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FLUID STRUCTURE INTERACTION ANALYSIS ON FAILURE OF FRANCIS TURBINE RUNNER BLADES

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ABSTRACT

This paper describes the influence of tail profile of francis turbine blade on creation of vortexes and cavitation and its effects on initiation of crack. Fluid structural analysis is utilized to determine the location of Von-Karman vortexes and the positions in which cavitation occurs. Incompressible viscid Navier-Stokes formula was solved by CFD numerical method, meanwhile the stress distribution on the runner blades are calculated in FEM. It led to indicate the situation of crack nucleation and the results are perceived for both existence and retrofitted blades.

Keywords: crack propagation, francis turbine, runner, vortex.

1. INTRODUCTION

Renewable energy is one of the most important sources of energy in the recent years; especially hydro electric power plants play an important role in nowadays industrial world. Regarding to high pollution of air and problems in ozone layer, these power plants produce clean electric energy without any CO2 emission and save the environment.

Cavitations and vortexes may cause erosion damage, noise, vibration which leads to hydraulic performance declination. However, a vast amount of researches have been performed towards understanding the reality of the vortexes phenomena, the impact of cavitation destroys blade surfaces yet. The critical cause of the vortexes and cavitation is generating cracks on the blade surfaces which lead to dysfunction of turbine set and electric generation.

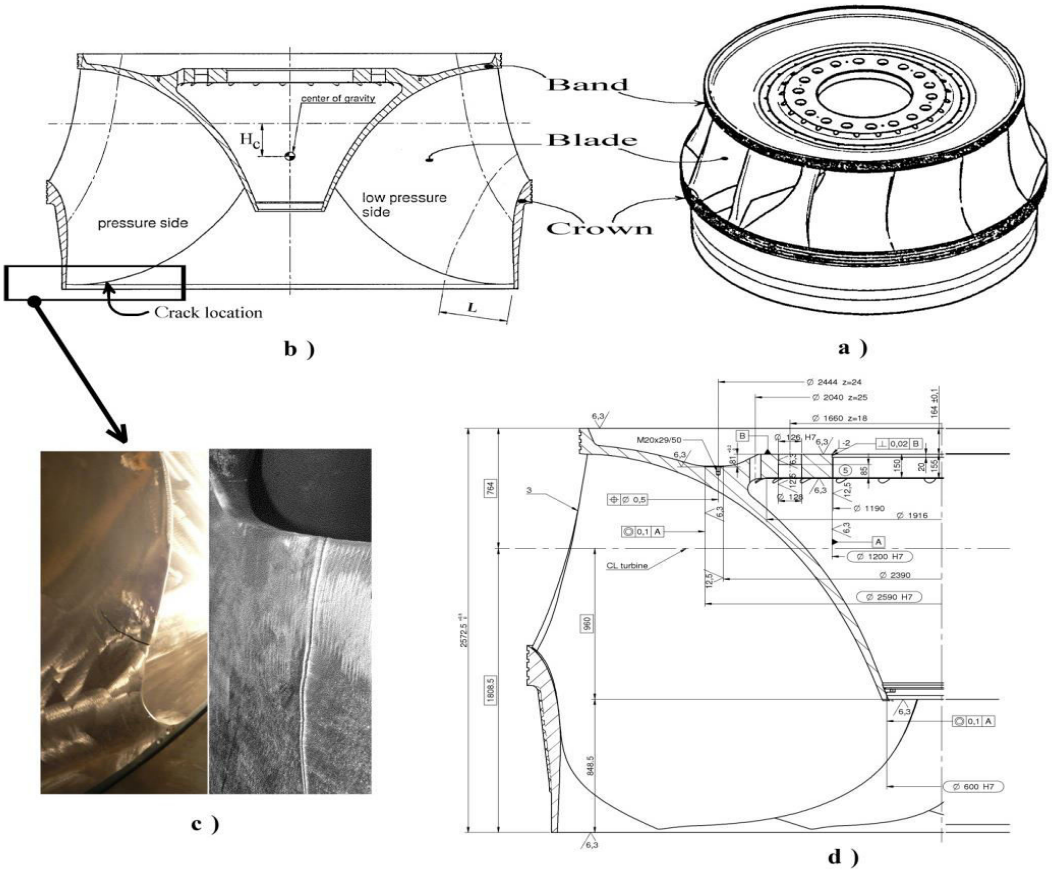

Figure-1. General view of runner a) Isometric view b) Section view c) crack d) General dimension.

