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Analysis of erosion hazards in turbines due to power units operating in low load conditions

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Abstract

Coal fired power units are having to operate with higher operational flexibility due to changes in the structure of energy systems brought about by the increased production of electric energy from renewable sources. The flexibility at issue relates to frequent changes of generated power and long-running operation at minimum load. By operating in this mode coal fired power units compensate for the stochastic character of energy generated from renewable sources and ensure a desirable reliability level for energy systems, but at the same time it has various impacts on the durability and failure frequency of their component parts. One of the problems which can arise during the operation of turbines working at low loads is increased erosion of the last stage blades of the LP part. This paper presents an analysis of turbine operation conditions which may lead to increased erosion hazards for the blades of the LP part. We address the problem of temperature drop of the re-superheated steam during low load operation of the unit and investigate the impact of erosion losses on the change of dynamic state of the turbine's last stage blades.

Keywords: Erosion hazards; turbine blades erosion; erosion; low load conditions

1. Introduction

The development of renewable energy sources is becoming a key factor triggering changes in the energy systems of many countries. The impact of increased energy production from renewable sources is particularly visible in systems dominated by coal fired power plants [1], which are typically designed to operate in a continuous mode. Now, they are having to operate more flexibly [2]. Flexibility refers to among others such factors as: wide range changes of generated power, capability to quickly change loads, ability to operate long term at maximum or minimum power output, ability to execute frequent shutdowns and restarts of the power unit, and fast change of load, shutdowns and restarts. Flexible operation of coal fired units can ensure stable and reliable production of the required amount of energy, but on the other hand it can cause a number of system operation problems and can influence the durability of major components of the units. Flexible operation also brings about significant changes of heat and affects the strength conditions of boiler and turbine components, which in turn impacts the safety of their operation. The scheduling of maintenance and repair works is also affected. Operational experience to date shows that changes to the operational mode of a power unit generally increases operational risk and operational costs, and can lead to the early replacement of components.

The problems of increased operational cyclicality of coal fired units have been the subject of many works to date. In the paper [3] issues involving damage done to power unit components caused by the cyclicality of thermal and mechanical stresses were discussed. The impact of thermomechanical fatigue of boiler tubes on their residual durability and on the durability of the whole unit was estimated as were the economic and ecological profits obtained due to higher operational flexibility. The change of operational conditions of coal fired power generating units imposed by the development of renewable energy sources and the liberalization of energy production market was also discussed in [4]. The papers demonstrated that the increased number of restarts and the changes in power output at the units necessitate the introduction of a wider range and higher frequency of repair works. The economic effects of various operational strategies of power units and their impact on the durability of boiler components were discussed in [5]. The increased technical risk involving the operation of turbines due to the intensification of fatigue processes was discussed in [6]. The conclu-

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Figure 1: Erosion of turbine blades

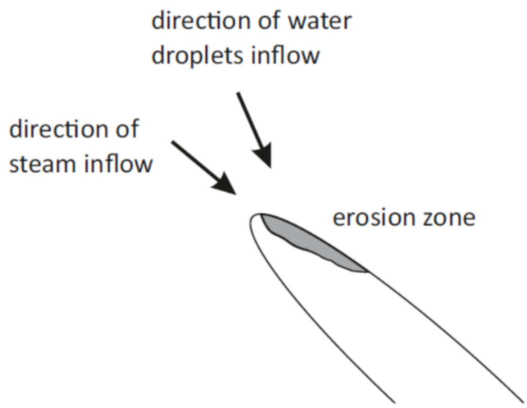

Figure 2: Direction of steam and water droplets inflow on the leading edge of the rotor blade

sions presented in the above papers suggest the possibility of increasing the operational flexibility of the units, while acknowledging the fact that certain related costs i have to be incurred. Another problem that can arise with higher operational flexibility in power units is increased erosion in the low-pressure part of the turbine at low loads. This is a well-known phenomenon [7] and can substantially intensify due to new operational conditions of turbines. An example of erosive wear of the last stage blades of the LP part of the turbine is presented in Fig. 1. Analysis of this hazard in turbines and its consequences are discussed later on in this paper.

