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New Approach in Steam Turbine Rotor Balancing Procedure

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نهج جديد في إجراء موازنة دوار التوربينات البخارية

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Abstract
Rotor balancing can be performed on a dedicated balancing machine or in-situ (field balancing). Machine balancing allows for precise mass correction, particularly for dynamic unbalance, but neglects field installation factors. Conversely, field balancing, conducted in the rotor's operational environment, accounts for these factors (e.g., bearing clearances, support stiffness), potentially resulting in improved vibration performance. This paper addresses a specialized challenge: balancing steam turbine rotors with low journal surface hardness. A novel method, utilizing a custom-designed detachable ring adapter to protect the journal during machine balancing, was developed. The design, application, measurement, and verification of this method are detailed.

Keywords: Balancing, Steam Turbine Rotor, Detachable Ring Adapter.

الملخص
يمكن إجراء موازنة الدوارات باستخدام آلة موازنة مخصصة أو في الموقع (موازنة ميدانية). تتيح موازنة الآلة تصحيحًا دقيقًا للكتلة، وخاصةً في حالات عدم التوازن الديناميكي، ولكنها تتجاهل عوامل التركيب الميداني. على العكس من ذلك، فإن الموازنة الميدانية، التي تُجرى في بيئة تشغيل الدوار، تأخذ هذه العوامل في الاعتبار (مثل خلوص المحامل وصلابة الدعامة)، مما قد يؤدي إلى تحسين أداء الاهتزاز. تتناول هذه الورقة البحثية تحديًا متخصصًا: موازنة دوارات توربينات بخارية ذات صلابة سطح منخفضة للمحور. طُوِّرت طريقة جديدة، تستخدم محولًا حلقيًا قابلًا للفصل مصممًا خصيصًا لحماية المحور أثناء موازنة الآلة. ويرد تفصيل لتصميم هذه الطريقة وتطبيقها وقياسها والتحقق منها.

الكلمات المفتاحية: الموازنة، دوار التوربينات البخارية، محول حلقة قابل للفصل.

1. Introduction
Steam turbine rotors are mostly designed to run between their first and second critical speed. During the starting procedure, the turbine rotor must pass through its critical speed quickly to avoid building up any vibration. Each turbine rotor has a certain degree of flexibility, and when supported between the bearings, it will bend under its own mass. Also, in operation, it will bend under the influence the imbalance should be kept as low as possible. In this paper, the steam turbine rotor has a low surface hardness at journals of the main shaft.
The original idea, how to overcome the problem of the low surface hardness and support the rotor on a universal balancing machine, is accomplished by the ring adapters. Then, the ring adapters were designed and machined. They should consist of two detachable segments to provide easy mounting. After that, the ring adapters were assembled at both journals of the main shaft rotor. Now the complete mechanical conditions for the balancing were achieved, and it was done on the universal balancing machine. The correction weights were fixed at the required position, got in the measuring sequences.

Finally, the measurement of the vibration severity was taken on the assembled steam turbine machinery.
The start of operation of the complete turbine machinery was successful, according to the low measured vibration.

2. Turbine rotor description

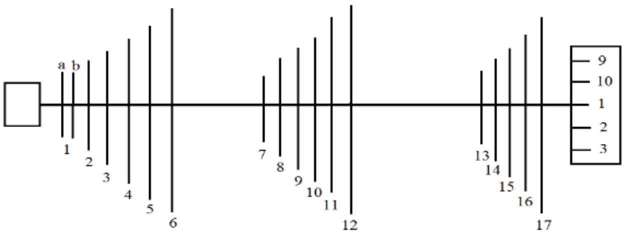


Figure 1 Turbine rotor description.

The turbine rotor, as shown in Figure 1, contains 17 stages (disks), each disk carrying blades. From stage 1 up to 5, the blades are fixed on the disk with the peripheral rim; in stages 16 & 17, every 10 blades are fixed together by a rod as shown in figure 2.

Figure 2 Blades of end stage.