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Cracking phenomena is investigated in runners of turbine in a various field. First of all, it is researched separately in mechanical and metallurgical or in other words macro and micro views. Second, the crack was seen as the results of manufacturing process, heat treatment and the quality of material used in the production of runners. Third, it is studied to detect the defect in the runner during the working condition.

Fatigue cracks on runner were studied in static and dynamic conditions. It shows the resulting stresses on the runner causes to start micro cracks and grows up due to the stresses [1-3].

Fatigue failure starts at a constant depth under surface in which the stress equals the fatigue strength of the material [5]; and the stress concentration factor at the root of a sharp notch to the average stress of critical distance is another approach [4, 6].

Fatigue, erosion and cavitation are the factors affecting failure mode and increases maintenance. Metallographic investigations showed that the cracking of the blade was caused by fatigue and was initiated by non metallic inclusions existing in the vicinity of the blade surface. The crack propagation occurred gradually due to high content of non-metallic inclusions and the inhomogeneous structure of the blade material, additionally numerous secondary cracks developed inside the material [7].

Defects such as pores or cracks, originated in manufacturing process and local stress concentration arising by inadequate design features, are the main factors of failure [8]. Although, the majority of failures could be addressed to high-cycle fatigue, the common factor is high local stresses and also stresses gradients [9, 10].

Appropriate manufacturing process and quality control lead to coincident the theoretical design to the final products. The gas holes, heat treatment, casting and machining process are the factors that the crack appears in the runner. Austenitic heat treatment broke the microstructure remaining from casting and cast ferrite-pearlite with oxide non-metallic inclusions and with dendrite structure is observed in the laboratory results [11].

The low pressure helical vortex in the draft tube originated near the runner and moved down in the draft tube. The movement changed the water pressure inside the draft tube, and eventually produced the water pressure pulses in the draft tube and at the runner vane [12].

Dynamic stress variations due to sudden alteration of load case were studied utilizing the fluid structural coupled numerical analysis method [13]. High head, rated head and low head in multiple step of rotation of runner with respect to wicket gates were opted [14].

By measuring the natural frequencies of blade and shaft, it may be tracked to determine any shifting due to cracking or other phenomena affecting torsional natural frequencies [15]. Being difficult in very small signal of blade and shaft torsional vibration, optimized transducer and data acquisition were implemented for dynamic range of signal to noise ratio [16, 17, 18]

However, experimental or theoretical methods have been implemented; there is no comprehensive method to express the modality of cracks, its initiation and growing up in the runner under the high water pressure.

In Figure-1-a the isometric view of the runner is shown which consist of 15 blades. In Figure-1-b the cross section of runner is depicted to illustrate the dimension and the overall shape of blades. In the Figure-1-c the created crack in the reality of existence runner is shown. In part d of Figure-1, overall and detail dimension of runner were illustrated. It includes the dimension of crown, band, blade and the detail of the runner connection.

Purpose of this study is to demonstrate the influence of tail profile on the crack initiation and propagation by implementing numerical fluid structural interaction. Two critical cases are considered and the affecting stresses were calculated in the existence blade airfoil and the retrofitted one.

2. THEORETICAL FORMULA

Effect of shocking flow on the tail of airfoil profile of blade of hydro turbine are studied numerically using unsteady Reynolds averaged Navier-Stokes formula. The main Navier-Stokes formulas are the governing equations for incompressible viscid flows. These equations interpret the physics behind the fluid dynamics and the mathematical statement of three physical principles upon which the fluid dynamics are based on [19].

$$\rho \frac{Du}{\mathrm{Dt}} = -\nabla p + \mu \Delta u + F_B, \tag{1}$$

$$\nabla . u = 0, \tag{2}$$

where ρ is density of the fluid; **u** is the velocity vector of fluid; p is fluid pressure; $\mu$is viscosity, and **F** is a body force. $D/$Dtis the substantial derivative expressing the Lagrangian acceleration of a fluid parcel; ∇ is the gradient operator; Δ is the Laplacian operator, and ∇.is the divergence operator. Equation (1) which is a three component vector equation is just Newton's second law of motion applied to the fluid particle. Equation (2) is simplified conservation of mass in the context of constant-density flow.

