HYDRODYNAMIC LOADS ON A HYDRAULIC TURBINE WICKET GATE

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Abstract. *This work has the objective of introducing a methodology to estimate loads on wicket gates' shear pins of a Kaplan turbine and relate its failure events to overload with hydrodynamic origin. The study was held on the Hydro Power Unit of Coaracy Nunes, situated in Amapá (Brazil). There are many aspects that may be considered as causes of the shear pins failures such as fatigue failure, excessive static loads due to bad alignment and assembly problems. The main factor that is considered in this research is the study of hydrodynamic loads caused by the flow passage through distributor's vanes and transmitted to the remaining of its structure. This could cause cyclic overload and, consequently, lead to the shear pin damage. To investigate this phenomenon, an analysis of the distributor structure was performed in order to estimate the acting transient loads on each component of its drive system caused by the flow. To determine the incident torque on the distributor's guiding vanes, data from CFD simulations of the flow on wicket gates were used. As result, the loads acting on the shear pins originated by the flow passage will be known. This research is important to determine the relation between hydro-induced instabilities and the shear pins failure events.*

Keywords*: Kaplan turbines, shear pins, wicket gate, fatigue failure*

1. INTRODUCTION

The Hydro Power Plant of Coaracy Nunes is situated at Araguari River, Amazonic region of Brazil. The Central has begun its commercial operation in 1975 with two Kaplan Turbines. Managed by ELETRONORTE (Centrais Elétricas do Norte SA) the units had been through a modernization process in 2003 that enhanced the capability of generation to 78MW. After this process, successive events of failure on shear pins from the distributor drive system have been reported. Shear pins are the bonding components of this assembly and its failure compromises the performance of the whole distribution mechanism.

Several factors would be indicated as cause of shear pins failure events, as the flow in a hydraulic turbine structure involves many important and complex factors. One of the most important is the presence of dynamic loads on its metallic components (Balint et al. 2002).

These phenomena are known as fluid-structure interaction and are responsible for many critical problems such as vibration, cavitation, among others. The hydrodynamic loads may be pointed as cause of many others damages related to cyclic stresses caused by the flow, what may cause defects to many mechanical components of the structure.

These failure events on shear pins have been object of some studies and re-projects. The work of Azevedo et al (2009) investigated the mechanical properties of the material that composes the shear pins installed in Coaracy Nunes Unit. Finite Element simulation was held to determine the maximum load applicable to the shear pin considering first, the component submitted to ideal operation conditions – with shear only. The other simulation considered spurious bending loads acting on the shear pin. As a result, it was known the limits to prevent failures resulting from static and variables loading, considering pure shear condition and the presence of spurious bending loads.

Recent work of Santos et al (2008) presented a CFD study on the turbulent flow inside a Kaplan Turbine's spiral case. The main objective was analyzing the incident torque on Coaracy Nunes Unit's distributor blades and also observing the flow effects that could possibly cause spurious loads with a hydrodynamic origin, such as vortex shedding.

This work considers the resultant force on shear pins, taking into consideration the hydrodynamic loads acting on the wicket gates and transmitted to the other components of the system. To do so, the estimative of torque caused by the flow on each blade was considered. These torque values were obtained by CFD studies of Coaracy Nunes' spiral case developed in the work of Noleto (2009), in which a scale adaptive simulation of the turbulent flow inside the spiral casing was performed. The results of torque values were used to estimate the reaction acting on shear pins by the computation of the force transmitted to the blade structure.

This article is important on the research context as it considers the analysis of the dynamical loads caused by the flow and its effects transmitted to the shear pins. This could signalize new hypothesis on the shear pins failure events and contribute to find a solution to this problem.

1.1. Turbine's Characteristics

The machine of this analysis is a Kaplan turbine, with nominal capacity of 24MW after the modernization process held in 2003. After that, the events of shear pin failure have started. Failures from one single pin up to every 20 shear pins at once of the distributor drive system were reported. These events cause many disturbances on the unit's production routine, as turbine halt for pins substitution and maintenance what implies on pecuniary losses and decrease on the generation capacity.