Misalignment of rotating parts in a turbine can be dangerous, because of their characteristically close clearance. While blades and nozzle are in close proximity to each other, the critical clearance occurs between moving and stationary strips in the seals and sealing strips at blade tips and on dummies. The thin edges of these strips wear down quickly if accidental contact should have been made, at the expense of enlarging the leakage area. The turbine is anchored to the foundation at the exhaust end and allowed to expand towards the inlet end as heat up. This arrangement keeps the coupling to the generator in a fixed location. The front end of the turbine slides on a plate as the unit expands and contracts. The turbine vibration, if a rotor is perfectly uniform in its weight distribution about the center line of the shaft, it can rotate at any speed up to its strength limit without vibration, provided it remains perfectly stiff. But all turbine rotors have a certain degree of flexibility and, when supported between the bearings, they will bend under their own weight. Every flexible structure natural frequency of vibration. This vibration will be set in motion by applying a force that varies at the same frequency. It is difficult to achieve perfect balance, with the same unbalanced weight may be left in a rotor even after adjustment with balancing weight. This unbalanced weight may act as the force that may set a shaft vibrating at its natural frequency when it is spinning. This unbalanced force pulls the shaft and structure out of alignment and prevents it from truing about its true center. This force must be withstood by bearings, which will be vibrated by the continuously changing direction of the unbalance force. Such an unbalanced force becomes dangerous when the speed of rotation causes this force to pass a given point in the bearing at the same frequency as the natural frequency of vibration of the rotor. This speed is known as the critical speed. This speed, if it is maintained for any length of time, causes the rotor to vibrate violently and it may eventually wreck the rotor. There is a second critical speed and also third occurs at the higher speed, and so on.

3. Definition of the balancing quality

The item rotor is considered an arbitrary object that rotates around its geometric axis. Regardless of the purpose, all rotating elements with operating speeds above 500 RPM should undergo balancing. That fact comes from bearing protection against the dynamic forces.

The basic classification of rigid rotors is:

Disk type rotor (A), and cylindrical ones (B), as shown in figure 3.

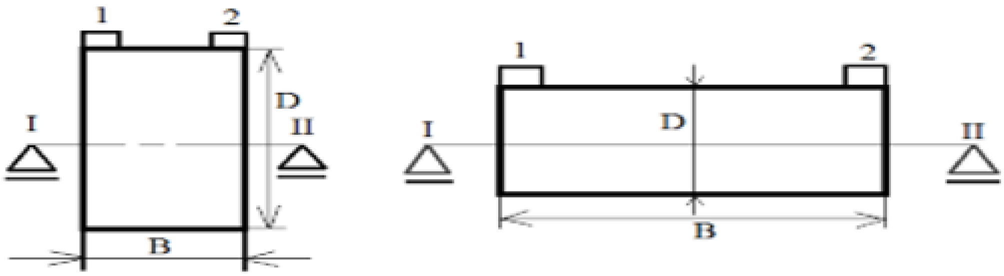


Figure 3 Classification of rigid rotors.

1-2 correction planes.

I-II measuring planes.

The rotor having the width (B) and diameter (D) relating B / D ≤ 0.3, are so called "STATIC" rotors and can be treated as disk rotors in balancing procedure (single correction plane). Values of B / D ≥ above 0.3 indicate a "DYNAMIC" nature of the rotor, and according to that, they must be treated as cylindrical rotors (couple or more correction plane).

The imbalance is a phenomenon when extending from the geometric axis. There is the rotor of mass M: mass rotating with angular speed ω figure 4.

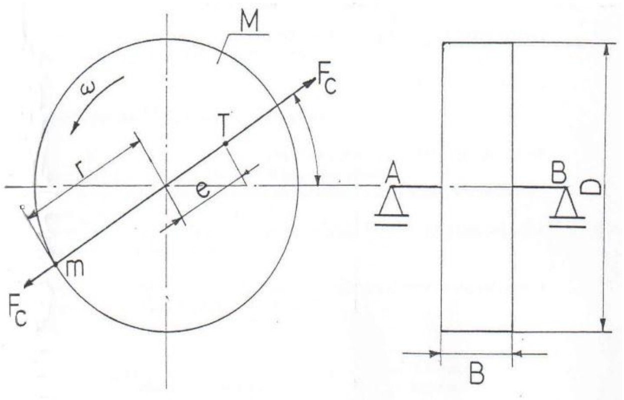


Figure 4 balancement of forces.

