Mounting fixtures are the tooling that adapt to the balancing machine and provide a surface on which a component or a coupling assembly is mounted.

Indicating or Aligning Surface

The indicating surface is the axis about which a part is aligned for the purpose of balancing. The aligning surface

Table 1. Typical Examples of Coupling Pilot Surface

COMPONENTS	USUAL PILOT SURFACES
Rigid Hub	Bore, Rabbet Diameter, Bolt Circle
Flex Hub (Gear Type)	Bore, Hub Body OD, Tooth Tip Diameter
Flanged Sleeve (Gear Type)	Tooth Root Diameter, End Ring ID, Rabbet Diameter, Bolt Circle
Flanged Adapter	Rabbet Diameter or Bolt Circle
Flanged Stub End Adapter	Stub End (Shaft) Diameter, Rabbet Diameter, Bolt Circle
Spool Spacer (Gear Type)	Tooth Tip Diameter
Flanged Spacer	Rabbet Diameter Or Bolt Circle
Ring Spacer	Rabbet Diameter or Bolt Circle

is the axis from which a part is located for the purpose of balancing. *Note:* Some coupling manufacturers do not component balance. Not all couplings can be component or assembly balanced without mandrels or mounting fixtures.

Pilot Surface

A pilot surface is that supporting surface of a coupling component or assembly upon which another coupling component is mounted or located. Examples are given in Table 1.

Why Balance a Coupling

One important reason for balancing is that the forces created by unbalance could be detrimental to the equipment, bearings, and support structures. The amount of force generated by an unbalance is:

$$F = 1.77 \times \left(\frac{rpm}{1000}\right)^2 \times \text{oz-in} = \text{lb}$$

$$F = \frac{\text{micro-inches}}{1,000,000} \times \text{wt} \times 16 \times (rpm/1000)^2 - \text{lb}$$

As can be seen from these equations, the amount of force generated by unbalance is proportional to the square of the speed.

Example:
2 oz-in of unbalance at 2000 rpm and at 4000 rpm
F at 2000 rpm = 14.1 lbs
F at 4000 rpm = 56.6 lbs

Therefore, if the speed doubles, the same amount of unbalance produces four times the force.
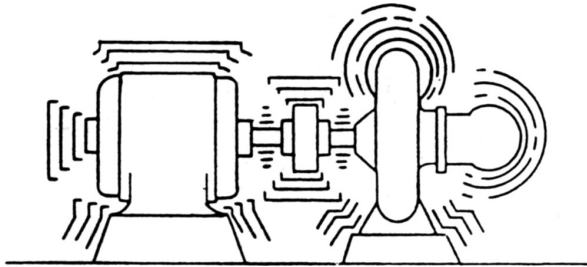
Figure 6. Excessive Equipment Vibration

Another important reason for balancing is vibration (Figure 6).

What Contributes to Unbalance in a Coupling

Contributors to Potential Unbalance of Uncorrected Couplings

Inherent Unbalance of Uncorrected Couplings—If the coupling assembly or components are not balanced, an estimate of inherent unbalance caused by manufacturing tolerances may be based upon either statistical analysis of the balance data accumulated for couplings manufactured to the same tolerances, or calculations of the maximum possible unbalance that could theoretically be produced by the tolerances placed on the parts.

Coupling Pilot Surface Eccentricity—is any eccentricity of a pilot surface which permits relative radial displacement of the mass axis of mating coupling parts or sub-assemblies.

Coupling Pilot Surface Clearances—are the clearances which permit relative radial displacement of the mass axis of the coupling components or sub-assemblies. *Note:* Some couplings must have clearances in order to attain their flexibility, i.e., gear couplings.

Hardware Unbalance—is the unbalance caused by all the coupling hardware including fasteners, bolts, nuts, lock-washers, lube plugs, seal rings, gaskets, keys, snap rings, keeper plates, thrust plates, retainer nuts, etc.

Others—Many other factors may contribute to coupling unbalance. The factors mentioned are of principal importance.

Contributors to Potential Unbalance of Balanced Couplings

Balance Tolerance Limits—are the largest amounts of unbalance (residual) for which no further correction need be made.

Balance Fixtures or Mandrel Assembly Unbalance—is the combined unbalance caused by all components used to balance a coupling, including mandrel, flanges, adapters,

bushings, lockings devices, keys, setscrews, nuts, bolts, etc.

Balance Machine Error—The major sources of balancing machine error are overall machine sensitivity and error of the driver itself. This unbalance is usually very minimal and can usually be ignored.

