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Causes of Rotor Distortions and Applicable Common Straightening Methods for Turbine Rotors and Shafts

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Abstract**—**Different problems may causes distortion of the rotor, and hence vibration, which is the most severe damage of the turbine rotors. In many years different techniques have been developed for the straightening of bent rotors. The method for straightening can be selected according to initial information from preliminary inspections and tests such as nondestructive tests, chemical analysis, run out tests and also a knowledge of the shaft material. This article covers the various causes of excessive bends and then some applicable common straightening methods are reviewed. Finally, hot spotting is opted for a particular bent rotor. A 325 MW steam turbine rotor is modeled and finite element analyses are arranged to investigate this straightening process. Results of experimental data show that performing the exact hot spot straightening process reduced the bending of the rotor significantly.

Key words**—**Distortion, FEM, Hot Spot Area, Rotor Straightening

I.INTRODUCTION

A large turbine rotor must run with low vibration levels during operation and when going through critical speeds. Rotors must be straight and true within a tight tolerance, typically, 0.0005 (half a mil) per foot length of span. For most HIP rotors, the Total Indicated Run out (TIR) should not exceed 0.007 (7 mils) [1]. Although all turbomachinery operators are aware of the potential dangers, turbine rotor bends are still a fairly common occurrence, even in the hands of highly skilled operators [2].

All incidents of rotor bends need to be investigated in depth, in order to establish the main cause to reduce or eliminate the possibility of a reoccurrence. Permanent turbine rotor distortion or bends may be caused by a number of factors, either simply and in combination. Permanent deformation of rotor due to rubbing is essentially affected by the loss of clearance between rotary and stationary turbine parts, and this is one of the most commonly encountered causes [2].

Through the years, different techniques such as cold mechanical, thermo mechanical, heating and cooling, Machining, Peening, Welding and Hot spotting, have been developed for the straightening of bent members by the precise application of heat, hammer blows, or transverse force, singularly or in combination [5].

Successful straightening of bent rotor shafts that are permanently warped has been practiced for the past 50 or more years, the success generally depending on the character of the stresses that caused the shaft to bend [3] [4].

In general, if the stresses causing the bend are caused from improper forging, rolling, heat treating, thermal stress relieving, and/or machining operations, then the straightening will usually be temporary in character and generally unsuccessful. If, however, a bent shaft results from stresses set up by a heavy rub in operation, by unequal surface stresses set up by heavy shrink fits on the shaft, by stresses set up by misalignment, or by stresses set up by improper handling, then the straightening will generally have a good chance of permanent success [3]–[4].

Before attempting to straighten a shaft, determination of how the bend was produced is necessary. If the bend was produced by an inherent stress, relieved during the machining operation, during heat proofing, on the first application of heat during the initial startup, or by vibration during shipment, then straightening should only be attempted as an emergency measure, with the chances of success doubtful [3]–[4].

The first thing to do, therefore, is to carefully indicate the shaft and the bend or bends to determine exactly where they occur and their magnitude. With this information, plus a knowledge of the shaft material available, the method for straightening can be selected [3]–[4].

II.CAUSES OF DISTORTION

Residual bent in shafts are prepared due to the different thermal and mechanical elements. Rapidly forming permanent rotor bent are invariably caused by thermal shock or rubbing due to lack of clearance between rotary and stationary parts, whereas slowly forming rotor bents are less common and are usually caused by either progressive cracking or metallurgical inhomogenity [2]–[6].

A. Rubbing

The imbalance of rotor causes variation at running speed, increasing as a function of speed and reaching a peak near to the rotor critical speed. Turbines are usually taken through their critical speeds as possible to avoid rubbing. If sufficient clearance is lost, rubbing will take place at the highspot, initially over a small arc. Local heating in this area causes

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localized thermal expansion and the resultant rotor bend increases the pressure and extent of rubbing in a progressive and unstable manner (Fig. 1).The local thermal expansion is restricted by the cooler bulk of the rotor and an axial compressive stress is thereby set up in the area of the rub. At the same time the local friction lead to reduce the local yield stress by temperature increase, and compressive yielding eventually takes place. Local softening or hardening of rotor body is occurs. The rubbed zone is now permanently displaced leading to a reversed bend when the rotor finally cools to a uniform temperature.