$$\sigma_{\mathrm{ij}} = \left(\frac{K}{\sqrt{r}}\right) f_{\mathrm{ij}}(\theta) + \sum_{m=0}^{\infty} A_m r^{\frac{m}{2}} g_{\mathrm{ij}}^{(m)}(\theta), \tag{3}$$

For cracked configurations subjected to external forces, it is possible to derive closed-form expressions for the stresses in the body, assuming isotropic linear elastic material behavior. Considering the origin of the polar coordinates at the crack tip, it can be shown that stress in any linear elastic cracked body is given by [19]:

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Where parameter$\sigma_{ij}$is the stress tensor of a defined element; r, $\theta$are the location of element with respect to crack tip in polar coordinates; $K, A$and m are constants, and$f_{ij}$is a dimensionless function ofθ.

3. SIMULATION METHODOLOGY

Unknown parameters caused crack initiation on the connection point of blade airfoil profile to the crown surface. The most important ones were vortex and cavitations which shifted the flow to unsteady patterns out of designed charts.

To overcome the problem four methods were considered. First of all, small welded parts added at the end of blade near the crown. It resulted that the vortexes effects decreased but again the crack initiated. Secondly, another part added to the tail of blades and it radial length increased. Experiments shown that a little later the end part of the blades separated from the crown. Thirdly, some parts of original blades were removed. In this method better flowing pattern results obtained, though the blades cracked again. Finally, retrofitting the airfoil profile of runner suggested. The metallic sheets of blades were stiffened near the tail with minority of airfoil change.

In this study, an existing runner of a Francis turbine of 250MW hydro power plant is considered. The static pressure that acts on the main inlet valve located just before the turbine is 1.5MPa gauge. The average velocity of water in nominal capacity of turbine in main pipeline is $8.7m/s$; the major diameter of runner is 4500mm and its height is 2000mm.

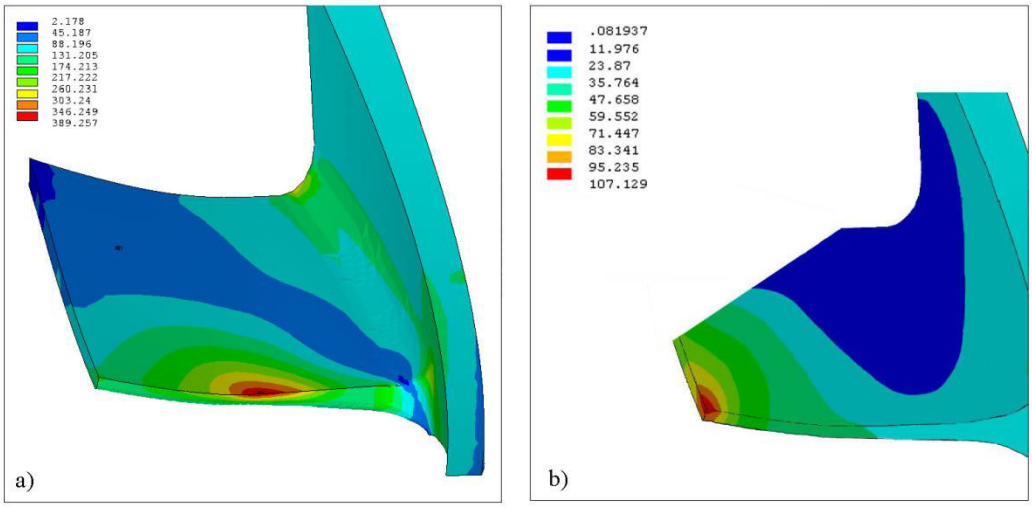
According to symmetric condition, in the FEM model only one blade and the half of distance between two adjacent blades are considered. The model is solved in ANSYS (CFD) simulation software that allows predicting, with confidence, the impact of fluid flows on the product in Viscous and turbulent flows. The coupled field solver is used to deriving the results of influences of viscid flow on structure of blades.

