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FAILURE PREVENTION OF ROTATING EQUIPMENT BY VIBRODIAGNOSTICS

PREDUPREĐIVANJE OTKAZA OBRTNIH MAŠINA POMOĆU VIBRODIJAGNOSTIKE

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- rotating equipment
- vibrodiagnostics
- inspection

Abstract

Heavy duty rotating equipment, like turbines and fans, frequently fail, sometimes with catastrophic consequences. Permanent improvement in material properties, manufacturing technology and inspection, supported by sophisticated testing instruments and strict requirements in regulations and codes significantly reduced the failures, but they still occur. Vibrodiagnostics significantly helps to avoid failures, enabling to continuously monitor the vibration behaviour during operation, not only periodically, during breaks, and the analysis to ensure safe and reliable service. Rotating equipment is in continuous operation, so damages and failures can occur instantaneously, if the amplitude increases above a limited value. Continuous monitoring has to be performed on selected critical locations in the system. With developed electronics, computers and software, the system can be switched off in a critical situation.

The design and capacity of a recently developed portable device MICROMON for vibrodiagnostics at the University of Belgrade, Faculty of Mechanical Engineering, and its in-service application are presented in this paper.

Ključne reči
- otkaz
- obrtna oprema
- vibrodijagnostika
- inspekcija

Izvod

Opterećene obrtne mašine, kao što su turbine i ventilatori, često otkazuju, ponekad sa katastrofalnim posledicama. Neprekidno poboljšavanje osobina materijala, tehnologije proizvodnje i inspekcija, podržano usavršenim uređajima za ispitivanje i strogim zahtevima u pravilima i propisima, znatno smanjuju otkaze, ali se oni i dalje javljaju. Vibrodijagnostika u velikoj meri pomaže da se izbegnu otkazi, jer omogućava neprekidno praćenje ponašanja vibracija tokom rada, ne samo periodično, za vreme zastoja, i analizu radi obezbeđenja sigurne i pouzdane eksploatacije. Obrtne mašine rade bez prekida, tako da do oštećenja i otkaza može doći trenutno, ako amplituda poraste iznad granične vrednosti. Neprekidni monitoring treba da se izvodi na izabranim kritičnim lokacijama u sistemu. Uz pomoć razvijene elektronike, kompjutera i softvera, sistem može da se isključi u kritičnim situacijama.

Konstrukcija i kapacitet nedavno razvijenog prenosnog uređaja za vibrodijagnostiku MICROMON, na Mašinskom fakultetu Univerziteta u Beogradu i njegova primena su prikazani u ovom radu.

INTRODUCTION

Rotating machines are a vital part of the power industry: turbines present the basis of thermal and hydro power plants. Turbines have to be maintained properly, since they are exposed to complex loading in service. In order to hold the risk at the lowest level, the probability of failure must be as low as possible. The risk level depends on consequences and probability of failure occurrence, so if the consequences are serious, the probability of failure has to be reduced as much as possible. Two presented cases will show how severe are the consequences of turbine failures. This implies strict requirements in their inspection and application of sensitive control devices.

Vibrodiagnostics is a valuable method for inspection of rotating machines, since small changes in vibration data can indicate initial disturbance. If the disturbance is continuous it is recommended to switch off the machine due to the risk of failure, in spite that forced break-out creates important direct and indirect costs.

FAILURES OF ROTATING EQUIPMENT

The failure of turbines can be catastrophic, as it has happened in two cases presented here as an illustration.

In the year 2009, turbine 2 of the Sayano–Shushenskaya hydroelectric power station failed violently, /1/. Before the accident, it was the largest hydroelectric power station in Russia and the sixth largest in the world by average power generation. The turbine hall and engine room were flooded, the ceiling of the turbine hall collapsed, 9 of 10 turbines were damaged or destroyed, and 76 people were killed. The report states that the accident was primarily caused by turbine vibrations which led to the fatigue damage of the mounting components for the cover of turbine 2.