2. Erosion in the low-pressure part of the turbine

2.1. Formation mechanism of erosion losses

In the low-pressure part of steam turbines, the last stages operate in a wet steam environment, which increases the risk of damage to blade systems, principally due to erosion. In view of the collected experience, the last stages of the low-pressure part account for about 20–25% of turbine breakdowns or failures. The main mechanism of liquid phase formation is subcooling, i.e., the difference in saturation temperature for a given pressure and steam temperature. In the case of pure water steam, for subcooling of about 30–35 K, the liquid phase is formed by spontaneous condensation and this area is referred to as the Wilson zone [8]. When salt (mainly NaCl) or other admixtures are present in the steam, the Wilson zone moves towards the saturation line, i.e., towards higher pressures. For water steam containing impurities in the form of salts, the formation mechanism of the liquid phase corresponds with heterogenic condensation. At low pressures, the salts and acids dissolved in the steam begin to form condensation nuclei. The liquid phase formed through condensation has the character of mist, containing droplets measuring ~10–100 nm. The droplets carried by the expanding steam are deposited on the walls, limiting the flow channels, i.e., the blades of guide vanes and rotors, forming a water film on them. A water film on the blades is also formed due to the difference between steam saturation temperature and wall temperature [9]. According to calculations, when this difference is of the order of 0.3 K, about 10^8/cm^2 droplets with a diameter of 0.01 μm settle, forming a water film. The water film formed on the guide vanes is then broken off in the area of the trailing edge, and “thick” droplets are formed by the atomization process [9].

Droplets leave the surface of the guide vanes at a different angle than water steam, leaning more towards the axial direction. This means that, in the relative system of the rotor, the inflow direction of droplets is not optimal (Fig. 2). As a result, erosion affects part of the leading edge of the rotor blade on the suction side.

The amount and size of water droplets formed in the atomization process are obviously dependant on the size of the water film leaving the trailing edge of the guide vanes and on flow conditions, mainly velocity. The impact force of the droplet on the blade surface can be described by the following formula:

$$F = \rho v a \frac{\pi}{4} D^2 \tag{1}$$

where ρ stands for water density, v is the velocity of the moving droplet, a is the speed of sound in water and D is the droplet diameter.

The size of the water film on the last stage guide vanes depends principally on the formation place of the liquid phase, which depends on the operational parameters, i.e., load and pressure in the condenser. When this process takes place in the last stage guide vanes, the size of the water film formed and, consequently, the diameters of the water droplets formed by atomization are small and the erosion hazard is low. When the liquid phase is formed in the penultimate stage, the size of the water film and that of the droplets is much bigger, which increases the risk of erosion considerably.

The formation place and the amount of the liquid phase also depend on steam purity. When there are impurities such as

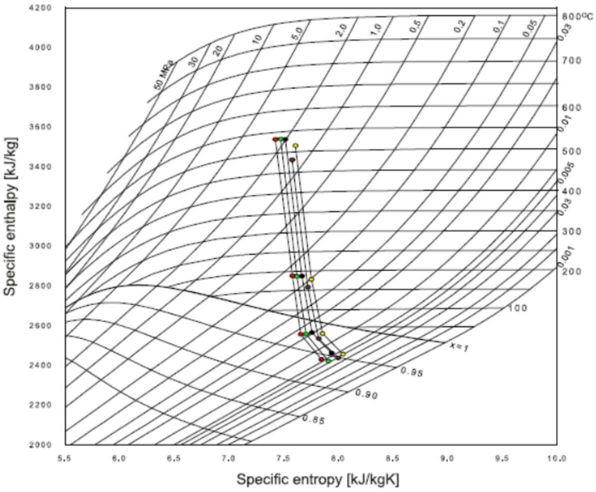

Figure 3: Expansion line in the IP and LP parts of turbine A—red for the load of 218.82 MW, green for the load of 199.92 MW, black for the load of 178.98 MW, yellow for the load of 139.12 MW and brown for the load of 119.42 MW

salts or acids, the liquid phase is formed earlier due to heterogenic condensation. The pH of the condensate should be tested: for pure steam it should be about 9. A pH value below 5 suggests the presence of a considerable amount of impurities dissolved in the boiler water.