4. RESULTS AND DISCUSSIONS

In order to validate the simulation methods, strain gauge installed on the various points of the blades of the real working runner. The runner was taken under the partial loads, full load, no load, and rejection load. The results show that increasing or decreasing of tail has no effect on the crack initiation. Changing of tail of runner shape toward the upstream lines, led to stabilized the effects of vortex and cavitation on the solid airfoil profile; nevertheless, the vortexes did not fully diminished, it shows that the last method highly declined the connecting point stresses which was due to the influences of vortex and cavitation forces acting on the tail of blades. The predicted results have compared with the comprehensive data available by the experiments. Simulated results show the tail stresses due to tail vortex on the blade of the turbine.

In the Figure-2a the Von-Mises stress due to runaway of runner are shown. The stress distribution of existing runner illustrates that the max stress are located near the connection line of blade and crown and at the connection also the stress range is high, though near this region the stresses are a little decreases. The stress concentration come out of the area of blade and crown connection and the amount of stress declined significantly.

This condition is not a safe mode for operation of turbine; the turbine parts are designed to convert the water kinetic energy to electrical, but when the crack initiate a part of kinetic energy is absorbed to create the crack and propagate it. Secondly, the efficiency of runner comes down as the length of crack increases. Third is propagation of crack will led to unbalance of the runner which causes high unforeseen forces that may disturb generator, shafts and other rotating part.



a) welded tail b) modified model

Figure-2. Von-Mises stress in runaway condition.

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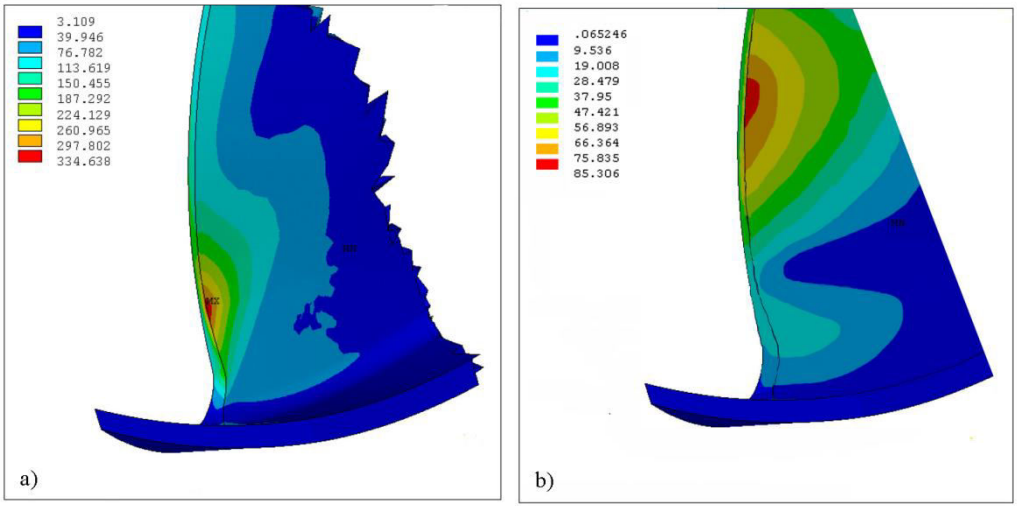
In the Figure-2b, the Von-Mises stress distribution in rehabilitated runner is shown. The results of modified case demonstrates that the stress concentration come out of the area of blade and crown connection and the amount of stress declined significantly, too. Also the distribution of energy and stresses on the tail of blade become wider, so the minimum energy to initiate the crack will not be gathered in a point.

In the Figure-4, Von-Mises stresses due to no-load case of runner working condition are shown. In the left, the stress distribution of existing runner demonstrates the location of maximum Von-Mises stress at the tail of blade which is not far from crown; also its magnitude is too high.



a) welded tail b) modified model

Figure-3. Von-Mises stress in no-load condition.

This case is not a safe mode for operation of runner; the runner is not designed to bear this high stress load continuously; and it affects seriously on the efficiency of turbine and declines it. In this case as the crack propagates, being near the crown, it may cause to separate the blade and crown.

In Figure-3b, the Von-Mises stress distribution in rehabilitated runner is shown. In this case, the stress concentration come out of the area of blade and crown connection and the amount of stress declined significantly. In Figure-4a the graph of Von-Mises stresses in runaway condition in the tail line of blade is shown. The curves are normalized in the direction of tail line by x/Lwhich starts from the crown side as zero point. In the vertical axis the stresses are normalized by$S/S_{\max}$. The first curve shows that the location of maximum stress is near to the crown and with a high slope its amount decreases as it moves far from the crown. But in the rehabilitated blade the maximum is a little farther from the starting point and in both side of the peak point there are smoother slope of variation of stresses. It demonstrates that gradient of stresses is higher in the first curve and it located in the region in which the cracks created in the existing runner.