The mechanism of distributor's blades opening control is made through the actuation of two pistons, assembled on turbine's external structure. This hydraulic control is performed by the synchronized action of two actuation arms. While one rod is in its maximum course, the other is on the opposite condition, determining the degree of opening of all 20 directional vanes of the distributor and consequently, the power output of the unit. The hydraulic pistons are linked to the control ring, which will determine the whole assembly movement. This ring is responsible for the transmission of movement on the distributor's mechanism.

Each distributor's blade has a central axle mechanically connected to the control ring by the actuation of a crank-rod system, which drives each blade. The connection between these two elements is made by a pin, known as shear pin.

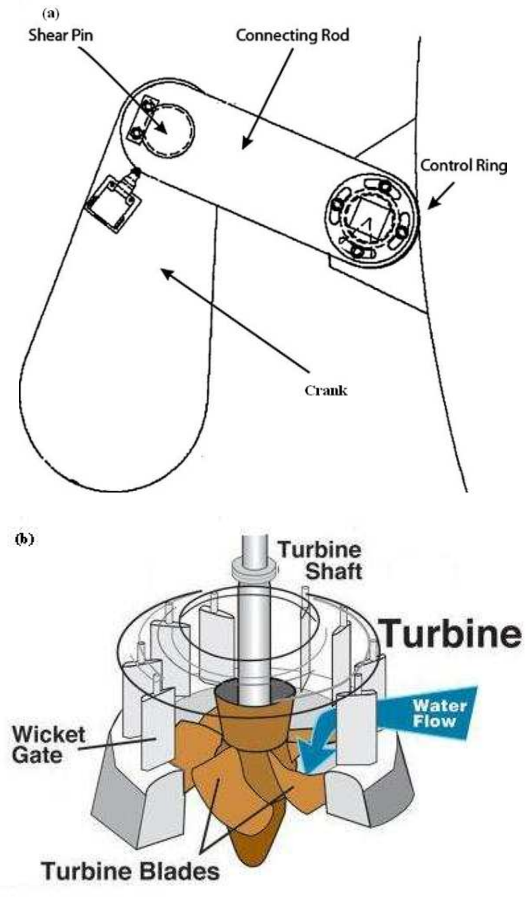


Figure 1. (a) Shear pin and crank-rod assembly, (b) Kaplan Turbine – adapted from www.wikipedia.com

The shear pin is made of an ASTM 410 Stainless Steel and has the main function of being a load transmission element between the rod and the crank, while the control ring is put into movement. However, the shear pin also plays the part as a mechanical fuse of the whole assembly, avoiding damage caused by shear stress overload.

Considering the distribution system present at UHE Coaracy Nunes, it is composed by 20 blades, each of them controlled by its own crank – rod drive system.

1.2. Hydrodynamic Loads

Hydrodynamic Loads are those ones that result from water flowing against and around a rigid system. Considering the guiding vanes of the distributor, this kind of load is caused mainly by the distribution of pressure on its surface when in contact with the flow (Santos et al, 2008). In ideal project conditions, considering that the unit operates at full load, it is expected that the angle of the hydraulic profile of the blades leads to a minimally disturbed flow and a totally attached boundary layer. However, the flow over the distributor blades has highly complex hydraulic characteristics. These effects occur mainly by the turbulent nature of the incident flow on blades, which naturally leads to an effect of temporal variation of the gradients of velocity and pressure. Besides the random behavior of turbulence, another factor that influences on time variation of velocity fields is the flow's behavior for certain angles of blades' opening, when typical structures of flow separation are present, with presence of Von Karman's vortex street. Thus, the superposition of random phenomena with the vortex emissions, compose a transient behavior of pressure and velocity fields on the proximity of each blade.

Taking into consideration the hydrodynamic phenomena on blades' incident flow, it is possible to analyze the way that load transmission occurs between the distributor's structures. Inherently to its function, the articulations that activate the wicket gate are submitted to complex loading, specially shear. Drag and Lift loads are transmitted directly to the axis of the guiding vanes, defining the forces that act on each blade's holding mechanism. On the other hand, the torque due to the flow, acts on the blade support axis and is transmitted to the crank-rod system of the control ring and consequently to the shear pin, that bonds these two elements. As the blades positions are circumferentially distributed, the flow that comes from the spiral case will have a particular incidence on each blade, resulting on very complex hydrodynamic characteristics and causing different forces and torques for each blade.