2.2. Risk indexes of droplet-induced erosion in steam turbines

To assess erosive risk we applied in the present work the index proposed by KWU, which can be defined by the following relation [10]:

$$E = k y_0^2 \frac{u^3}{p_0} \tag{2}$$

where: $y_0 = (1 - x_0)$—level of steam moisture before the stage, u—peripheral speed, p_0—steam pressure before the stage, k—a number allowing for material properties and structural details.

The above index was obtained from experience of the stages existing in the wet steam environment. It follows from the above relation that the erosive risk depends principally on the content of the liquid phase before the stage, the peripheral speed and the pressure before the stage. The index is applied principally to assess the impact of these parameters on the risk induced by droplet erosion.

In the analysis the above relation was applied to assess erosive risk in the last stage subjected to the work in different conditions resulting from changes in both the load and the temperature of the re-superheated steam.

2.3. Analysis of the expansion line in the turbine and the assessment of erosive risk

The erosive risk index was assessed based on the results of thermal measurements of 200 MW turbines carried out for several load values within the range from the maximum load

Table 1: Steam parameters for different load values and the related erosion index, turbine A

N_{el}	218.82	198.92	178.98	139.12	119.42
p_{0_SP}	2.4760	2.2310	2.0270	1.5170	1.3260
t_{0_SP}	533.10	532.60	531.10	514.50	480.90
p_{0_NP}	0.1552	0.1401	0.1276	0.0978	0.0863
t_{0_NP}	188.50	186.60	187.20	178.10	157.90
p_{0_4st}	0.0246	0.0222	0.0207	0.0162	0.0148
x_{0_4st}	0.9740887	0.9761662	0.9804409	0.9825287	0.9733312
p_k	0.0066	4.178815	0.0067	0.0051	0.0049
x_k	0.9416897	0.9413227	0.9545881	0.9564301	0.9491481
E	4.457216	4.178815	3.018219	3.075314	7.874768

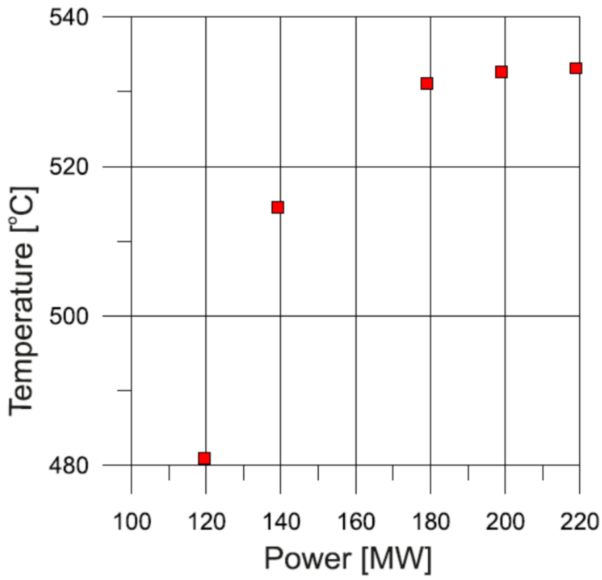

Figure 4: Temperature of re-superheated steam for different load values, turbine A

of 220 MW to the technical minimum of 120 MW. Exemplary expansion lines in parts IP and LP of the turbines for two different 13K215 turbines (described as A and B) are presented in Figs. 3 and 6, and the related temperature values of steam before the IP part as well as the values of erosive risk index are presented respectively on Figs. 4, 5 and 7, 8. Detailed values of steam parameters are presented in Tables 1 and 2, where the following denotations were assumed:

- N_{el}—electric power,
- p_{0_SP}—steam pressure before the IP part,

Table 2: Steam parameters for different load values and the related erosion index, turbine B

N_{el}	220.56	199.56	179.87	149.7	119.9
p_{0_SP}	2.4800	2.2080	1.9910	1.6570	1.3280
t_{0_SP}	531.10	536.60	530.40	499.50	480.80
p_{0_NP}	0.1491	0.1335	0.1208	0.1029	0.0845
t_{0_NP}	182.70	187.10	183.60	165.80	156.70
p_{0_4st}	0.0252	0.0225	0.0205	0.0176	0.0146
x_{0_4st}	0.9760481	0.9827222	0.9816340	0.9755027	0.9739906
p_k	0.0055	0.0049	0.0047	0.0039	0.0039
x_k	0.9381101	0.9454635	0.9455479	0.9398921	0.9434623
E	3.717922	2.166794	2.687173	5.555974	7.577498

