The Maintenance of Rotor Assemblies from Strategic Rotating Machines - On Site

– The Way Forward –

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ABSTRACT

Throughout the more enterprising countries of the world, the benefits to industry of undertaking on site, the complete servicing and repair of strategic rotating machines have long been recognised and applied with considerable reward. The higher the capacity of the machines and the more strategic their nature of operation to production demands, the greater are the benefits to be realised in terms of reduced overall costs and machine downtime.

The most difficult maintenance procedures to undertake on site are always seen as the final machining and balancing of rotor assemblies, particularly the higher capacity and more precise “Flexible” rotors from machines such as turbines, compressors, electrical motors and generators.

This led to the development of a range of special purpose, fully transportable balancing machine systems with turning capability, and the special techniques for applying them to best effect in the field.

This paper covers experiences gained and developments to date on the design and application of these **“Transportable Maintenance Facilities”** and provides a discussion document on how this growth business can best be adapted to the needs of industry world wide.

Introduction

Throughout industry, it is accepted that the most time-efficient and cost-effective means of maintaining fixed plant, is to undertake as much as possible, if not all of the work, on site; the growing trend being to promote complete on site maintenance. This applies mainly to rotating machines that are critical to production processes, such as: turbines, generators, compressors, pumps, fans and motors and, in particular, to the electrical power generation industry. The higher the capacity of the machines and the more strategic the nature of operation, the greater are the benefits to be realised.

Final machining and balancing of many types of rotor assemblies have always been perceived as being amongst the most difficult procedures to undertake on site, particularly with larger rotors and the higher speed "Flexible" rotors. Historically ingrained misconceptions have led to the sometimes widespread belief that this type of work can only be done "back at the factory" or equivalent facility where the necessary machine tools and operator expertise are readily available.

LP Rotor from a Steam Turbine in a Power Station

For obvious reasons, this view has always been encouraged by original equipment manufacturers and owners of the more comprehensive, high cost workshop facilities. Manufacturers of certain "hard bearing" type rotor balancing machines that are not suitable for use as transportable machines for site work, have also done little to dispel these misconceptions.

Unfortunately, "back at the factory" usually means somewhere a long distance away, even halfway around the world, and will therefore incur considerable transportation costs and delivery times, with the associated risks of damaging the precision rotor assemblies before and after the scheduled repair work has been completed. As the facilities for handling large capacity and high speed rotors are also very few and far between, and the nature of the work to be done requires that they be specialised, high cost equipment centres, they are always in demand. As a consequence, the service charges rendered are invariably very high, and considerable periods of time can be spent waiting for equipment availability. The time taken to complete the repair work can also be inordinately long because of applied procedures, as laid down by the manufacturers of the test equipment and the rotors, which may not necessarily be relevant to the particular repair or service that is required. These laid down procedures may also dictate more extensive dismantling and testing of the rotors than is actually necessary.

Although the high cost of "factory" maintenance, and the risk of subsequent rotor damage are often considered to be unacceptable in context with the extent of the service work undertaken, of primary concern is always the duration of the overall exercise and the consequent extended period of machine downtime. Periods anywhere from two weeks and up to as much as six months are not unusual. A report has even been received of a case where a critical compressor was out of service for over 18 months because, at the manufacturer's insistence, the rotor was returned to the factory for "Overspeed Balancing" as part of routine maintenance. With the right equipment and application knowledge, the work required could very easily have been done on site within a week, and at a fraction of the cost.

Another big advantage of having full maintenance facilities on site is that the means of compensating for any handling, re-assembly or operational inconsistencies is readily available. An example is the ability to trim balance rotors should there be any undue changes in mass concentricity as a result of induced load and/or running temperature changes.

Transportable Maintenance Facility

Recognising the benefits to be achieved by overcoming the problems associated with having to ship rotor assemblies away from site for repairs and balancing, has led to many joint ventures between original equipment manufacturers, service organisations, end users and balancing machine/machine tool manufacturers.

Transportable Balancing Machine with Machining Attachment being used as part of a major overhaul of Turbines in a Power Station in Zimbabwe

Having full maintenance facilities permanently located at all production sites has always been discounted as not being practical. The ventures have therefore involved the development and application of transportable maintenance facilities that can be easily moved from site to site as demands dictate. These facilities are usually based around transportable balancing machine systems that can be used with or without machining attachments or, to a lesser extent, transportable lathes that have balancing capability.