It was found that at the moment of the accident, at least six nuts of the mounting were missing from the bolts securing the turbine cover. After the accident, 49 bolts found were investigated for fatigue cracks. For 8 bolts, the fatigue damage area exceeded 90% of the total cross-section area.

The operating life defined by the manufacturer for the turbines is specified for 30 years. At the moment of the accident the life was almost exhausted, since the turbine was 29 years and 10 months in service.

The turbines of this type have a very narrow working band at high efficiency regimes. If this band is exceeded the turbines begin to vibrate, caused by the pulsation of water flow and water strokes. These vibrations and shocks on the turbines will degrade them over time. These problems are observed many times in the plant and in turbine 2.

In order to get an insight into experienced working conditions and loads, the operation and maintenance history is presented, followed by the events on the day of the accident.

Turbine 2 had experienced problems from the very beginning of operation. After installation in 1979, the first problems appeared. During 1980-1983, many problems are associated with seals, turbine shaft vibrations, and bearings. From the end of March to the end of November 2000, a complete reconditioning of turbine 2 is performed. Cavities up to 12 mm deep and cracks up to 130 mm long are found on the turbine wheel, and they were repaired. Many other defects are found in the turbine bearings and subsequently repaired. In 2005 further repairs are made. From January to March 2009, turbine 2 was undergoing scheduled repairs and improvement. It was the only turbine in the station that had been equipped with a new electro-hydraulic regulator of rotational speed. During the course of the repair, the turbine blades were welded, because, after a long period of operation, cracks and cavities had appeared. However, the turbine wheel was not properly rebalanced after these repairs: turbine 2 had increased vibration, cca 0.15 mm for the main bearing at the full load. This did not exceed specification, but the increased vibration, causing variable loading and fatigue of components, was unacceptable for long term operation. The higher vibration compared to other turbines is recognised for turbine 2 also before the repair. The vibration exceeded the allowed specification in the beginning of July 2009 and continued to increase with accelerated speed.

On the day of the accident, the turbines worked as the plants power output regulator and due to this, its output power changed constantly at working level 212 m. At this pressure, the recommended power band for the turbines is 570-640 MW (band III) and the allowed band is 0-265 MW also (band I). Band 265-570 MW (band II) at this pressure is not recommended, and output over 640 MW (band IV) is forbidden. The turbine often operated in band II regime which is accompanied with pulsation and strokes of water flow. On the night of 16-17 August, the level of vibration increased substantially. There were several attempts to stop the turbine. On August 16, up to 20:30, the load of turbine 2 was 600 MW, then it was reduced to 100-200 MW. On August 17, 2009, at 3:00, the load was increased again to 600 MW; at 3:30, the load was decreased to 200 MW; and at 3:45, it was increased again to 600 MW. During this time, the level of vibration was so high, that it was registered by seismic instruments in the plant. During attempts to shut it down, the rotor inside the turbine was pushed up, which in turn created pressure pushing up the turbine cover. The cover was kept in place by 80 bolts of diameter 80 mm. At the moment of the accident, at 8:13, its load was 475 MW and water consumption was 256 m^3/s. Vibration of the bearing was 0.84 mm which exceeded the values of other turbines by more than fourfold.

It is clear that this catastrophe could have been avoided by proper control and shut down of turbine 2 in due instant.

Scene of the Sayano–Shushenskaya hydroelectric power station after the accident is presented in Fig. 1, /1/.

Figure 1. Scene of the Sayano–Shushenskaya hydroelectric power station after the accident, /1/.
Slika 1. Izgled električne stanice Sajano-Šušenskaja posle otkaza, /1/

The second example of failure is the fracture of steam turbine blades, /2/. Until the accident, a power plant was operating in full capacity. Suddenly, abnormal sound was heard, followed by intensive shock and crashing, and ended by fire. In the analysis of turbine failure, the blades were examined in detail after the casing was opened. The turbine failure was attributed to blade fracture. Simultaneous fracture of three blades in one flux produced unbalance in the turbine and caused an overloading, which could not be sustained by the rotor shaft. Steam turbine blades are exposed to high variable loading, and sometimes also to corrosive environment. In the low pressure turbine, three successive blades are found fractured. The initial fatigue crack in one blade was 1100 mm^2 or 14% of cross section area (Fig. 2). The rest of the fractured surface is brute, dominantly ductile. Probably this blade had broken first. Due to the redistributed loading after the first blade had fractured has increased the stress in the second blade with initial fatigue crack of 280 mm^2 or 4% of cross section. The third blade broke 40 mm above the root by overloading.