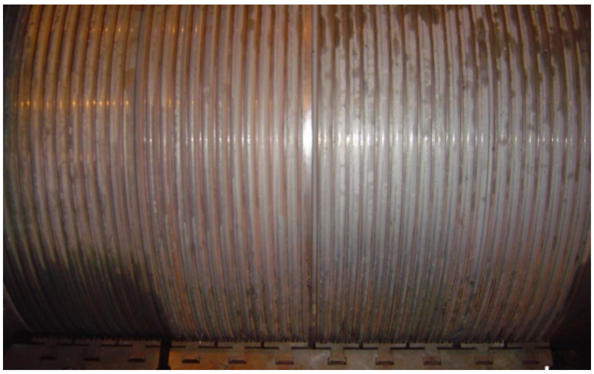

Fig. 1 Effects of rubbing on rotor surface

B. *Cracking*

Transverse cracking in rotors can be initiated at surface stress concentrations by corrosion, pitting, thermal fatigue (starts related), or by high cycle fatigue due to self weight rotating bending stresses (Fig. 2). Transverse crack propagation is eventually driven by the bending stresses and this phase can take place over time scales in years. Because they do not directly affect the balance of a rotor, such cracks will not have much effect on normal vibration levels until they occupy a significant portion of the rotor cross section (e.g. 25%). Large cracks can have a sufficient effect in changing the compliance (transverse stiffness) of a rotor that clearances are lost and then rubbing, followed by the bending mechanisms described above takes place.

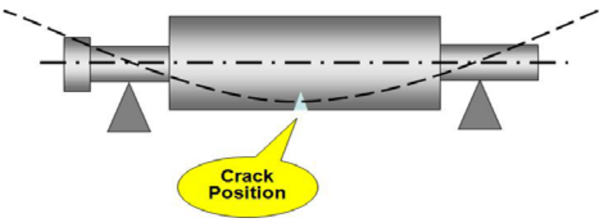

Fig. 2 Schematic of bending due to cracking

C. *Metallurgical or Thermal Inhomogenity*

Only high temperature rotors suffer from this behavior, because it is due to differential axial creep strains that develop during operation. Its occurrence is highly dependent on the design of rotor and the degree of inhomogenity [7].During steady running, and more particularly during start up, a temperature gradient exists across the radius of a rotor. For a plane cylinder this causes compressive axial stress on the surface, and if they are sufficiently large, they can cause the axial creep strain, in the softer region to be significantly larger than in the harder region. If the hardness level is distributed, a bend can slowly develop with time. Such bends usually manifest themselves by uniformly increasing vibration levels. Top to bottom severe variations in heat transfer along the rotor can also cause bending.

D. *Loss of Clearance*

There are many reasons for the loss of clearance between rotary and stationary turbine parts. Some of the major reasons include:

1) Incorrect relative movement between rotor and casing which can occur due to wear or excessive friction at sliding surface, bearing damage and alignment errors.
2) Rotor distortion that occurs due to the mechanisms described above and by excessive imbalance.
3) Casing distortion that can be caused by out of uniform and convective flow, inadequate drainage, not in uniform insulation or water ingress. It can also be caused by leakage in externally mounted valves or internal steam paths, and excessive external loads due to poor support of connecting pipework and other components.

III.ROTOR AND SHAFT STRAIGHTENING METHODS

The aim of straightening is to re-establish the balance of the stresses in the rotor/shaft, by exposing it purposefully to tensile and compressive stresses [8]. Before selecting an effective straightening method, it is necessary to do some tests and typical evaluations on the rotor to determine exact metallurgical, mechanical and thermal specifications of the rotor material and also to detect the exact position of bending and its causes. In addition, nondestructive tests should be done to study the variations of hardness in the critical area of the rotor.