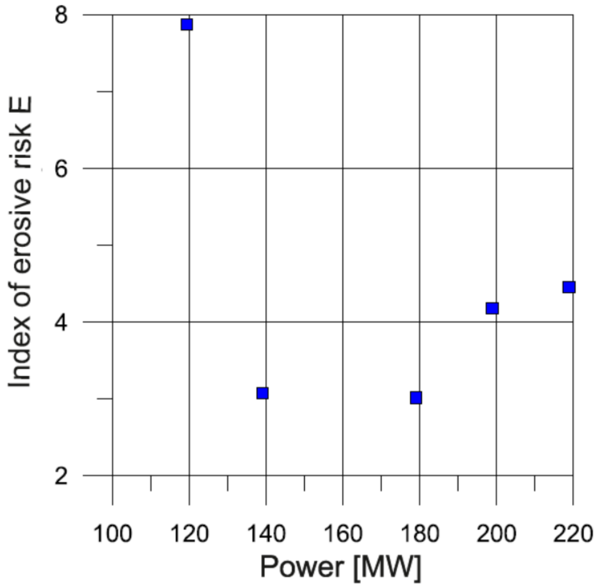

Figure 5: Erosion index for different load values turbine A

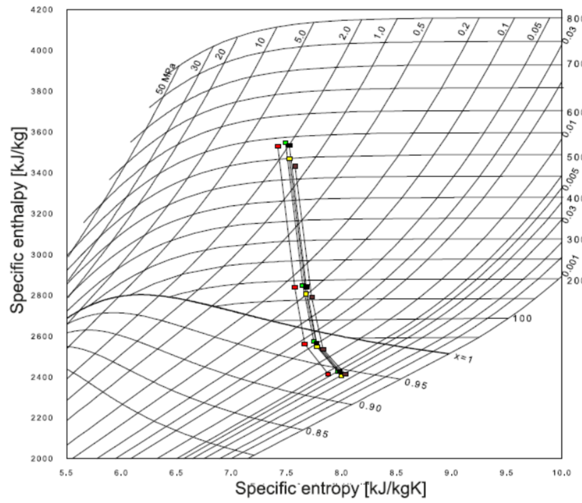

Figure 6: Expansion line in the IP and LP parts of the turbine B—red for the load of 220.56 MW, green for the load of 199.56 MW, black for the load of 179.87 MW, yellow for the load of 149.7 MW and brown for the load of 119.9 MW

Table 3: Steam dryness level before the last stage of the LP part and the index of erosive risk E of that stage as a function of re-superheated steam temperature

t_0, °C	E	x_0
480	7.22213697	0.975776732
490	4.97485304	0.979895651
500	3.15910482	0.983979285
510	1.76384687	0.988029003
520	0.778690815	0.992046058
530	0.193795487	0.996032000

- t_{0_SP}—steam temperature before the IP part,
- p_{0_NP}—steam pressure before the LP part,
- t_{0_NP}—steam temperature before the LP part,
- p_{0_4st}—steam pressure before the last stage,
- x_{0_4st}—steam dryness level before the last stage,
- p_k—steam pressure in the condenser,
- x_k—steam dryness level after the last stage,
- E—index of erosive risk.

The calculation results show that the index of erosive risk can assume different values even for the same load of the turbine set. The highest impact on the erosion of rotor blades for a given turbine load is exerted by steam pressure, and in particular by steam moisture before the last stage which, in turn, depends on the temperature of the re-superheated steam. It is illustrated by the data presented in Table 3, which contains the calculation results for the erosive risk index "E" of the last stage of the LP part and for the dryness level as a function of steam temperature at the inflow to the IP part, for constant power of the turbine set of 120 MW.

The drop in steam temperature before the IP part results in a reduction of the steam dryness level (increased moisture) and in a radical rise in the erosive risk index.

3. Analysis of the impact of erosion on the dynamic properties of blades

To investigate the impact of erosive losses on the dynamic performance of blades, we applied numerical simulations using the finite element method. Based on real data, several geometrical models were produced for blades at different developmental stages of erosive processes. The model referred to as "new" blade (Fig. 9) was made on the basis of the scanned geometry of an unworn blade of the last stage of a 13K215 turbine. The model referred to as "worn" blade was made on the basis of a real blade with visible but moderate erosive wear.