Mandrel Assembly Mounting Surface Eccentricity—is the eccentricity, with respect to the axis of rotation, of the surface of a mandrel assembly upon which the coupling assembly or component is mounted.

Component or Assembly Indicating Surface Eccentricity—is the eccentricity with respect to the axis of rotation of a surface used to indicate or align a part on a balancing machine. On some parts, this surface may be machined to the axis of rotation rather than to the indicating axis.

Coupling Pilot Surface Eccentricity—is an eccentricity of a pilot surface which permits relative radial displacement of the mass axis of another coupling part or sub-assembly, upon assembling subsequent to the balancing operation. This eccentricity is produced by manufacturing before balancing or by alternations of the pilot surfaces after balancing. For example, most gear couplings that are assembly balanced are balanced with an interference fit between the gear major diameters and after balancing are remachined to provide clearance. This may produce eccentricity.

Coupling Pilot Surface Clearances—are the clearances which permit relative radial displacement of the mass axes of the coupling component or sub-assemblies on disassembly/reassembly. The radial shift affecting potential unbalance is equal to half of this clearance. *Note:* If this clearance exists in a coupling when it is balanced as an assembly, the potential radial displacement affecting potential unbalance is equal to the full amount of this diametral clearance that exists in assembly at the time of balance.

Hardware Unbalance—is the unbalance caused by all coupling hardware including fasteners, bolts, nuts, lock-washers, lube plugs, seal rings, gaskets, keys, snap rings, keeper plates, thrust plates, retainer nuts, etc.

Other—factors which may contribute to coupling unbalance may also be significant.

Component Balancing—is usually the best for couplings which have inherent clearances between mating parts or re-quire clearances in balancing fixtures. Component balance offers interchangeability of parts usually without affecting the level of potential unbalance. In most cases, component balanced couplings can approach the potential unbalance limits of assembly balanced couplings, and in some cases,

it can produce even lower potential unbalance levels. This is particularly true when a large, heavy mandrel or fixture must be used to assembly balance a coupling.

How To Bring A Coupling Into Balance

Couplings can be brought into balance by four basic methods:

- Tighter manufacturing tolerances
- Component balancing
- Assembly balancing
- Field balancing on the equipment

Tighter Manufacturing Tolerances—The majority of unbalance in most couplings comes from the tolerances and the clearance fits that are placed on components so that they can be mass produced and yet be interchangeable. Most couplings are not balanced. The amount of unbalance can be greatly improved by tightening fits and tolerances. By cutting manufacturing tolerances and fits in approximately half, only half the amount of potential unbalance remains. If a coupling is balanced without changing the tolerances, the unbalance is only improved by five to twenty percent. Remember, the tighter the tolerances and the fits, the more couplings are going to cost. A real life practical limit is reached at some point. As tolerances are tightened, the price of the coupling not only increases, but interchangeability is lost, delivery is extended, and in some instances, the choice of coupling and potential vendors is limited. An attempt to show how tolerances affect the cost is shown in Table 2.

Assembly Balancing of Couplings—may provide the best overall coupling balance. This is true when no clearance exists between parts (i.e., disc or diaphragm couplings).

The balancing fixtures and mandrels are light weight, and are either manufactured to extremely tight tolerances (0.0003 total indicator readings (TIRs) to 0.0005 TIRs, this is 300 to 500 micro-inches) or somehow the coupling is locked or rigidized without the use of a fixture or a mandrel. For relatively large assemblies, the mandrels and fixtures may introduce more error than if the coupling was not balanced at all. It is possible to unbalance the coupling more than it was originally unbalanced. Assembly balanced couplings are matchmarked and components should not be interchanged or replaced without rebalancing.

Field Balancing—On very high speed equipment and/or lightweight equipment, it may not be possible to provide a balanced coupling to meet the requirements due to the inherent errors introduced when balancing a coupling on a balancing machine. When this occurs, the coupling manufacturer can provide a means where weight can be easily added to the coupling. Then the coupling can be balanced by trial and error on the equipment itself. Couplings can be provided with balancing rings that have radial setscrews or tapped holes so setscrews or bolts with washers can be added or subtracted. There are also other means that can be used.