In designing these transportable balancing machines, the following basic specifications must be met:-

1. For ease of transportation and handling, the machine system must be compact, self-contained and as light a weight as possible.
2. There should not be any need for special foundations or installation requirements at each new site.
3. Setting up the machine system must be quick and easy, without the need for any prolonged calibration procedures or special calibration rotors.
4. For reasons of safety, and to minimise drive power requirements, the machine system must be able to perform to the highest standards at very low rotational speeds.
5. The system must be very versatile and easily adapted for handling all types of rotor configurations of various sizes and weights over a wide range.
6. The rotor supports must have universal roller assemblies that can accept a wide range of journal diameters. The rollers must also be self-aligning to eliminate the need for time consuming alignment and levelling procedures when installing rotors, and to prevent journal damage.

Loading the End Drive Unit and pair of Pedestals of a 100 tonne capacity Balancing Machine System for transporting to the next work site

7. The system must be very adaptable for use as a complete work station for all types of field service applications, not only for balancing. Such as:

- General turning/grinding operations, when used in conjunction with a transportable machining attachment;
- Rotor inspection and Non Destructive Testing;
- Re-blading of bladed rotors;
- Geometric tolerance measurements;
- General electrical and mechanical repairs.

Basic System Design

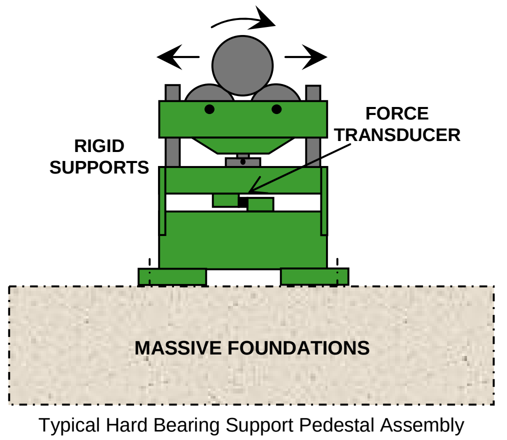
Many years of application experience has shown that the requirements of a truly transportable maintenance facility can only be met if it is designed around a "Soft Bearing" type of Balancing Machine.

Essentially, there are two types of balancing machines:

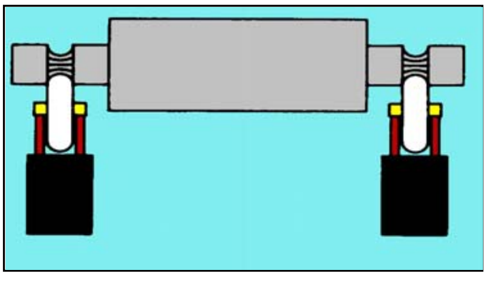
- **"Hard bearing"**, also known as "Sub-critical" or "Force Measuring"
- **"Soft Bearing"**, also known as "Super-critical" or "Displacement Measuring"

Hard Bearing Balancing Machines, by nature of their design, are best suited to being permanently installed for production and "high speed" balancing. They are most unsuitable for use as transportable machines for the following reasons:-

- The performance of these machines is dependent on a constant high mass / high stiffness rotor supporting structure, including a rigid bed and special concrete foundations. Even minor changes in system rigidity will have a significant effect on overall system calibration and balancing sensitivity;
- Because the machines are designed to measure unbalance forces, which are proportional to the square of the rotational speed, the sensitivity to a given unbalance level is speed dependent; the higher the rotational speed of the rotors, the higher the sensitivity. Hence, Hard Bearing machines are not the most suitable for low speed balancing;



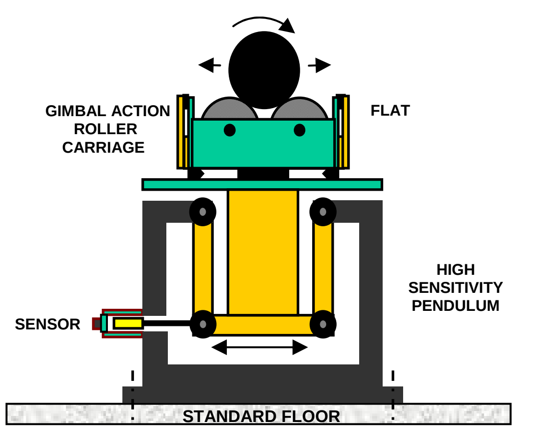
Typical Hard Bearing Support Pedestal Assembly with Crowned Rollers