Pre-Stress Modal Analyses were carried out for the above geometrical models, i.e., modal analyses to determine the frequencies of own vibration of the components, allowing their "stiffening" due to the impact of the loads induced by the blade rotating at the speed of 3000 rev/min. The calculations were carried out on nets consisting of about 500000 nodes. A linear-elastic model of material was applied for the analysis. Fig. 10 presents the stress induced by rotation of the new blade. Figs. 11 and 12 set out the stress values for the first and second form of own vibrations of that blade.

The highest stress values induced by rotation can be observed in the grooves of the new blade root. As regards stresses related to vibrations, the maximum occurs on the blade surface. The values of the first six frequencies of own vibrations of the new blade, as determinedby the modal analysis, are presented in Table 4.

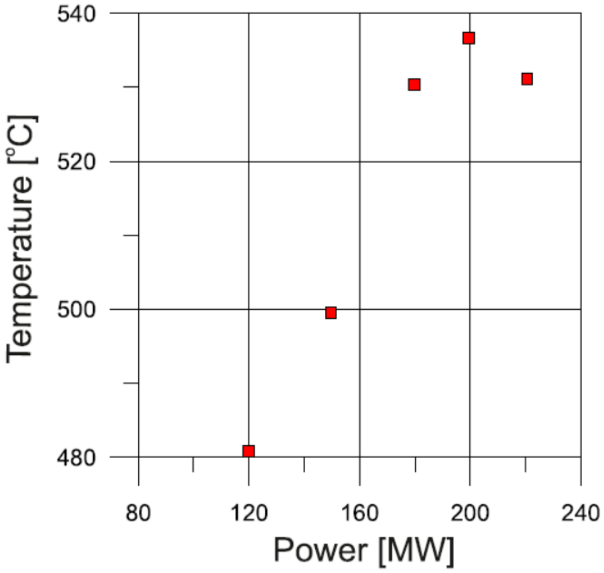

Figure 7: Temperature of re-superheated steam for different load values turbine B

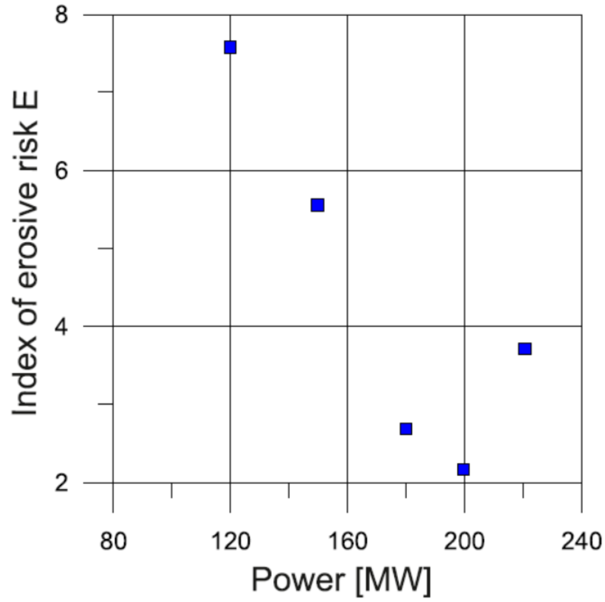

Figure 8: Erosion index for different load values turbine B

Table 4: Frequency of own vibrations of the "new" blade

Form of own vibrations	Frequency, Hz
1	64.118
2	134.600
3	217.440
4	268.240
5	437.350
6	469.640

Fig. 13 presents the stresses induced by the vibration of the blade worn out by erosion, and Figs. 14 and 15 present the stresses for the first and second component of own vibrations.

As in the case of the new blade, the highest values of stresses induced by vibration can be observed in the grooves of the blade root. Maximum stresses related to the dynamics of the worn blade are concentrated on the blade surface around the notch, made by the erosive loss of blade material. The values of the first six frequencies of own vibrations determined by means of modal analysis are presented in Table 5.