The rotor center of gravity is displaced from the geometric axis O, for the eccentricity "e". Rotation of the object at angular speed ω, causes the centrifugal force F_c= M.e. ω^2 (N), in the center of gravity figure 4. This force decomposes on A and B, components acting on the bearings.

Analytical presentation of the imbalacement is:

$$U= e.M \text{ (grmm)}$$

Balancing of disk rotors involves determining of two variables:

$$M; \alpha$$

i.e., the amount of the correction weights m and its angular position α.

The dynamic balancing is related to some more variable definitions, which are:

$$m_1, \alpha_1 \text{ and } m_2, \alpha_2$$

i.e., the correction mass and its position in the first (LEFT) and in the second (RIGHT) correction plane. That is the case with the rotor of the steam turbine.

The balancing tolerance, defined by the permitted remaining imbalancement (P.R.I), is being calculated from the ISO Standard 1940. The permitted residual imbalancement is denoted by the following units:

$$\varepsilon_{perm}\ in\ \left[\frac{g\ r\ m}{kg}\right]\ i.e.\ \varepsilon_{perm}\ in\ [\mu m]$$

And its application will provide more efficient balancing process, as the remaining imbalancement should not be to the extreme limits.

Balance quality of rotating rigid bodies.

Generally, for rigid rotors with two correction planes, one-half of the recommended residual unbalance is to be taken on each plane.

These values could be applied for any two arbitrarily chosen planes, but usually the closet planes to the bearing are selected.

The rotor of the steam turbine is classified into G2.5 quality group (gas and steam turbines, including marine main turbines).

For the specified speed n= 3000 RPM, and quality G2.5 cross point on the diagram is ε = 8 (gr.mm/kg) as shown in the figure 5.

The permitted specific remained imbalacement (n = 300 RPM, G2.5) per correction plane is:

$$\varepsilon_I = \varepsilon_{II} = \varepsilon/2 = 8/2 = 4\ (grmm/kg)$$

As the mass of the rotor is 6000 kg, the permitted remained imbalancement per correction plane is:

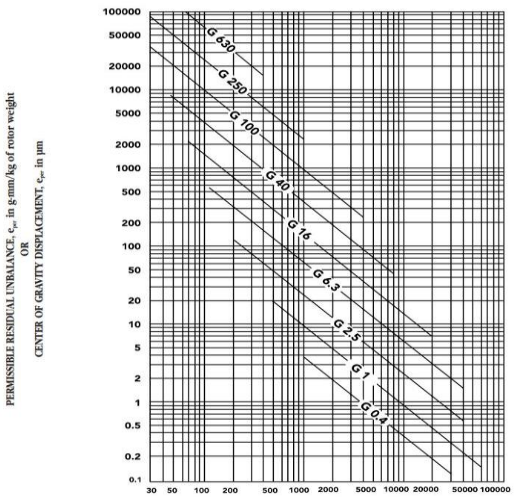
$$U_{Iperm} = U_{IIperm} = \frac{\varepsilon}{2} \times m = \frac{4grmm}{kg} \times 6000kg = 24000grmm$$

For the first correction plane, the residual correction mass is:

$$M_{I\ corr} = \frac{V_{I\ perm}}{r_1} = \frac{24000}{440} = 54.5(gr)$$

For the second correction plane, the residual correction mass is:

$$M_{II\ corr} = \frac{V_{II\ perm}}{r_2} = \frac{24000}{420} = 57.1(gr)$$



Maximum service speed in RPM

Figure 5 Maximum permissible residual unbalance, ε_{perm} (From ISO 1940).

4 Concept of balancing ring adapter

The idea of steam turbine rotor balancing on a universal balancing machine because of the low surface hardness of journals forced the application of special protection rings.

The polished, detachable rings are mounted on the journals of the main shaft and their role are to prevent the structure of the surface during rotation. The two ring adapters were mounted on the rotor shaft at the left end (1), and the right end (2), as shown in figure 6.