Corrosion attack due the improper water preparation took place in the blades, where fatigue cracking initiated (Fig. 3), and this contributed to introduce initial damages, followed by the fatigue process, /2/.

The critical cross section of blade, shown in Fig. 2, had been continuously reduced during the fatigue process. As a consequence, stiffness of the blade was reduced, affecting the vibration state. When vibration behaviour corresponded to resonant regime, the cross section of blade could not sustain the applied stress state, and the critical blade failed. Misbalance induced by the fractured first blade produced fracture of second blade with critical cross section reduced by 4% in fatigue and after that the third blade, which was not exposed to fatigue, had fractured. Eventually, even a very small crack might change the vibration state sufficiently to be recorded by a sensitive device and indicate a critical situation. Proper application of vibrodiagnostics monitoring in this case might be helpful, since this failure can be prevented after detecting the occurrence of resonance.

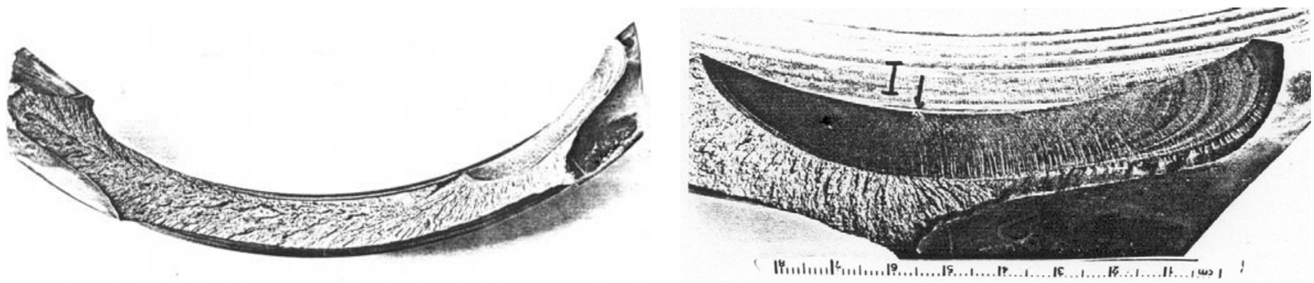

Figure 2. Blade fracture from fatigue crack A in upper corner (left) and development of striations during fatigue process (right). The initiation site is marked by an arrow.
Slika 2. Lom lopatice zbog zamorne prsline A u gornjem delu (levo) i razvoj strija tokom zamornog proces (desno). Mesto inicijacije je označeno strelicom

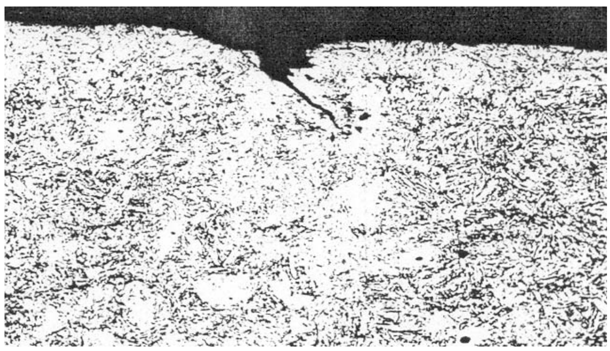

Figure 3. Corrosion attack as initial fatigue crack.
Slika 3. Korozijski ujed kao inicijalna zamorna prslina

The operation of a rotating machine is defined by specified values of parameters (pressure, temperature, flow, vibration), which are limiting for the applied regime. When problems in operation occur, some of the parameters pass over given limits. Continuous monitoring of parameter values enables to react in a proper way.