While the determined forms of own vibrations are similar for all blade models, the extent of erosive loss has a major impact on the location of maximum stresses for the particular forms of vibrations. The first two forms of own vibrations have the character of buckling vibrations of the blade tip in the plane of its lowest stiffness. In the investigated blade, the incurvature of the profile in its final part is missing, which lowers the bending strength index in the direction corresponding to the deformations for the first two forms of own vibrations. The other forms of vibrations have the character of torsional vibrations of the blade tip. The place where the highest stresses occur for the two first forms of own vibrations for all models is similar to the place where the undercutting of the blade's attack edge occurs. When stresses happen around the place where the undercutting of profile occurs, and additionally there is a change of blade material hardness induced by e.g. stiffening of the fragment of the attack edge, then the related structural notch which is created can help accelerate erosive or fatigue processes.

Table 5: Frequency of own vibrations of the "new" blade

Form of own vibrations	Frequency, Hz
1	63.844
2	134.270
3	218.190
4	269.600
5	437.770
6	471.440

The analyses carried out show that, for the first two forms of own vibrations, as the erosive wear increases the frequency of own vibrations drops. The drop in frequency values of own vibrations can bring them closer to the extortion frequency and consequently damage the blade. An example of such damage done to the blade is presented in Fig. 16.

4. Summary

The ability of coal fired power plants to change their operational mode from regular operation to cyclical to operate at minimum load for frequent and long-running operation periods provides operational stability for the energy system and a certain degree of cost rationalization. However, it poses a number of problems in the longer perspective. One of them involves the increased risk of erosion on the blades of the

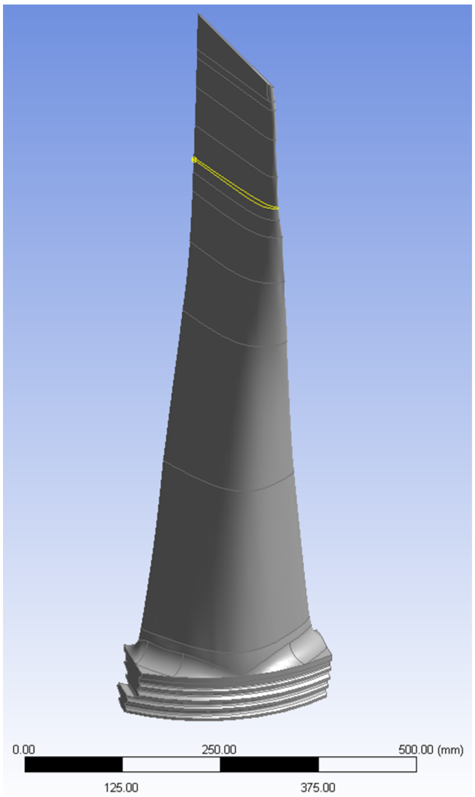

Figure 9: Model of the blade

turbine's last stages. The extent of this risk depends on the temperature, pressure and moisture of the steam environment and they, in turn, depend among others on the load. In view of the analyses performed involving real parameters of power unit performance and the expansion line in turbines, operation at low load can generate serious problems involving, e.g., maintaining re-superheated steam at an appropriate temperature. The erosion index values calculated for different loads demonstrate the resulting significant differences in outcome. The erosion risk differs accordingly, as does the scope of the generated erosive losses of blades. Every corrosive loss is a focal point of stresses. It changes the dynamic properties of the blade and enhances the risk of serious damage. To prevent such situations we can make structural changes to the boiler and the turbine and can ensure continuous monitoring of steam parameters and the erosive risk index in the last stages of the turbine selected for cyclical operation.