2. LOAD TRANSMITION

2.1. Parametrization

To optimize the comprehension of the dynamic behavior of the system that activates the wicket gates, a simplified model of the mechanism was developed. It considered the components of the assembly, such as control ring, crank, rod and blade. These elements were studied to develop the computation of load transmission through the system. The components were simplified as undeformable solids, connected by perfect links. By this way, the drive system of wicket gates was modeled in multi-corps elements, represented by simple bars. The parametrization of the assembly permits to locate each component in function) of the other, through relative angles (relative parametrization). The parametrized multi-corps model is shown on Figure 2.

In this model α is defined as the opening angle of each distributor's blade, θ_1 is the angle between the control ring and the fixed point O', θ_2 defines the angle between the control ring and the rod and θ_3 is the maximum opening angle of the blade. The point C represents the shear pin, while l_3 is the distance between the shear pin and the fixation point of the blade on the rod. θ_4 and ψ are intermediate angles.

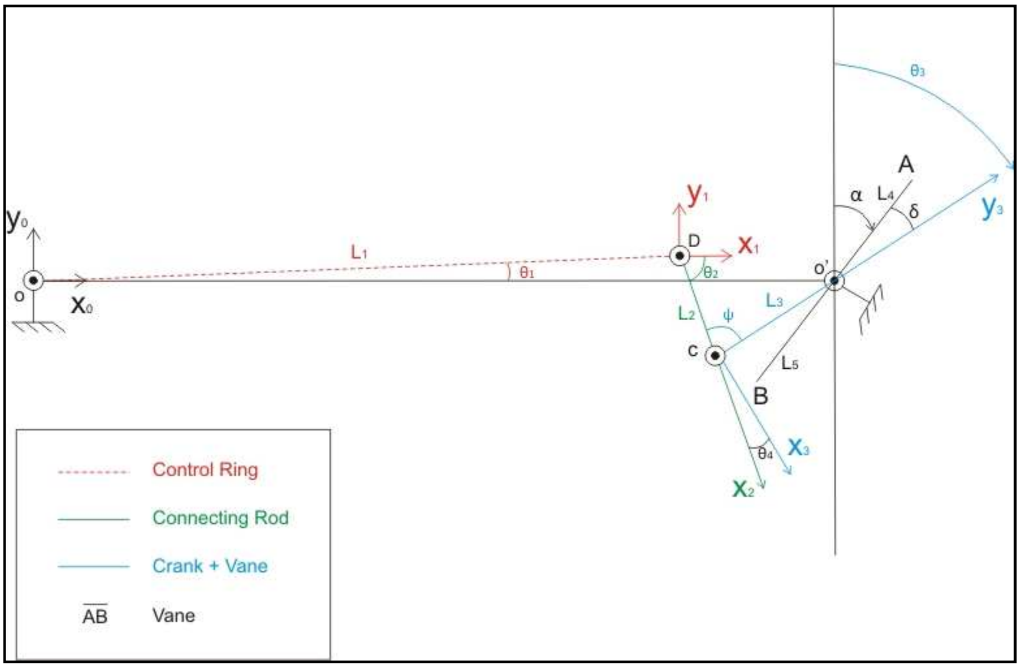


Figure 2. Distributor's Parametrization

2.2. Mathematical Formulation

Using the torque values acting on the blades, obtained by the CFD simulation carried through by Noleto (2009), the acting loads on shear pins were computed using the parametric equations. Following, the computation of estimated load with hydrodynamic origin for one of the blades is presented and the same methodology was used for the other blades. The pivoted links in “*D*”, “*C*” e “*O*’” are considered perfect.