In rotating machines vibrations most precisely describe the situation about the quality of operation, enabling to assess the vibration state of a machine. In this way monitoring of the vibration trend indicates how to assure safe and reliable operation of rotating equipment.

VIBRODIAGNOSTICS

Vibrations are oscillating movement of a mechanical system about the equilibrium state. In an ideal, theoretical situation (symmetric and balanced masses) vibrations are not present. In real operations, due to present imperfections, the rotating machine inevitably vibrates. Analysis of imperfections enables to defined the normal (expected) vibration level for the considered machine, which can be found in the machine manual or by applying standards (ISO, VDI, ICE). If vibration overpasses a specified level, the situation is critical and the problem has to be solved to avoid failure. Increase in the vibration level can be caused by imbalance, misalignment, wear of supports or gears and resonance. Analysis of these effects allows to define the problem in machine operation and to discover its cause in the scope of vibrodiagnostics, which assess the quality of machine operation.

Determination of machine state

Comparing the measured vibration state with the specified level, it is possible to assess whether the machine operation of is satisfactory or not. The level is determined according to the machine type, its dimensions and mass, rotational speed and other relevant parameters. If the vibration level is under the specified value, machine operation can be continued, otherwise the problem has to be analysed.

Determination of problem cause

It is necessary to predict the most probable among all possible causes. Response to this question is given by vibrodiagnostics using Fast Fourier Transformation (FFT) for vibration analysis. It transfers monitored vibrations from time domain into a frequent domain, in which each of cited problems has a typical vibration picture. Comparing the obtained picture with known pictures for most problems it is possible to reveal the cause of increased vibration level.

Imbalance is the most frequent cause of increased vibration level in rotating machines. It is often a consequence of misalignment of rotation and inertia axes, due to non-uniform distribution of masses about the rotation centre, by accumulation or loss of material in some part of the rotor during operation. At highest pressure, turbine steam can condensate and drops impact the blade, ripping-off the material. Increased vibrations are the symptom of blade trouble. A similar effect is produced by fatigue cracks (Fig. 2), and also casting defects and manufacturing tolerances.

Resonance is the tendency of a mechanical system to absorb more energy when the frequency of its oscillations matches the system's natural frequency of vibration. Sometimes the amplitudes are so high that it is impossible to achieve nominal regime and loading. Resonance should be detected and eliminated.

Continuous monitoring of vibrations

It is not possible to have a continuous control of the machine state if vibrations are measured only periodically. Preventive maintenance would be possible only if the measurement is done when the vibration level changes significantly, but sufficiently before final failure. Continuous monitoring enables preventive actions. The period prior to failure can be divided into several levels depending on vibration intensity. First levels might indicate unexpected, but negligible changes. The last levels require to stop the operation in a shorter period to protect personnel and the machine, /3/.

DEVELOPMENT OF THE DEVICE FOR VIBRATION MONITORING AND ANALYSIS (MICROMON)

The preventive maintenance system enables optimal operability of industrial systems. For inspection, monitoring and control, convenient devices are necessary, capable to register system behaviour, the changes, store the results and indicate when the level has exceeded. In this group is a portable device for monitoring and analysis of vibrations, MicroMon (Figs. 4 and 5), newly designed and developed at the University of Belgrade, Faculty of Mechanical Engineering. It serves for measuring and diagnostics of mechanical systems, including the trend of vibrations, FFT analysis, modal testing and expert report. By developing proper software it would be possible to assess the risk level of machine operation, /4/.

Operation modes of the MicroMon device

The device logic is designed so that alarm levels might be set. This enables to detect irregularities in operation in an early stage (RPM, increased vibrations, and bearing problems). Via Ethernet port, MicroMon could be connected to the control unit of the rotating machine. In case of emergency it could send a signal of exceeded vibration level, and stop the machine. Total vibrations are often the result of disturbing forces (Fig. 5).

In the addition of the time domain, vibrations can be presented in the frequency domain (FFT analysis). In this way the obtained picture allows determining the origin of measured vibrations more easily, since each of the causes has its own typical picture in this domain.