When To Balance And At What Level

The amount of coupling unbalance that can be satisfactorily tolerated by any system is dictated by the characteristics of the specific connected machines and can best be determined by detailed analysis or experience. Factors which must be considered in determining the system's sensitivity to coupling unbalance include:

Shaft End Deflection—Machines having long and/or

Table 2. Approximate Cost as Affected by Tolerances

	*GENERAL TOLERANCES	**IMPORTANT TOLERANCES	DBC TRUE LOCATION	APPROXIMATE COST
Low Speed	±1/64	±0.005	±1/64	1
Intermediate Speed	±0.005	±0.002	±0.005	1.5-2
High Speed	±0.002	±0.001	±0.005	3-4

*General tolerance applied to non-critical diameters and lengths. (Example: Coupling OD)
**Important tolerances apply to critical diameters and lengths. (Example: Bores, Pilots)

Table 3. Typical Values of Coupling Balance Class.

| SELECTION BAND | TYPICAL AGMA COUPLING BALANCE CLASS | | |
| | SYSTEM SENSITIVITY TO COUPLING UNBALANCE | | |
	LOW	AVERAGE	HIGH
A	5	6	7
B	6	7	8
C	7	8	9
D	8	9	10
E	9	10	11
F	10	11	12
G	11	12	—

flexible shaft extensions are relatively sensitive to coupling unbalance.

Bearing loads relative to coupling weight—Machines having lightly loaded bearings or bearing loads determined primarily by the overhung weight of the coupling are relatively sensitive to coupling unbalance. Machines having overhung rotors or weights are often sensitive to coupling unbalance.

Bearings, bearing supports, and foundation rigidity—Machines or systems with flexible foundations or supports are relatively sensitive to the coupling unbalance.
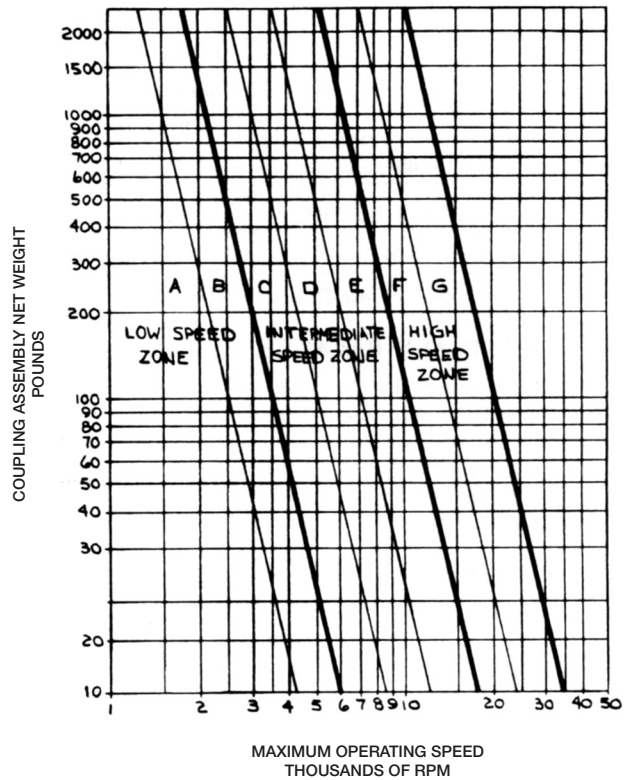

Figure 7. Selection Balance Bands.

Table 4. AGMA Coupling Balance Classes.

AGMA Coupling Balance Class	Maximum Displacement Of Principal Inertia Axis At Balancing Planes (rms micro-inches)
4	Over 32,000
5	32,000
6	16,000
7	8,000
8	4,000
9	2,000
10	1,000
11	500
12	250

Table 5. Residual Unbalance Limits.

SPEED CLASS	RESIDUAL UNBALANCE LIMITS (MICRO-INCHES)
Low Speed Couplings	* 500 (µ- inches)
Intermediate Speed Couplings	200
High Speed Couplings	50

*Low speed couplings are usually not balanced.

Machine separation—Systems having long distances between machines often exhibit coupling unbalance problems.

Others—Other factors may influence coupling unbalance sensitivity.

The data in Table 3 was taken from American Gear Manufacturers Association (AGMA) 515. In general, selection bands can be grouped into the following speed classifications:

- Low Speed—A and B
- Intermediate Speed—C, D, and E
- High Speed—F and G

The speed classifications from AGMA 515 are also presented in Figure 7. The graph has also been extended to 2000 lb.