The point loading of Crowned Rollers often results in the grooving of journals on heavier rotors

- The rigid construction requirement also does not allow for using universal, self aligning type bearing rollers. Crowned rollers are therefore used for balancing lighter weight rotors. However, the point loading on these types of rollers will cause damage to journals on heavier rotors. Special purpose, high cost, pressure lubricated bearings therefore need to be manufactured for each rotor, which also involves applying time consuming alignment and setting up procedures;

- The constraints introduced by the need to maintain the high mass / stiffness constants, severely limit the overall system versatility, and the ability to adapt to differing service application demands and environmental situations, which are essential requirements of a fully transportable service facility.

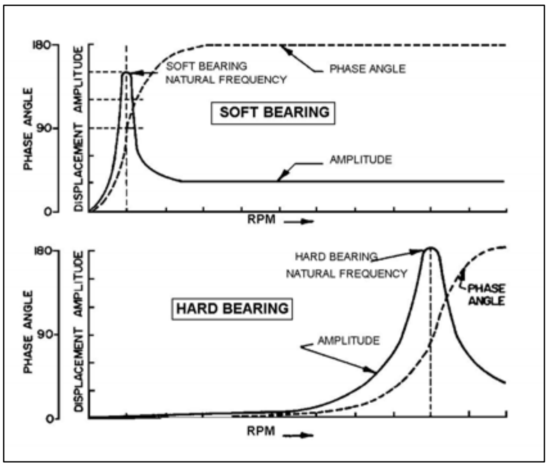
Soft Bearing Balancing Machines, in contrast, are ideally suited as the basis for the truly transportable service facility, particularly machines whose design incorporates high sensitivity, minimal stiffness pendulum suspensions and universal, self-aligning, flat surfaced rotor support rollers. The primary features include:-



Typical Support Pedestal Assembly of
IRD Soft Bearing Balancing Machine

- The balancing speed range of this type of machine is above the natural frequency of the suspension system, and the rotor is essentially isolated by the pendulum action of the suspensions. Its performance is therefore not influenced by the mass and/or stiffness of the supporting structure and foundations. Hence, the machine can be mounted very easily and quickly at any location that is capable of supporting its static weight and that of the rotor;

- The free moving suspensions and support rollers provide a high degree of sensitivity because they do not restrain the free vibratory motion of the rotor. This provides for optimum balancing accuracy at low rotational speeds, and linear response to unbalance vibration displacement throughout the balancing speed range;

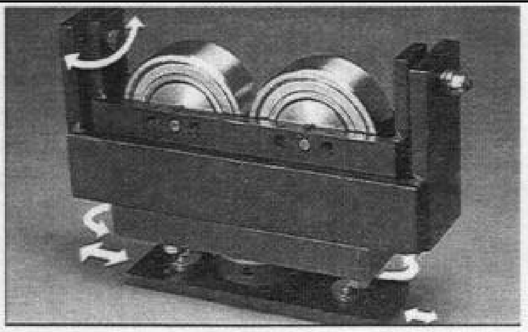


Comparing Amplitude/Speed Response of
Hard & Soft Bearing Balancing Machines

- The principle of operation is such that machines can be manufactured using a lightweight airframe construction which, together with the fact that only minimal power is needed to drive the rotors at low and safe speeds, provides for a compact, self-contained and lightweight system which is ideal for transporting. The machines are also very adaptable in the field for handling rotors of all types, sizes and configuration without affecting their high degree of balancing sensitivity;

- These machines perform equally well when using either built-in dedicated balancing instrumentation, or a fully portable unit that can readily be detached for in-situ balancing applications;

- The self-aligning, flat rollers obviate the need for time consuming alignment and levelling procedures and make sure of line contact with the rotor journals under all normal conditions of operation, thereby preventing journal damage and ensuring ease of set up for a wide range of journal diameters;


Self - Aligning Roller Bearing Carriage

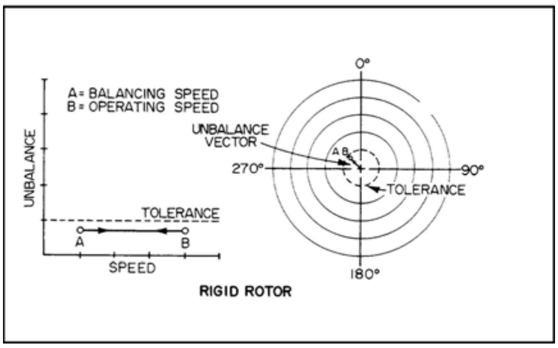
- Although having been designed specifically for low speed balancing, the self-centring pendulum suspensions and self-aligning rollers, in either free or locked up mode, provide a very good pair of "steadies" for supporting all types of rotor assemblies during various maintenance and testing operations. In fact, the versatility and application of the overall machine system is limited only by the ingenuity of the operating personnel concerned.