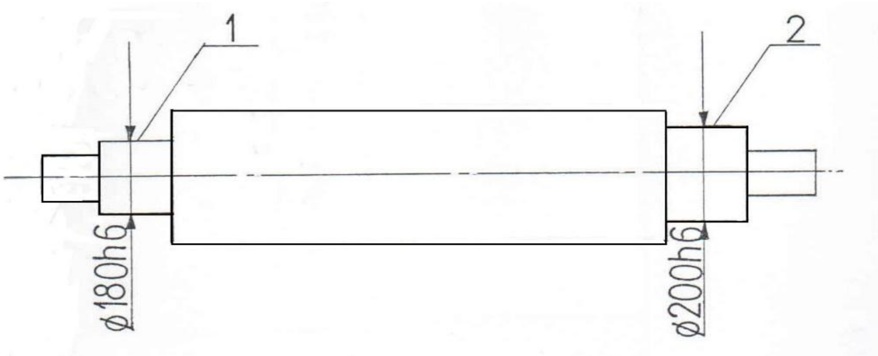


Figure 6 Main rotor shaft.

The design of ring adapter should be very accurate in the shape and dimension. That means surface finish should be very high, tolerance between the shaft and ring adapter very close to get exact results during the balancing.

4.1 Explanation of the idea of ring adapter

1- It must be detachable to be fixed on inaccessible diameter.
2- It must be of a certain width to reduce surface load.
3- Detachable segments must be, each time, ideally positioned one to another.
According to these facts, a ring adapter was designed.

4.2 Description of the ring adapter

The ring adapter consists of two detachable segments. The diameter of the adapter ring number 1, $d = \emptyset 180\ h6$ which the same diameter of the journal, the ring contains 8 holes, 4 holes for pin and another 4 holes for screws fix the ring together. The dimensions of ring number 1 are shown in Figure 7.

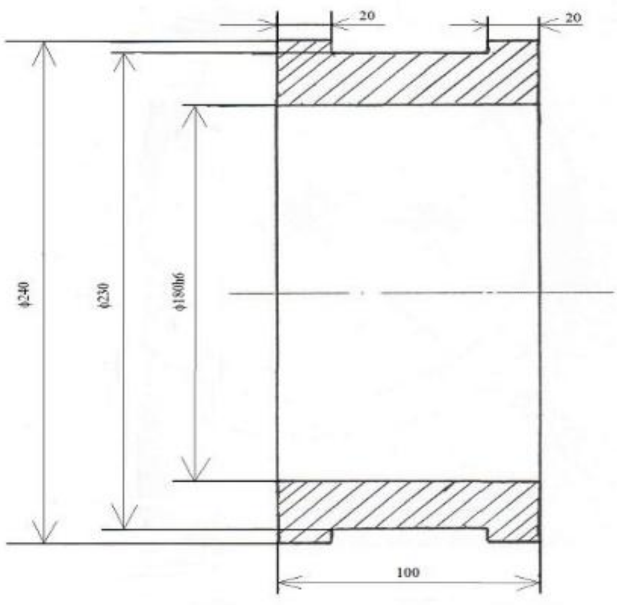


Figure 7 Ring adapter 1

The steps to design the ring adapter number 1
a- The initial inside diameter of the ring $d = \emptyset 165\ mm$ and outside diameter $D = 240\ mm$ as shown in figure 8.

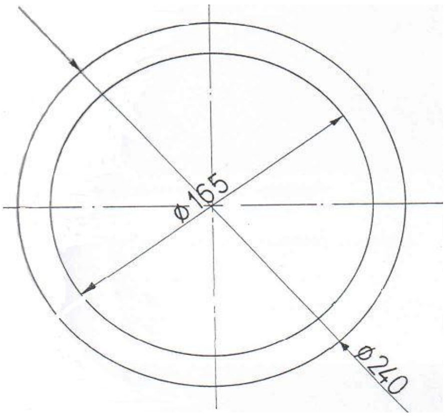


Figure 8 Ring adapter pre-machined dimension.

b- Cut the ring into two parts (detachable ring). As shown in Figure 9.

Figure 9 Detachable ring adapter.

c- Drilling, 4 holes for screws and 4 holes for pin as shown in figure 10.