In order to monitor machine behaviour in a longer time period, the MicroMon allows storage of relevant results up to one year. So the formed vibration trend makes preventive maintenance easier. The signal taken from the vibration sensor in last ten minutes is given in Fig. 6.

Two simultaneously measured channels (P1; P2) are shown. Vertical line presents a cursor for the selection of the particular moment in the recorded trend. It is also possible to present an FFT analysis for that moment /4/.

The device enables the rotor balancing in its own bearings. Vibrations detected at the fundamental frequency are most often caused by imbalance.

Figure 4. The general view of MicroMon portable device for vibrodiagnostics.
Slika 4. Izgled prenosnog uređaja Mikromon za vibrodijagnostiku

During start up and shut down some of machines pass the critical revolution per minute (RPM). If the passing period is to long, resonance can cause high increase of amplitude, ending in mechanical damage. MicroMon software supports measurements in these regimes also (START UP / SHUT DOWN analysis). Measured amplitudes and FFT analysis are presented in the waterfall diagram (Fig. 7), composed of the data of vibration amplitudes, frequencies and rotational speed (RPM) /5/.

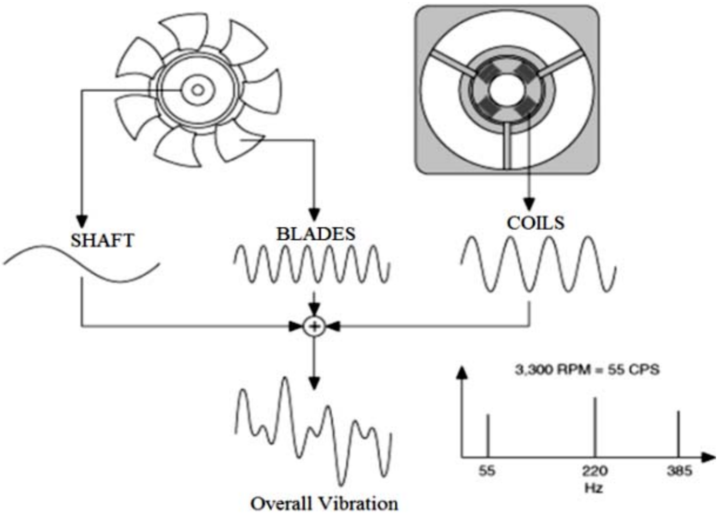

Figure 5. Different origin of vibrations.
Slika 5. Različite pobude vibracija

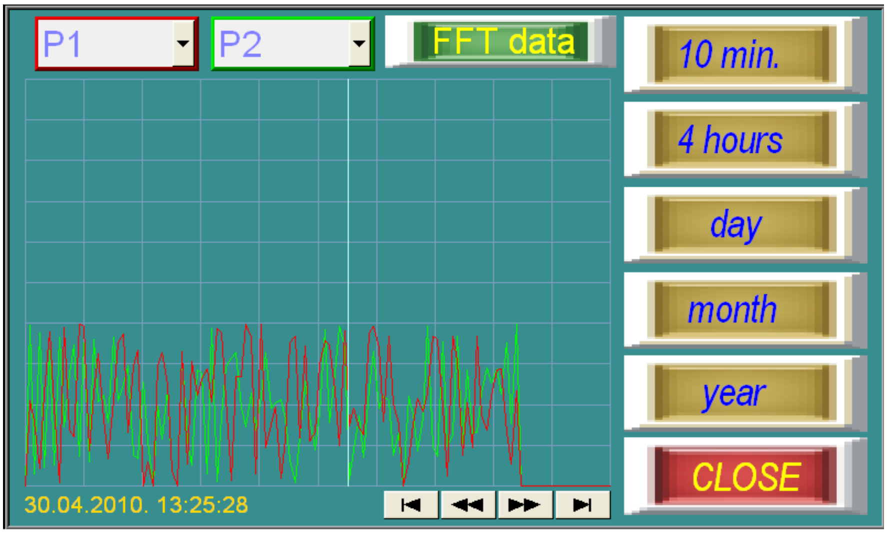

Figure 6. Trend of vibrations.
Slika 6. Trend vibracija

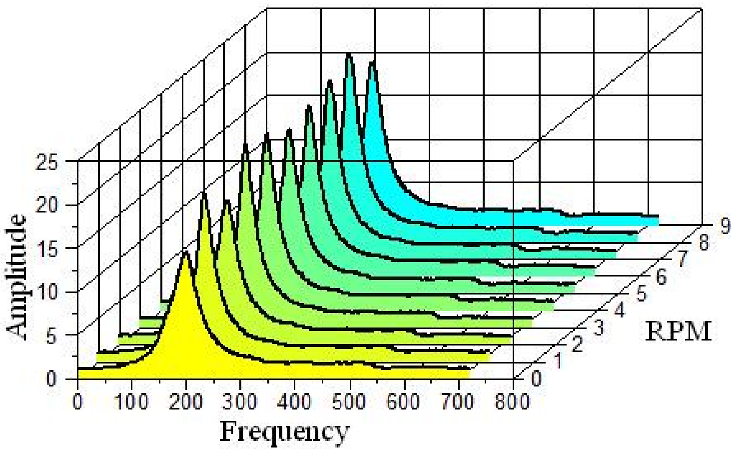

Figure 7. Waterfall diagram.
Slika 7. Spektralni dijagram

DISCUSSION

MicroMon offers the complete picture of dynamic behaviour, from standstill to the operating rotational speed of the rotating machine Zones with increased amplitudes and corresponding operating regime can indicate possible cause of improper machine operation and prevent damage.

In a large steam turbine system, consisting of low, medium and high pressure turbines, the required stiffness can be achieved only by very large dimensions. In that sense, they are designed so that their resonant frequency is about 20% lower than the operating frequency.