Rotor Types

For balancing purposes, there are essentially two types of rotors: "Rigid Rotors" and "Flexible Rotors".

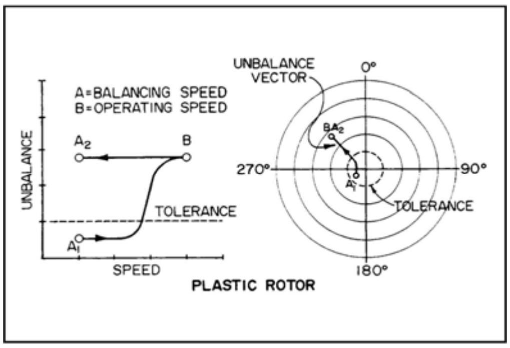
A **Rigid Rotor** is that which, when balanced in any two arbitrarily selected planes, will remain within the specified balance tolerance at any speed up to and including its maximum service speed.

Balancing rigid rotors in a low speed, transportable balancing machine is a straight forward exercise when applying recognised balancing procedures, providing the specified permissible residual unbalance, calculated to the rotor's maximum service speed, can be achieved with repeatable results.



Typical variation of unbalance amount & phase angle relative to changes in speed for a rigid rotor

There are occasions when it may be difficult to ascertain whether or not a rotor meets the true definition of a rigid rotor. The best advice in this case is: if in doubt, treat it as "Flexible".



Typical variation of unbalance amount & phase angle relative to changes in speed for a plastic rotor

A **Flexible Rotor** is that which does not satisfy the definition of a rigid rotor and which has a tendency to bend or distort due to centrifugal and unbalance forces, the effect of which can be induced or aggravated by changes in operating loads and temperatures.

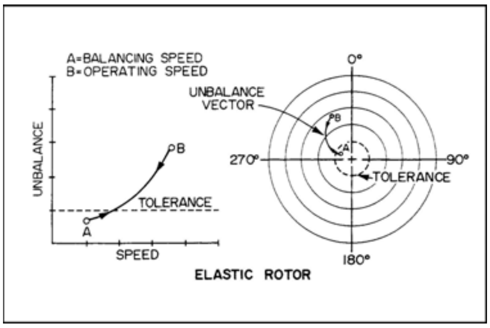
For practical purposes, flexible rotors can be considered one of, or a combination of, three types:

Type 1 Those which lack inherent rigidity to an extent that causes them to whip, even at low speed.

Type 2 Those which are subject to plastic deformation, induced by centrifugal forces, and changes in operating load and/or temperature.

Type 3 Those which are subject to elastic deformation as operating speeds approach and coincide with rotor natural frequencies or "critical speeds".

A good example of rotor **Type 1** is a long, narrow paper roll which, because of its high degree of flexibility, normally needs to be balanced in a number of planes and at various speeds up to its maximum operating speed. This is to ensure that it also runs true to its rotating centreline by applying balance correction weights at determined points along the length of the roll to offset any tendency for it to bend or whip due to the forces of unbalance. Because the



Typical variation of unbalance amount & phase angle relative to changes in speed for an elastic rotor body of a paper roll is manufactured from a single component, running it up to speed is the only sure means of determining the points of unbalance or deflection. Fortunately, paper rolls generally operate at comparatively low speeds which are within the scope of a transportable balancing machine.