Figure 10 Ring adapter.

d- Grinding the inside diameter to the final diameter $d = \emptyset 185\ h6$.
Finally, we assembly the adapter ring together on the rotor shaft (1) left end by fix 4 pins then 4 screws. The design of the second adapter ring (2) the same procedure of the first adapter (1), but only two different points the initial inside diameter $d = \emptyset 185 mm$ then in the final step (grinding) $d = \emptyset 200\ h6$ and the outside diameter $d = \emptyset 240 mm$ as shown in figure 11.

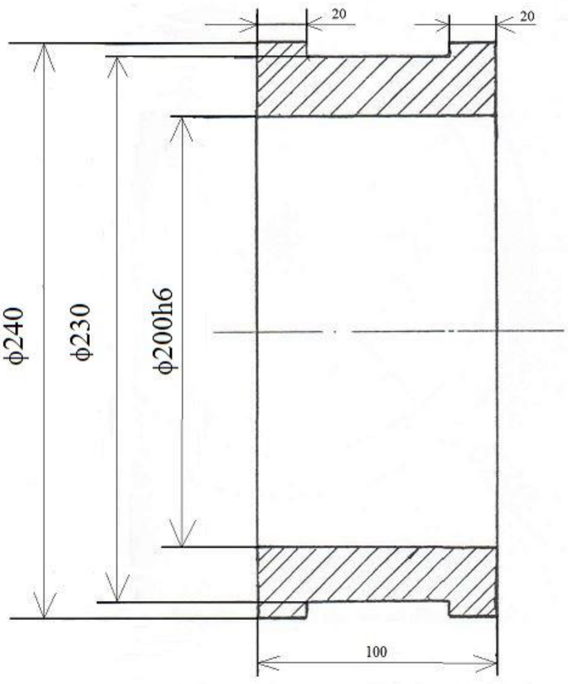


Figure 11 Ring adapter 2

Finally, we assembly the adapter ring on the rotor shaft at the right-side end (2) by fixing the 4 pins then the 4 screws.
Now the two adapter rings are mounted on the rotor shaft. After that to make the measurement on the universal balancing machine.

5 Results & measurement

Universal balancing machine HBM-10000 is equipped with the driving unit that covers some range of operational speeds.
Balancing is usually conducted on the balancing machine at the appropriate speed. Rotor with high value of imbalancement should be balanced at low rotational speed. During balancing rotor rotational speed must not vary more than ±5%. The range of operation speed on the balancing machine is from 50-40 RPM.
The initial run of the rotor on the universal machine should start at the 150RPM. During first initial run the smoothness of rotation is tested and the stability of the complete mechanical system. Then the second run was 200 RPM after that 250 RPM, finally 300 RPM. When the stability of measurement results is achieved that means the mechanical condition of rotation provided.
After that we start to repeat to take the measurement again for the trial correction weight. When the measuring electronics is preprogrammed, and the rotor is brought to the desired speed (280 RPM) the measurement can be started by pressing the key start. It takes 2-3 Sec to complete the results and the left and right planes imbalancement is displayed. After that we fix the trial weight in two planes and we start again to take results for the and right planes, the unbalance in the left plane stage 1 was 230 gr, at a radius of correction r_1= 440mm, and in the field of angle 2 (as shown in fig 1), the unbalance in the right plane stage 17 was 40 gr at a radius of correction r_2= 420mm in the field of angle 2.
In general, mass correction is a convergent demanding a few, iteration. That means the measurement and correction should be repeated as many times until the balancement quality is reached. The type of the trial weight, which can be used is a specially produced weight or small plate. Usually it is welded, or grinned, if necessary, but in this case of steam turbine rotor we used specially produced weight, which is fixed on the radius of correction on stage 1 and stage 17 in the prepared circumference groove as shown in figure 12.