Different common methods to straighten bent rotors and shafts that are used either singly or in combination consist:

1) Cold mechanical straightening
2) Thermo mechanical straightening
3) Heating and cooling straightening
4) Straightening by machining
5) Straightening by peening
6) Straightening by welding
7) Hot spot straightening

A. *Cold mechanical straightening*

This method is usually used for rather small diameter shafts. Since cold mechanical straightening is to be performed only at normal temperature, the stresses imposed by this process can be dangerously high, particularly when shaft materials are of high yield strength. Hence heating method is normally preferred to cold mechanical method [9].In this method the shaft is to be set up between two adjustable supports (i.e. a lathe) such that the point of maximum eccentricity is the highest point. A hydraulic jack is to be positioned immediately above that point (Fig. 3) and a dial gauge in contact with the shaft surface immediately below. A load is to be carefully applied by the jack at the shaft surface, and it is to be increased very slowly and smoothly and the deflection is to be measured by suitably located indicators [9].

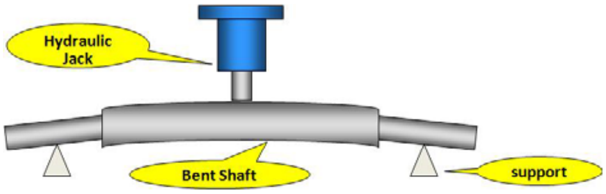

Fig. 3 Schematic of cold mechanical straightening

B. Thermo mechanical straightening

This is a very operative and rather safe method which is applied to modify the severe bent happened to the large rotors. At the first stage of the procedure, maximum bending area is to be heated using inductive method while the rotor has been fixed between two suitable supports, then applying a transverse mechanical load by means of a hydraulic jack (Fig. 4), is caused to occur a plastic deformation in heated portion which is needed to reverse the deflection.

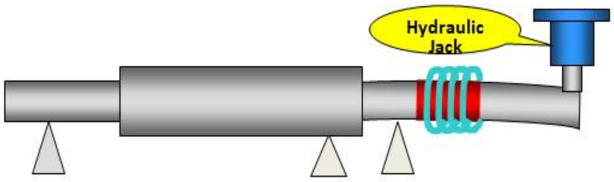

Fig. 4 Schematic of thermo mechanical straightening

C. Heating and cooling straightening

This is especially applicable to large shafts, which cannot be supported so as to get appreciable compressive stresses at the point of the bend, and it is best used for straightening shaft ends beyond the journals or for large vertical shafts that are bent anywhere. The action is that the shaft side having the long fibers is artificially contracted by the application of cold (dry ice) on the convex side, that sets up a tensile stress in the fibers on the opposite side, therewith the shaft is bent in the opposite direction from the initial bend, about twice the amount of the initial bend, and then quickly heating the small spot on the concave side of the bend by an oxyacetylene torch which sets up compressive stresses in this side that balance the compressive stresses in the opposite side [3].

D. Straightening by machining

If the rotor design and type of bend permits, machining by turning with false centers can be an effective method. In this general machining methodology, the possibility of completely removing a section of a bent rotor and replacing it with a welded-on new forging should be considered. This has been a sound option in some instances, particularly if the rotor was of a welded design to begin with, or where the bend was in a geometrically simple location, such as a coupling shaft.

As the machining partially relieves local residual stresses, rotors can distort in an unpredictable fashion during the machining operation, and it is necessary to continuously clock along the length of the rotor to monitor its response. Clearly, if the bend is in a bladed area this method is unlikely to be possible [2].

E. Straightening by peening

For medium carbon steel shafts (carbon 0.3% to 0.5%) this method is generally most satisfactory where shafts of small diameters (diameters of 100 mm or less) are concerned. It is also preferred method of straightening shafts that are bent at the point where the shaft section is abruptly changed at fillets, ends of keyways, etc.This method consists of peening the concave side of the bend at the bend, By using a round end tool ground to about the same radius as the fillet and a machinist’s hammer. Peening results in cold working of the metal, elongating the fibers surrounding the spot peened, and setting up compression stresses that balance stresses in the opposite side of the shaft, thereby straightening the shaft [3].The peening method also is the preferred method of straightening shafts bent by heavy shrink stresses that sometimes occur when shrinking turbine discs on the shaft. Peening the shaft with a light peening hammer near the disc will often stress-relieve the shrink stresses causing the bend without setting up balance stresses [4].