Coupling Balance Limits

The balance limit placed on a coupling should be its potential unbalance limit and not its residual unbalance limit. The residual unbalance limit usually has little to do with the true coupling unbalance (potential). It can be seen in many cases that by cutting the residual unbalance limit in half, the coupling potential unbalance may only change by five percent. The best method of determining the potential unbalance of couplings is by the square root of the squares of the maximum possible unbalance values. These unbalances are mostly from the eccentricities between the coupling parts, but include any other factor that produces unbalance. The coupling balance limit is defined by AGMA as a range of unbalance expressed in micro-inches (μ-inches). The potential unbalance limit classes for couplings are given in Table 4. They are given in maximum root mean squared (rms) micro-inches of displacement of the inertia axis of rotation at the balance plane. Limits are given as displacement per plane.

The residual unbalance limit for a part of an assembly balanced coupling is shown in Table 5. Tolerances tighter than these usually do very little to improve the overall potential unbalance of a coupling assembly.

The Arbititrary Balance Criteria

What is meant by the arbitrary balancing criteria? The limits (potential and residual) described in the previous section give the most realistic values for unbalance limits. There are many criteria presently being used, and are generally referred to as the *arbitrary limits*. They are used in several coupling specifications. The most common limit is to express unbalance as

$$\text{oz-in (unbalance)} = \frac{K \times W}{N} = U \text{ per balanced plane}$$

where

W = Weight of the part per balance plane (lb)
N = Operating speed of coupling (rpm)
K = 40-120 for potential unbalance limits
K = 4-12 for residual unbalance limits

The most common valves for these arbitrary limits (API 671) are:

| *Residual Limit* | *Potential Limit* |
| oz-in = 4 W/N | oz-in = 40 W/N |

In general, these limits are not too bad, but in some cases a very expensive balanced coupling may result when it is not really necessary. In other cases, specifying limits beyond the "Real World of Practicality" will result in arguments, delays, etc., while everyone involved regroups and tries to place blame for not specifying the limits correctly and/or not balancing the coupling correctly.
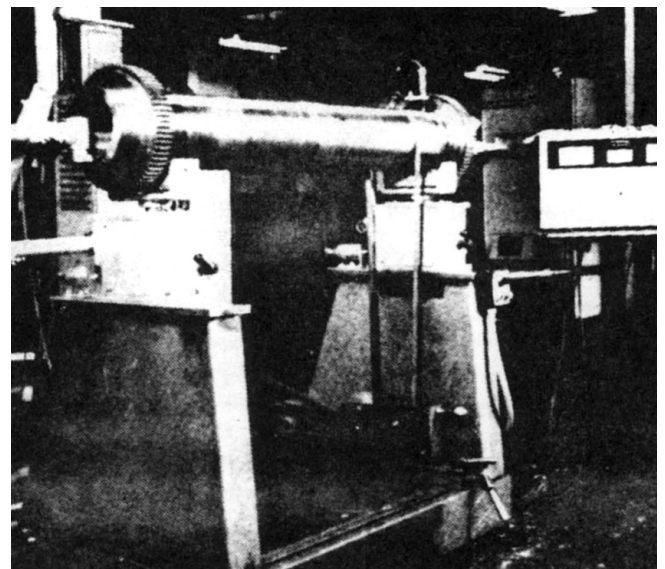