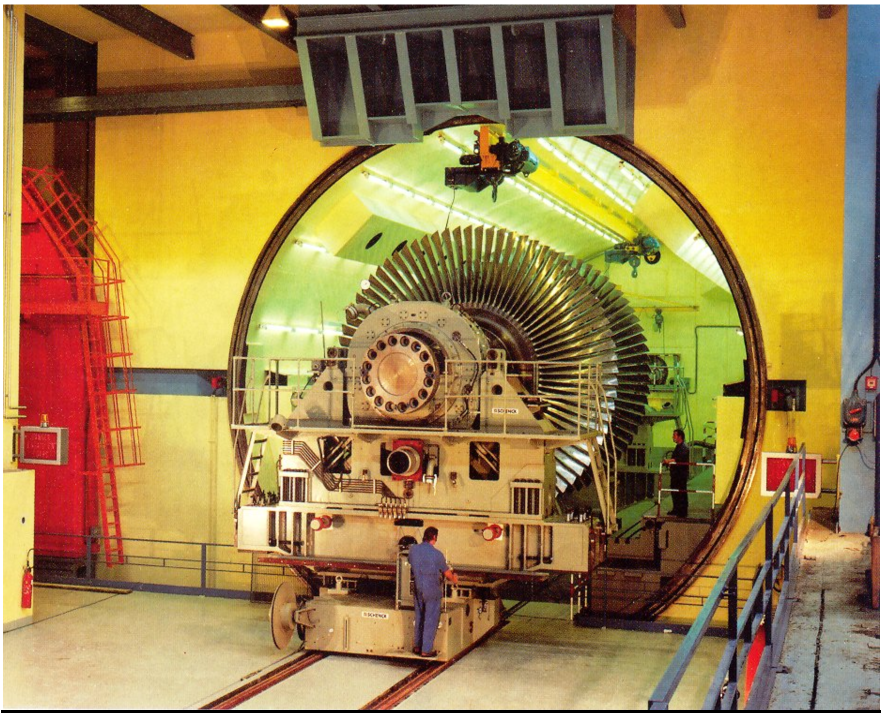
When newly manufactured rotors are first put into service, many undergo some degree of plastic deformation. In most cases, this is only to a small extent that has no significant effect on the overall balance condition. However, some rotors, electrical rotors in particular, can undergo marked changes in mass distribution due to the displacement and "settling" of component parts, such as electrical windings. These rotors fall under **Type 2**.

Machining and final balancing of a "Flexible", 83 tonne Generator Rotor on the suspended floor, alongside the Turbine / Generator Set in a Power Plant

Type 3 rotors include those from most high speed turbines, compressors, pumps and generators.

Those that need special attention when balancing are from large electrical generators which can have the characteristics of all three types of flexible rotors.

Production Balancing of Flexible Rotors



Factory based Overspeed Balancing and Integrity Testing Facility

The balancing of flexible rotors as part of production processes, involves the application of proven specialised procedures that have been developed by manufacturers from experience gained over many years. The main objective is to eliminate all internal bending moments by correcting for any mass eccentricities in the exact transverse planes of unbalance. Where possible, this normally includes balancing each individual component separately, at low balancing speed, as part of building up a complete rotor assembly. The overall integrity of the assembly is then proven by "Overspeed Testing" up to around 120% of the rotor's maximum service speed in a special purpose test facility. Rotors that are subject to undue plastic deformation are also run up to these high speeds, often under controlled conditions of load and temperature, prior to final balancing.

Rotors that cannot be balanced in component form, such as those from large generators, are balanced in stages, at incremental speeds up to and including their maximum service speeds. The procedure includes overspeed, testing and making balance weight corrections in three or more transverse planes to offset any tendency for the rotor to bend when running within the influence of its critical speeds.

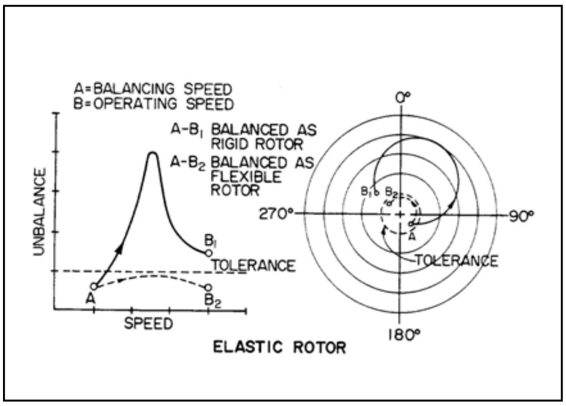
Service Balancing of Flexible Rotors

Although the low speed balancing of flexible rotors using transportable machines is practised with considerable success by many service organisations world wide, it is a compromise because the results can never be guaranteed to produce a perfectly balanced rotor under all conditions of operation. Nevertheless, satisfactory rotor performance is achieved in most cases, by applying a fundamental understanding of rotor dynamics, assessing the cause of any unbalance, and using recognised and well proven balancing techniques.