F. Welding straightening

Welding has a same process of hot spot straightening method which is described following in detail, but in this method, thermal energy is transformed to the rotor by wire electrodes instead of oxyacetylene torch in hot spotting, and excavation for welding straightening is to be ground out in a boat-shaped depression with 15° min slopes leading in and out and in cross section. The minimum length is to be 75 mm [9]. Local phase transformation of the material composition during welding which has undesirable effects straightening, make an extremely sensitive method that is rather difficult to control.

G. Hot spot straightening

This method is generally the most satisfactory with large-diameter shafts (112.5mm or more). It is also the preferred method of straightening shafts where the bend occurs in a constant diameter portion of the shaft (i.e. between discs) [3].Hot spotting is one of the most complex but successful of available straightening methods. The practitioners of this method have traditionally been very secretive about their black art, so it is worth while explaining the underlying mechanisms and the possible variations in some details [10]. It basically involves rapid heating the extrados of the bend with a suitable torch, consequently local plastic deformations (compressive stresses) is produced, and then cooling down the material and producing tensile stresses which contribute to the internal compensation of stresses [11]. To reach an effective straightening, the related practitioner must pay close attention to the following parameters such as local metal temperature, hot spotting time, the position of maximum distortion, cooling

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media and the correct control of restraint.In order to achieve a desired straightening effect, the local material temperature must exceed 600°C and will usually require a temperature of 700±10°C (cherry red). Metal temperatures are checked using a thermo graphic camera in the best condition [12].The action of heat applied to straighten shafts is that the fibers surrounding the heated spot are placed in compression by the weight of the rotor, the compression due to the expansion of the material diagonally opposite, and the resistance of the other fibers in the shaft. As the metal is heated, its compressive strength decreases so that ultimately the metal in the heated spot is given a permanent compression set. This makes the fibers on this side shorter and by tension they counterbalance tension stresses on the opposite side of the shaft, thereby straightening it [3].It is necessary for the hot spotting temperature to not exceeding 750°C because in that condition, local transformation to austenite will be occurred, and also upon heat removal, the cooling action of the surrounding cool material locally transforms this zone to martensite [12]. This structure has two severe effects. First, the phase transformation to martensite, produces a volume dilation increase which counteracts the desire crushing effect produced by the combination of thermal expansion and yield point decrease. The provided local residual stress pattern is complex as it is formed by the combine effects of these two actions. Second, transformation to martensite causes hardening, and in normal 1CrMoV, HIP rotor steels, it has a very notch-brittle microstructure. Such hot spots have been known to crack either during transformation or subsequent service [13].Previous investigators have indicated that the residual stress and the hardness distribution are occurred by reheating the same area and/or overlapping hotspots which causes cracks. Thus it is very important to be ensured that hotspots remain discrete and not to be overlapped. It is of course, not possible to rehotspot in the same place if a bend develops on the some future occasion [2].After finishing the procedure and machining the detective area, a non-destructive examination is to be ensured that there is no defect, and measured eccentricity is not outside of the standard limit.

IV.SIMULATION OF HOT SPOTTING

In April 2006, a 325 MW steam turbine rotor failed during its normal operation, after about 30000 hours being in service. In fact, this failure was local bends at stages 3 & 4 due to an unexpected contact between rotary and stationary parts. After providing the initial information, the hot spot straightening method was opted according to available facilities.

Simulation and stress analysis of hot spotting process was done in order to achieve optimum conditions of heating and determine the exact location and geometric size of hot spotting area.The 3D HIP steam turbine rotor was modeled and meshed to carry out finite element simulation by using ABAQUS software. Meshing also was refined in critical areas around hot spot zone, to ensure coverage for satisfactory resolution. The boundary conditions were applied to simulate the real experiment condition. The different sizes of hot spot area were modeled with different heat fluxes, in order to simulate various models. Thermal expansion coefficient and poisson's ratio were modeled as shown in Fig. 5 Also other parameters such as thermal conductivity, specific heat, mass density and elastic modules were defined considering rotor material properties at different temperatures. Initial temperature assumed as a uniform temperature of 21°C.