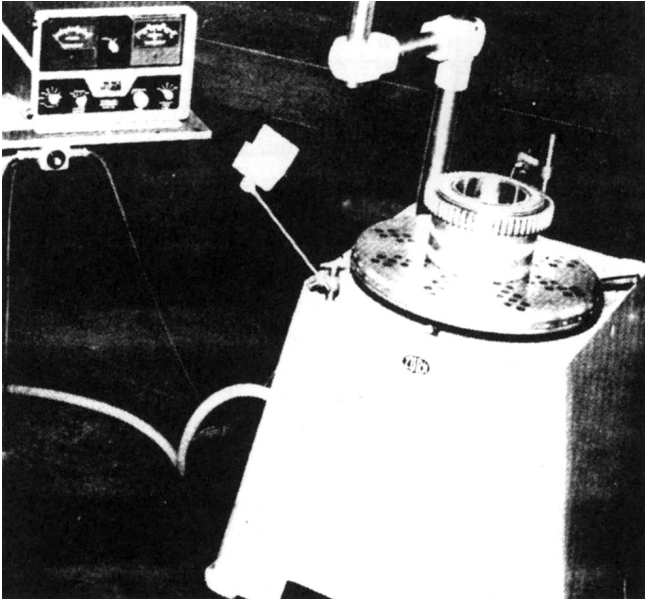Figure 8. Component Balancing of a Geared Spacer.
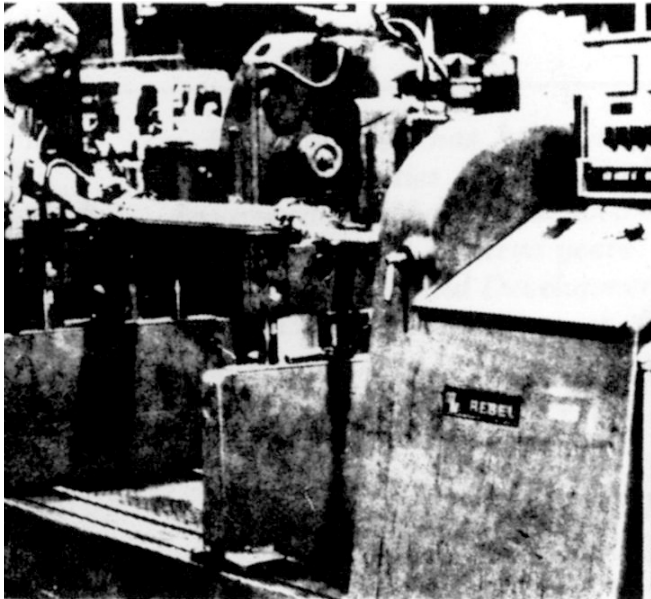
Figure 9. Component Balancing of a Flexible Hub.
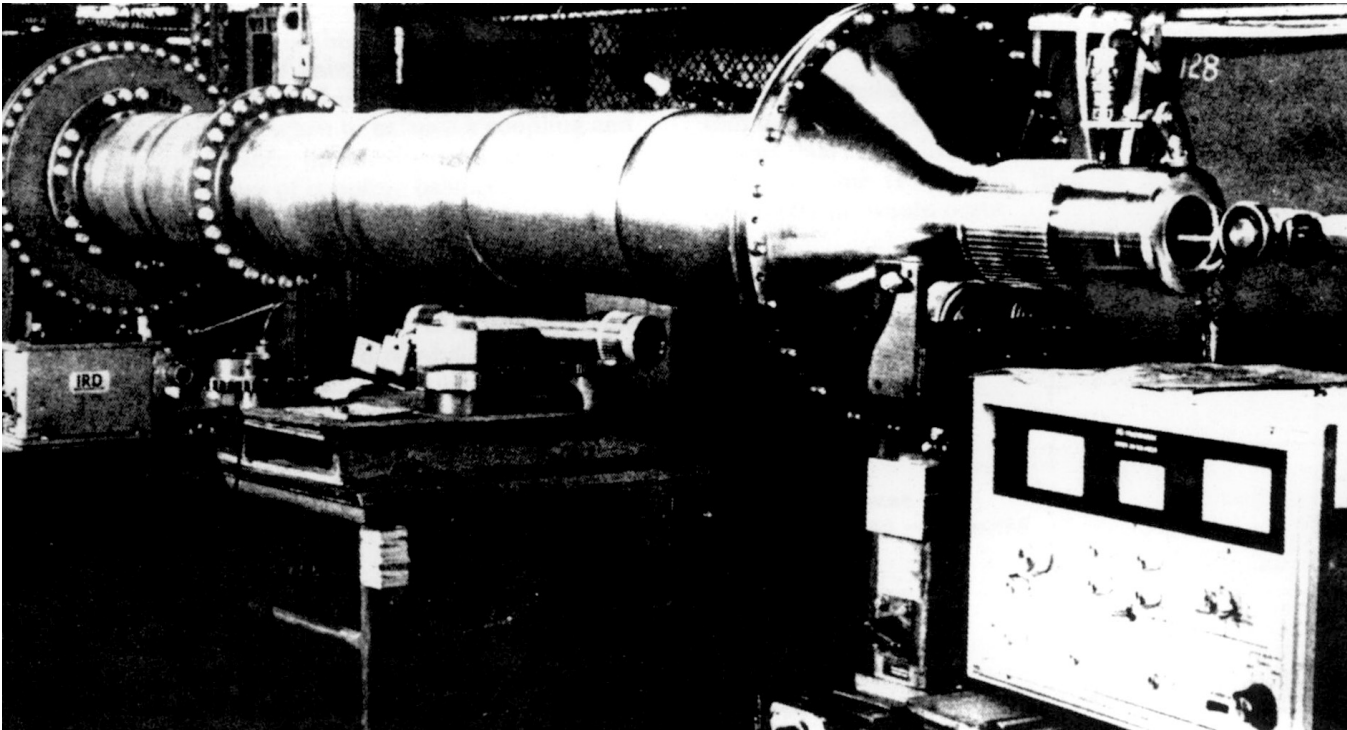

Figure 10. Assembly Balancing of Gear Coupling

Figure 11. Assembly Balancing of a Diaphragm Coupling without a Mandrel.