First, considering each element of the assembly separately, the loads acting in the rod was estimated by static forces equilibrium:

$$\vec{R}_C = \vec{R}_{3\to 2} = -R\vec{x}_2 = -R\left[\cos(\theta_1 - \theta_2)\vec{x}_0 + \sin(\theta_1 - \theta_2)\vec{y}_0\right] \tag{1}$$

$$\vec{R}_D = \vec{R}_{1\to 2} = R\vec{x}_2 = R\left[\cos(\theta_1 - \theta_2)\vec{x}_0 + sin(\theta_1 - \theta_2)\vec{y}_0\right] \tag{2}$$

The torques acting on the links are $T_{1\to 2}$ (action of the control ring on the crank) and $T_{3\to 2}$ (action of the rod on the crank):

$$T_{1\to 2} = \begin{bmatrix} R\cos(\theta_1 - \theta_2) & - \\ R\sin(\theta_1 - \theta_2) & - \\ - & 0 \end{bmatrix}_{D,x0,y0,z0}$$

$$T_{3\to 2} = \begin{bmatrix} -R\cos(\theta_1 - \theta_2) & - \\ -R\sin(\theta_1 - \theta_2) & - \\ - & 0 \end{bmatrix}_{C,x0,y0,z0}$$

The torque acting in the fixed point (*O’*) (coupling rod-blade) $T_{0\to 3}$ and the torque induced by the flow in the blade $T_{flow/vane}$ are given by:

$$T_{0\to 3} = \begin{bmatrix} X_{03} & - \\ Y_{03} & - \\ - & 0 \end{bmatrix}_{O',x0,y0,z0}$$

$$T_{flow/vane} = \begin{bmatrix} 0 & - \\ 0 & - \\ - & M_1 \end{bmatrix}_{O',x0,y0,z0}$$

As shown in Figure 3, The static equilibrium on the rod gives:

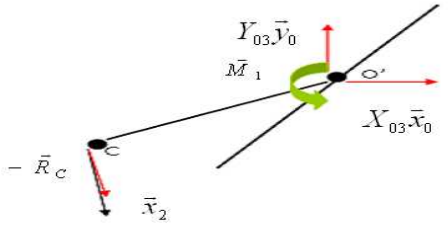


Figure 3. Static equilibrium on the rod

$$\sum T_{i\to 3} = 0 = T_{2\to 3} + T_{0\to 3} + T_{escoamento\,/\,pá} \tag{3}$$

The equilibrium condition gives:

$$\sum \vec{F}_{i \to 3} = \vec{0}$$
$$\sum \vec{M}_{i \to 3}(O') = \vec{0}$$

With:

In X direction

$$X_{03} + R\cos(\theta_1 - \theta_2) = 0 \Leftrightarrow X_{03} = -R\cos(\theta_1 - \theta_2) \quad (4)$$

In Y direction

$$Y_{03} + R\sin(\theta_1 - \theta_2) = 0 \Leftrightarrow Y_{03} = -R\sin(\theta_1 - \theta_2) \quad (5)$$

And the Momentum:

$$\sum \vec{M}_{i \to 3}(O') = \vec{0} \Leftrightarrow \vec{M}_{2 \to 3}(O') + \vec{M}_1 = \vec{0} \quad (6)$$

The momentum $\vec{M}_{2 \to 3}(O')$ in the origin is defined by:

$$\vec{M}_{2 \to 3}(O') = \vec{M}_{2 \to 3}(C) + \vec{O'C} \wedge \vec{F}_{2 \to 3}$$

$$= \vec{0} + (-l_3 \vec{y}_3) \wedge R(\cos(\theta_1 - \theta_2)\vec{x}_0 + sin(\theta_1 - \theta_2)\vec{y}_0) \quad (7)$$

$$\vec{y}_3 = sin\theta_3 \vec{x}_0 + \cos\theta_3 \vec{y}_0 \quad (8)$$

With

$$\vec{M}_{2 \to 3}(O') = l_3 R(\cos(\theta_3)\cos(\theta_1 - \theta_2) - \sin(\theta_3)\sin(\theta_1 - \theta_2))\vec{z}_0 \quad (9)$$

Thus, the resultant load transmitted to the shear pin, caused by the action of the flow in the blade, is:

$$R = \frac{-M_1}{l_3(\cos(\theta_3)\cos(\theta_1 - \theta_2) - \sin(\theta_3)\sin(\theta_1 - \theta_2))}$$

Applying the same method for all blades we can compute the resultant load on each shear pin, knowing that the rods and the cranks are identical and that the system rod-crank repeats every 18°. The angles θ_1 and θ_3 change according to the blade position in the distributor and the angle θ_2 is the same for all blades, changing in function of the opening angle of the ditributor.