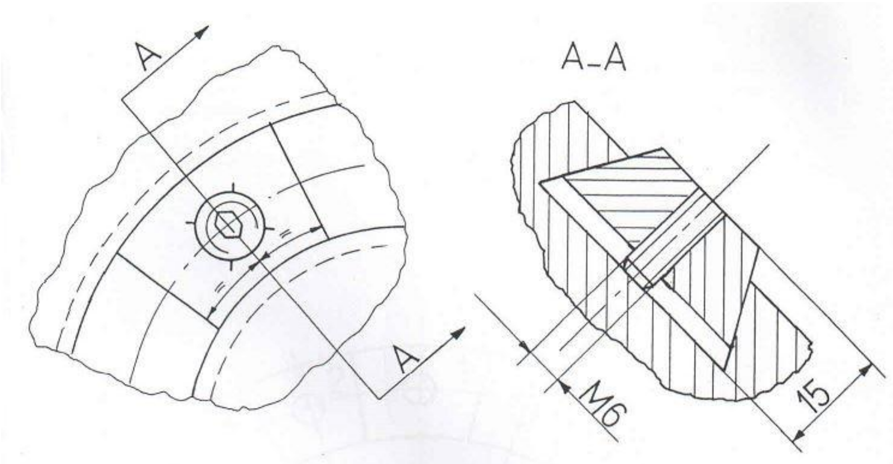


Figure 12 Form of the correction weight.

The correction weight at the left plane stage 1 was 230gr, we divided the 230gr in segment each segment has ≅ 20gr weight, this segment should be fixed on the groove circumference radius r_1= 440mm, as shown in figure 13.

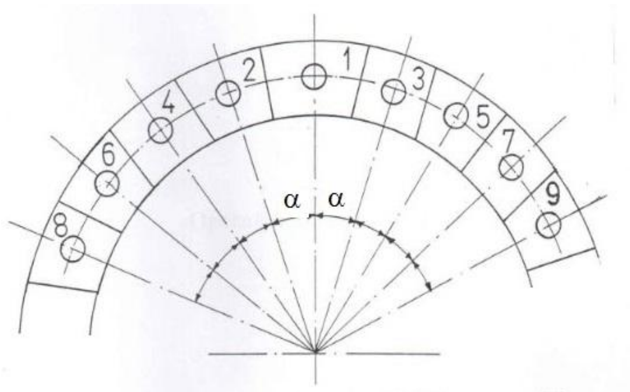


Figure 13 Series of correction weights.

The groove circumference = 2.π.r_1= 2.π.440= 2765mm
Groove circumference = 2765mm
The angle divergence for each next weight α

$$\alpha = \frac{weight\ width}{groove\ circumference}$$

$$\alpha = \frac{20}{2765} \times 360 = 2.6^{\circ} \cong 3^{\circ}$$

Table 1 The angle of divergence for each weight.

Angle	Weight (gr)	Effect (cosα)
0^0	1	1.00
3^0	2,3	0.999
6^0	4,5	0.994
9^0	6,7	0.987
12^0	8,9	0.978
15^0	10,11	0.965

That means the effect is very small between each weight.
The correction weight at the right plane stage 17 was 40gr in two segments, each segment ≅ 20gr. This segment should fix on the groove circumference at radius r_2= 420mm
The groove circumference = 2.π.r_2= 2.π.420 = 2639mm.

6 Operational verifications

The operational verification for the steam turbine rotor started with removing the casing. First, it was cheek the turbine rotor geometry (blades, shaft, and disks). After that we mounted the steam turbine rotor into the casing.

The operational speed test should start at approximately 10% - 20% of the actual speed (3000RPM). Start the test by increasing the steam inlet in the rotor gradually from the control valve, at the same moment rotor passes the critical speed, which will have a high vibration velocity. Then after that the rotor run in the actual rotational speed normal state (3000RPM).

In final will prepare for the vibration measurement. The vibration measurement will measure by using VIBROBALANCE. Vibrobalance is a device for vibration level measuring, frequency analysis. It is a portable multipurpose device, update conceived and assigned for a purpose of solving vibration problems in all industrial conditions and laboratories too. Vibrobalance wide spectrum of measuring possibilities makes it applicable in temporary repaired plants, servicing and production of rotary machines.

$V_{eff}\left(\frac{mm}{s}\right)$ - Effective speed of vibration

A (μm) – vibration amplitude

But for this case steam turbine rotor we use V_{eff}

6.1 Effective speed measurement

According to VDI 2056, DIN 45665 and 45666 and ISO 2372, 2373 and 2954, effective speed are used to show the state of the system from the viewpoint of vibration V_{eff} (mm/s).