The Arbitrary Potential Unbalance Limits—Applying the arbitrary limits to the three coupling speed classes results in the following values:

Speed Class	Unbalance Limit (oz-in)
Low Speed	120 W/N
Intermediate Speed	80 W/N
High Speed	40 W/N

As stated before, it is best to put unbalance in terms of micro-inches. If this is done, another arbitrary criteria results, but now if a low limit tolerance is applied (in micro-inches), the balance limit has some relationship to the real world of manufacturing of the coupling with tolerances and fits. Values that result from this criteria, with the highest values becoming limits, are:

Speed Class	Unbalance Limit (micro-in.)
Low Speed	7,500,00/N or 4000
Intermediate Speed	5,000,00/N or 2000
High Speed	2,500,00/N or 500

The Arbitrary Residual Unbalance Limits—The residual unbalance limits are approximately $\frac{1}{10}$ of the potential unbalance limits, with the highest values in each class becoming the limits, and are:

Speed Class	Unbalance Limit (oz-in)	Unbalance Limit (Micro-inches)
Low Speed	12 W/N	750,000/N or 400
Intermediate Speed	8 W/N	500,000/N or 200
High Speed	4 W/N	250,000/N or 50

Types of Coupling Balance

Most coupling manufacturers can and will supply couplings that are brought into balance. Some coupling manufacturers have what they call their standard balancing procedure and practice. Extra charges may be made for balance procedures other than standard practices. For example, some coupling manufacturers prefer assembly balanced couplings. The different types of coupling balance used by manufacturers are:

As Manufactured—Today most couplings are supplied as manufactured with no balancing.

Controlled Tolerances and Fits—usually provides the most significant improvement in the potential unbalance of couplings. This also can substantially increase the price of a coupling if carried too far.

Component Balance—can usually produce potential unbalanced values equal to assembly balanced couplings. It offers the advantage of being able to replace components (as related to balance, some couplings are not interchangeable for other reasons) without balancing. This technique is shown in Figures 8 and 9.

Assembly Balancing with Mandrels or Fixtures—offers the best balance, but it is usually expensive because the mandrels and/or fixtures must be made with extreme accuracy. The coupling is basically rigidized with the mandrel or fixtures and then balanced (Figure 10). On assembly balanced couplings, parts cannot be replaced without the rebalancing of a coupling.

Component Balancing with Selective Assembly—sometimes offers the best possible balance attainable without field balancing on the equipment. Parts are component balanced and then runouts (TIRs) are checked. The highs of the TIR readings between controlling diameters for mating parts are marked. At final coupling assembly the high spots are assembled 180° out of phase. This tends to negate eccentricities and reduces the potential unbalance of the coupling. The parts are still interchangeable as long as replacement parts are inspected and marked for their high TIRs.

Assembly Balancing without a Mandrel—is usually limited to disc, diaphragm and some types of gear couplings. The coupling is locked rigid with various locking devices that are usually incorporated into the coupling design (Figure 11). The coupling is rolled on rolling surfaces that are aligned or machined or the coupling bores or alignment pilots. This type of balance can usually provide a better balance than can be achieved using a mandrel. This is because there is no added weight to the assembly when it is balanced. On a very large or long coupling, a mandrel assembly can weigh almost half of the weight of a coupling. This can introduce very significant balancing errors.

Field or Trim Balancing on the Equipment—offers the best balance, but it is usually the most costly, because of the trial and error and time invoked. The coupling cannot be disassembled or reassembled without rebalancing.

Summary

Coupling balance requirements and limits are hopefully better understood. The balance limits (potential and residual) for couplings should be specified in micro-inches of mass displacement. This can put balance limits into perspective of the manufacturer's world. Specifying arbitrary limits without analyzing the system's real needs may unnecessarily increase the coupling cost or preclude the use of some perfectly acceptable couplings.

Some important things that should be remembered are that a coupling is a collection of parts that must be disassembled for assembly, and/or maintenance of the equipment and maintenance of the coupling itself. The balance level is most affected by the coupling's ability to be repeatedly assembled and disassembled without changing the various mass eccentricities of the coupling parts.

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