When introduced in operation they have to pass through critical RPM. This is of great importance to spend the shortest possible time in this regime in order to avoid failure. Since the start up could not be monitored continuously, the failure of two turbines 300 MW has been experienced (in 1983/84 in France, and in 1986 in Serbia /2/). Detailed investigation revealed that the cause was simultaneous fracture of three blades, with a fatigue crack (Fig. 2). The fatigue crack initiated in the start up procedure, because operating regimes did not register the overloading. It was concluded that turbines spent a to long time in the critical start up regime, sufficient for initiation and some growth of the fatigue cracks, with further development in operation. Referring to Figs. 4 and 5, and analysing the possibility of MicroMon, one can conclude that fatigue crack initiation, and growth in operation, as visible from the striation (see Fig. 2) corresponding to different operation regimes, the damage of this type is detectable since the stiffness of the blades has changed, enabling to avoid catastrophic failures.

In addition, the risk induced by damage might be also assessed, and could be of great help for maintenance, /6/.

Previously mentioned preventive maintenance is actually only one of many principles which are included in the sophisticated and complex types of maintenance.

Most of those current maintenance systems are primarily based on risk. According to the standard API 581, risk is defined as a product of the likelihood that the failure will occur and the consequence of a failure, /7/:

$$\text{Risk} = \text{likelihood} \times \text{consequence} \qquad (1)$$

Roughly, types of consequences can be categorized as financial, health, safety and environmental. Regarding probable failure of rotating equipment, all of these consequences are possible, only one of them or all as simultaneously acting. It is to have in mind that the severity of consequences of rotating equipment are at very high level, as it is shown in presented failure examples. Hence, risk related to the operating of rotating equipment must be reduced.

Examining Eq.(1) there are two possible ways to reduce risk, by reducing likelihood of occurrence or of severity of consequences. Since for rotating machines is not possible to reduce consequences, the only option is reducing the likelihood by sufficient quality of the maintenance and control of the system.

This is possible to achieve by applying vibrodiagnostics and MicroMon. Introducing continuous monitoring of equipment by a capable device, the irregularities might be detected on time, thus reducing the likelihood by applying proper maintenance action.

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