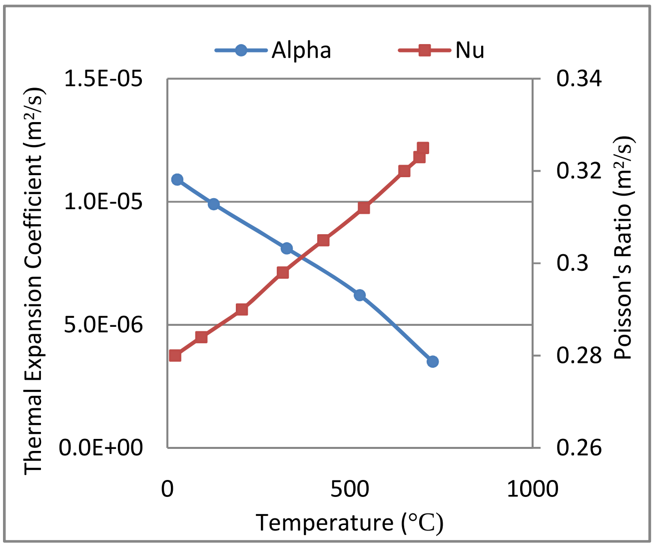

Fig. 5 Nonlinear material properties of the rotor

We considered the temperature of 700±10°C for the hot spot area conservatively, to prevent from the occurrence of martensite transformation.

V.DISCUSSION AND RESULTS

Simulation of hot spotting with three different hot spot areas and heat fluxes was done. The graph of thermal distribution along axial direction of rotor (Fig. 6) shows that the case (C) with the smallest hot spot area has the most thermal gradient between the hot spot area and its surrounding area which is ideal in straightening process but the amount of hot area (cherry red area) is too small to cause required bend. Also it shows that case (A) with the largest hot spot area has the least thermal gradient.The contour of plastic strain magnitude during hot spotting process for three aforementioned cases in Fig. 7 demonstrates that amount of plastic strain in case (A) is not enough to achieve required straightness. In contrast, magnitude of plastic strain in case (C) is the most rather than other cases which may cause some undesirable effects such as thermal shock and phase transformation of the rotor material. Therefore it is resulted that case (B) would cause the most satisfactory straightening effects.