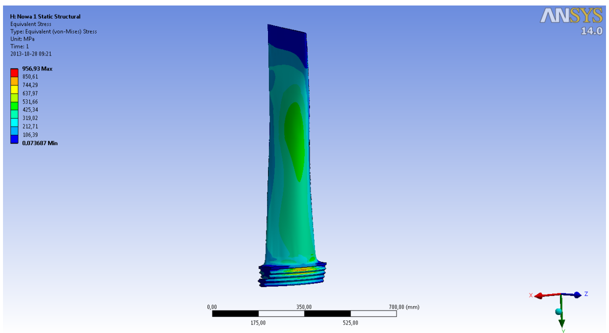

Figure 10: Stress on the “new” blade induced by rotation

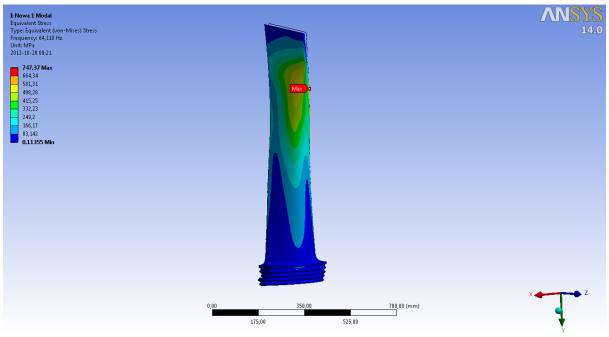

Figure 11: Stress for the first form of own vibrations of the “new” blade

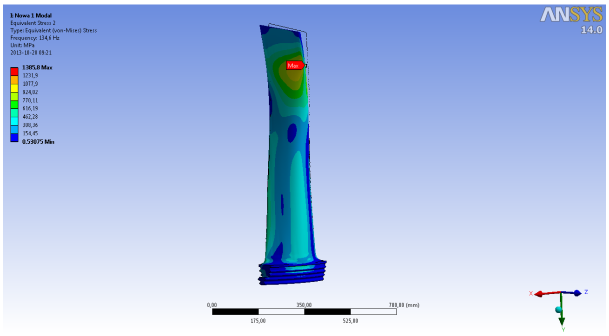

Figure 12: Stress for the second form of own vibrations of the “new” blade

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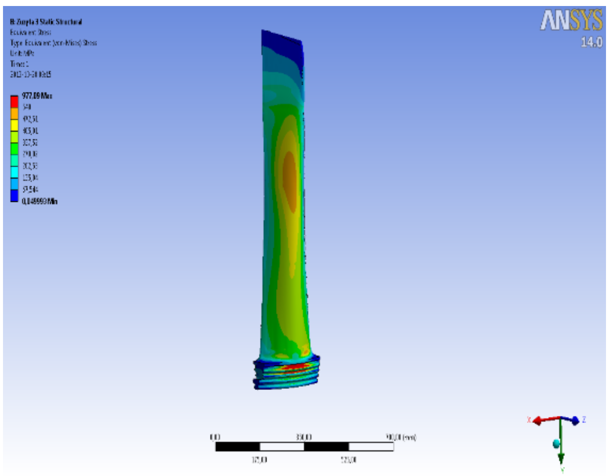

Figure 13: Stress in the “moderately worn” blade induced by rotation

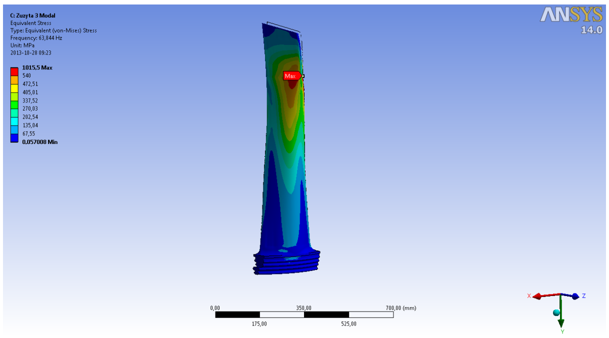

Figure 14: Stresses for the first form of own vibrations of the “moderately worn” blade

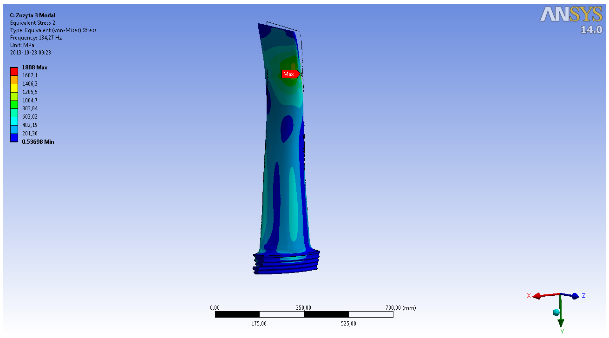

Figure 15: Stresses for the second form of own vibrations of the “moderately worn” blade

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Figure 16: Rotor with a damaged blade