During V_{eff} measurement, using VIBROBALANCE, one should pay attention to the following:

- The measuring point should be chosen on the bearing casing as near as possible to it.
- The measuring direction should be chosen according to the greatest expectable vibration.

6.2 Table for the measurement collection

The measurement should be taken in the turbine rotor at four points (1, 2, 3, and 4), as shown in figure 14.

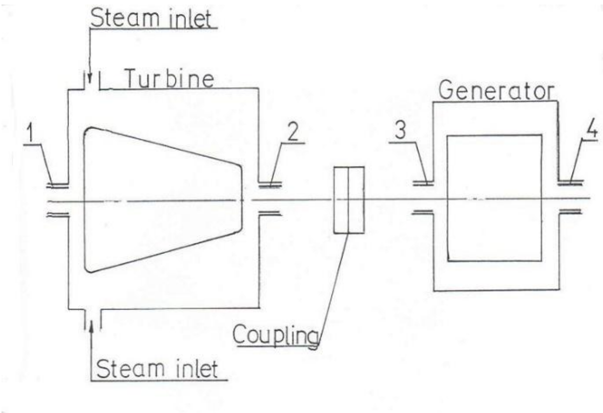


Figure 14 Steam turbine description.

The velocity transducer should be placed on the bearing casing and connected to the Vibrobalance device. After that we started to make the measurement, the measurement taken at vertical, then horizontal, final at axial, table (2) shown the measurement collection. The measurement taken for vibration velocity V_{eff} (mm/s).

Table 2 Measurement collection (N = 3000RPM).

	Measurements points			
Position	1	2	3	4
V	2.2	2	2.1	0.86
H	1.4	2.7	2.1	1.5
A	2.4	1.8	2.25	0.75

After realizing the measurements. Vibration data formed as effective speed were obtained. Based on VDI 2056, i.e. ISO 2372. The state of a rotating object generally can be estimated as “good”, “usable”, and “unhallowed”.
Previously, a steam turbine rotor was classified G class (larger machines with rotating masses mounting on rigid and heavy foundation) as shown in figure 15. The limit-line, which divides “good” and “usable” area on the diagram of the class G is V_{eff} = 1.8 mm/s. The limit-line between “usable” and “allowed” is 4.5 mm/s.
Obviously, the measured value is a little bit over the limit between “good” and “usable”.

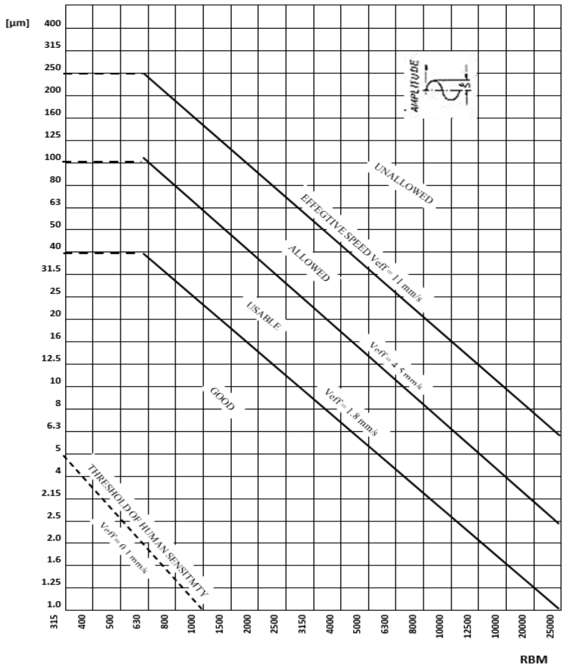


Figure 15 Machine class G recommendation VDI 2056

Conclusion

The idea implementation of ring adapter’s huge steam turbine rotor balancing provided the realization of the standard procedure on the universal balancing machine with rolling elements.
The main problem was to design, detachable ring adapters with adequate centric shape and appropriate dimension, and also to machine them. The centricity of ring adapter approved on the balancing machine with dial indicator. The accuracy of measurements in the balancing procedure was appropriate, and the recommended balancing quality (According to ISO 1940) was achieved.
Finally, the successful start, and operation of the turbine machinery, and its low level of vibration verified the applied innovative methodology of balancing the huge rotors on the universal balancing machine.

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