100 tonne capacity Balancing Machine set up on the Ground floor of a Power Plant for balancing an HP Rotor from a Turbine/Generator Set on the 4th Floor

When considering any particular rotating machine, it can be assumed that, prior to any service and repair exercise, the rotor assembly had been operating under normal conditions of speed, load and temperature, and has therefore stabilised plastically. It should also remain in a stable state unless any major structural modifications are undertaken, which would then need to be considered separately as part of the overall balancing procedure. Not having to contend with undue plastic deformations is a major advantage when service balancing on site. Particular care must therefore be taken towards not introducing any potential problems in this regard as part of any repair work that may be undertaken.

When balancing a flexible rotor at low speed, account must always be taken of the rotor's elastic response characteristics to unbalance forces, as a function of its maximum service speed, and any critical speeds within the speed range. Essentially, this means applying the basic rules for dynamic balancing of rigid rotors, but also eliminating, or minimising the effect of, any internal bending moments by making balance weight corrections in, or as close as possible to, the exact transverse planes of unbalance.



Typical variation of unbalance amount & phase angle of an elastic rotor as it runs up through its first critical speed

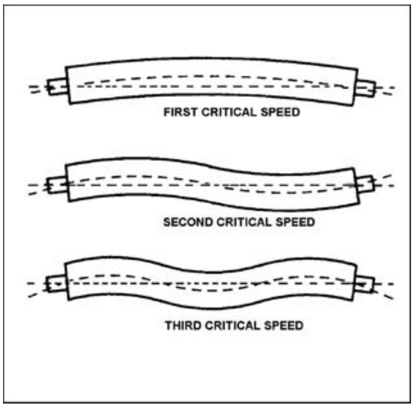
Another big advantage of service balancing over production is that, with a new rotor assembly, the exact causes of unbalance are usually unknown and are normally distributed randomly along the length of the rotor assembly, whereas, with service balancing, the cause is usually obvious and localised. This makes it much easier to decide in which planes to correct for any induced mass eccentricity. The ability to understand what will introduce an unbalance condition and compensating for this as part of the repair work is also very important. An example is ensuring that blades used for re-blading turbine wheels are moment weighed and diametrically matched when being installed.

Even in the unlikely event of the exact cause of unbalance being unknown, or where it may be distributed along the length of the rotor, the amount will be comparatively small, and applying what is known as the "Static / Couple Derivation" balancing technique will usually give very satisfactory results.

Static/Couple Balancing

Most elastic rotors operate above their first critical speeds (flexural modes) and below, but sometimes within the influence of their second critical speeds. Very few excite the third critical, and higher orders are rare.

Because the first and second flexural modes are excited by the "Static" and "Couple" components of the rotor unbalance, respectively, being able to isolate these two components and apply relative corrections at determined positions along the length of the rotor will normally eliminate, or reduce to an acceptable degree, the tendency to deform due to internal bending moments.



Typical flexural modes of a cylindrical rotor

Summary

Significant benefits can be realised by undertaking as much as possible of the maintenance of strategic rotating machines on site, by employing fully transportable maintenance facilities and applying recognised and well proven procedures.

"Soft Bearing" type balancing machines, particularly those with pendulum suspensions and self-aligning support rollers, are best suited as the basis for the design of a truly transportable system to meet all of the requirements of portability, adaptability, low speed sensitivity, versatility, etc.

Contrary to widespread belief, most types of "Flexible" rotors can be balanced on site and at low balancing speeds.

References

Recommended reference material to be used in conjunction with this Paper, and which can be obtained directly from the International Standards Organisation (ISO), should include:-

ISO 1925 : 2001 Mechanical Balancing of Rotating Machinery - Vocabulary

ISO 1940/1 : 2003 Balance Quality Requirements for Rigid Rotors

ISO 5406 : 1980 Mechanical Balancing of Flexible Rotors

ISO 5343 : 1983 Criteria for Evaluating Flexible Rotor Balance

Reference should also be made to the Paper: "**Recent Trends in Balancing Turbomachinery**" presented at the 1993 Symposium on Industrial Applications of Gas Turbines, in Alberta, Canada by Stewart Maxwell P. Eng. Toronto.

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