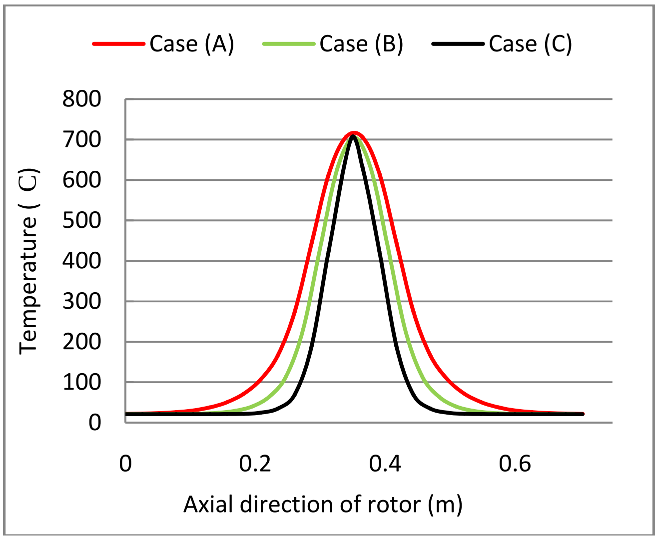

Fig. 6 Thermal distribution along axial direction of rotor

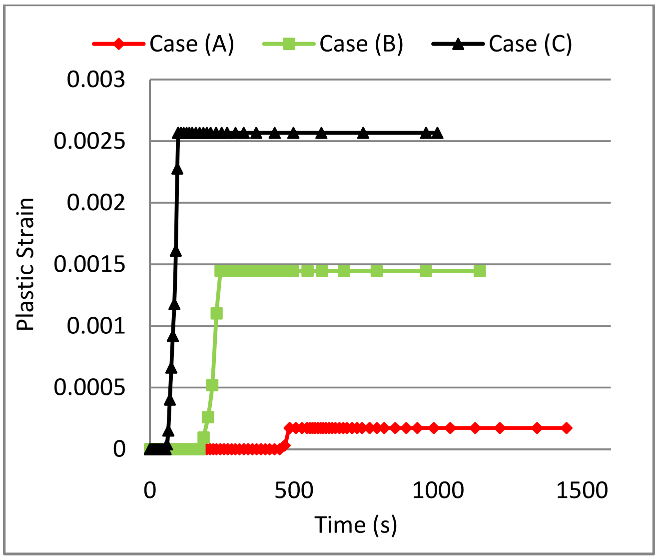

Fig. 7 Magnitude of plastic strain during hot spotting

Another simulation was done to investigate the effects of extra heating. Fig. 8 makes a comparison between the size of plastic area at two different temperatures of 705°C and 750°C. It illustrates that extra heating would significantly cause to develop the location of maximum plastic strain along the perimeter of the rotor. Yielding of the material through this large plastic area would contain extra energy to increase distortion of the rotor with no control. On the other hand, according to previous investigations exceeding permutation temperature will cause undesirable sequels on the material structure.

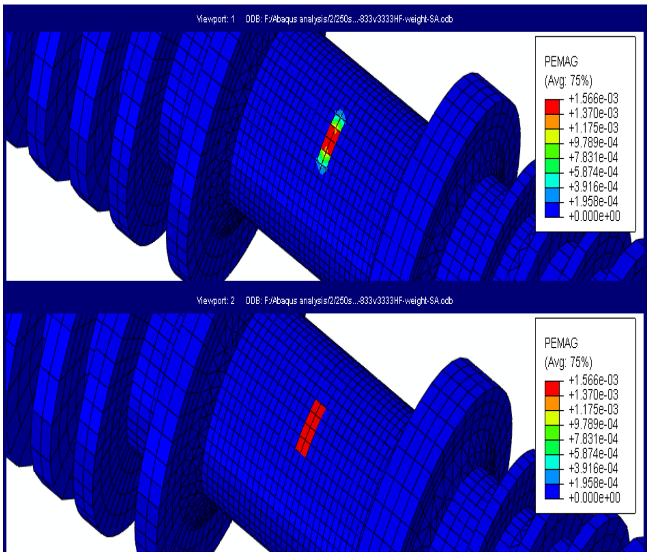

Fig. 8 Contour of plastic strain area at the temperature of (a) 705°C, (b) 750°C

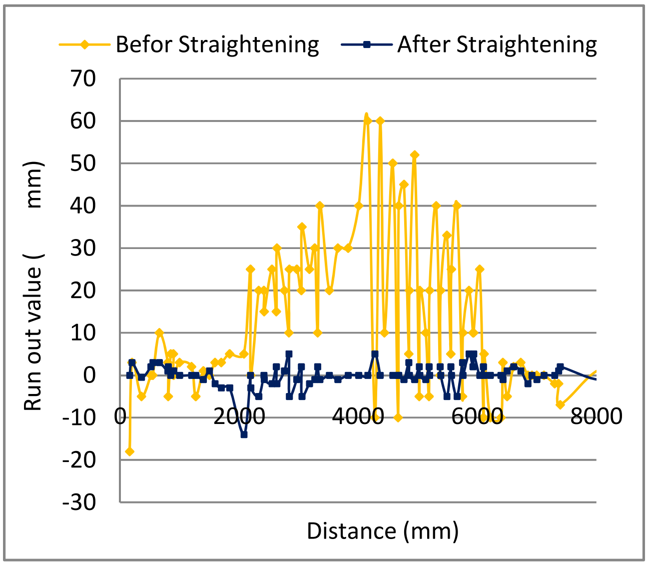

Fig. 9 Results of initial and final run out tests at an angle of 90°

A comparison between received experimental data from initial and final run out tests (Fig. 9) shows that performing the hot spotting execution according to simulated results, has been reduced the rotor eccentricity noticeably. Therefore we recommend using a numerical method before carrying out the selected straightening method.

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