In Figure-4b, the curves show the distribution of Von-Mises stress in no load condition. Like the Figure-4a, it is normalized in both axis. The graph expresses that in the existing runner the peak stress position is near the crown but not as close as in runaway condition. In contrast, in the second curve in this figure which belongs to the rehabilitated blade the maximum stress reduces in magnitude and is too far from the crown to induce stress concentration. Comparing these two curves illustrates that the gradient of stress in the existing model is bigger than the stiffened blade and the location of highest stress point in the first curve is nearer to the clamping side.

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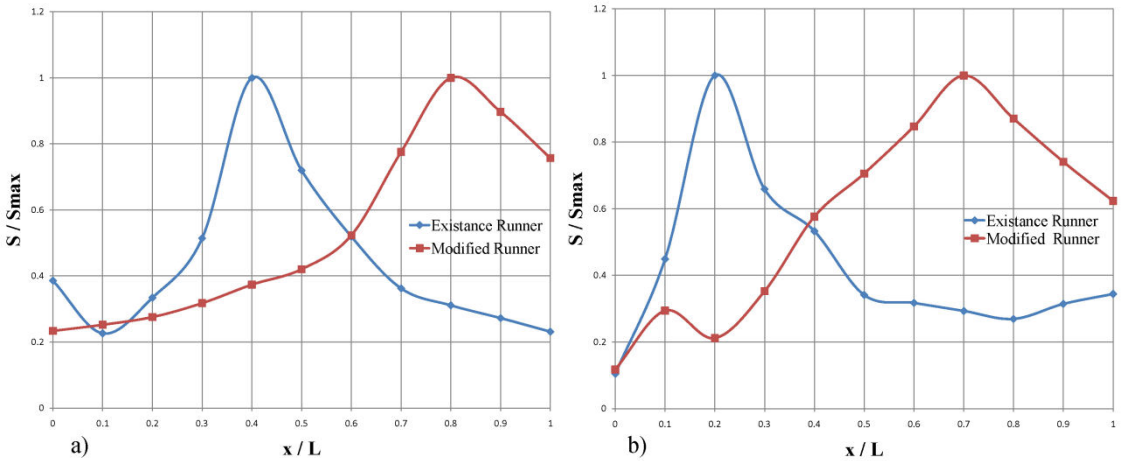

a) Runaway b) No-Load

Figure-4. Stress magnitude on tail line.

In both Figure (4-a) and (4-b), it is shown that the maximum Von-Mises stress occurs in the cracking area. Also the extreme amount of gradient exists near the maximum calculated point. Both of these conditions are the main phenomena to generating the crack. In the other hand, as the stress is distributes in stiffened blade, the energy exerted on the tail is distributes widely and restricts to act on specific point. Hence the minimum energy to create the crack will not reacted by the fluid on a point. It proves that by the new method of stiffening the energy of fluid distributed widely on the tail of runner and causes that the maximum stress decreases. It lead to a situation that the minimum energy to start cracking will not exist in the tail.

5. CONCLUSIONS

By the results of analysis it is proved that the new method can be implemented to modify or renovate the old outdated francis turbine. In the presented case the following outcome were gained:

a) The maximum stress reduced with respect to the primary condition which means the blades' material can withstand the stresses; therefore the life span has been increased.
b) The location of the maximum stress was relocated and moved toward the edge of blade out of the connection zone of blade and crown. It led to distribute the pressure so the maximum stress decreased. Also the maximum stress in new case is out of the welding affected zone of the crown and blade which may contain any dysfunction during welding process.
c) As the maximum stress decreased due to the distribution of pressure load over the blade, it means that the local amount of energy decreased which is not enough to initiate and propagate the crack.
d) By utilizing this method, it is possible to tremendously reduce the stress and energy localization, but it has little effect on the cavitation phenomena. In the other hand it can reduce the vortex or postpone its generation so that it does not occur over the blade edge. Also it empower the blade against flattering and unwanted vibration leading to higher life time.

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