The resultant load cosidering all blades together can be defined by the following expression, considering *i* a generic blade :

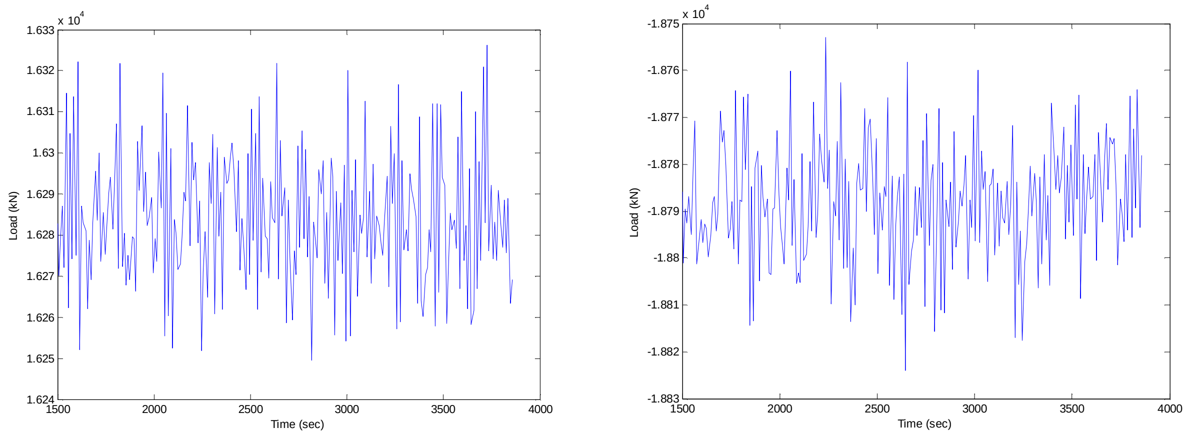
$$R_i = \frac{-M_i}{l_3(\cos(\theta_{3,i})\cos(\theta_{1,i} - \theta_2) - sin(\theta_{3,i})sin(\theta_{1,i} - \theta_2))} \quad (10)$$

2.1. Analisys Conditions

The presented results were obtained considering the condition of maximum power output of the unit nominal capacity). It means that the distributor's blades positioned on its maximum opening configuration. It means that the vanes had an opening angle of 48º (α=48°).

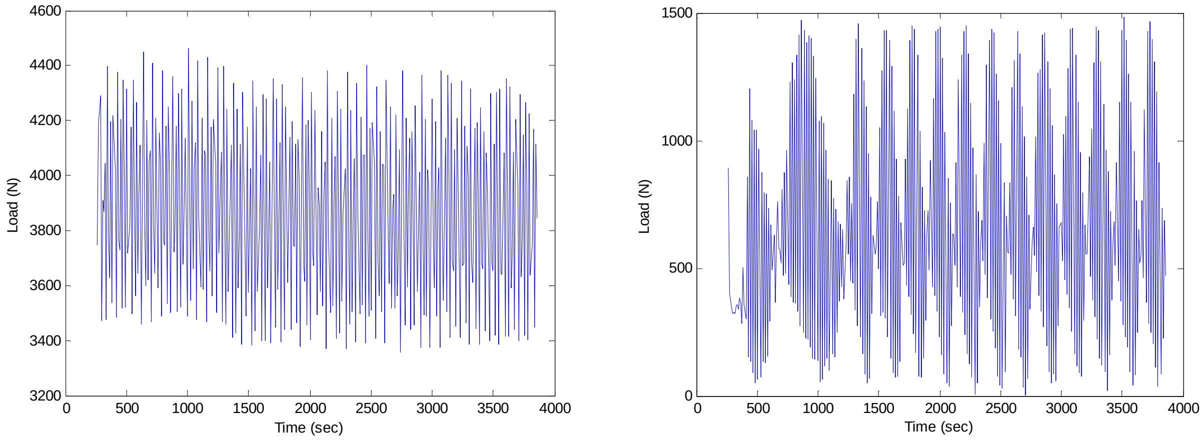
3. RESULTS

All the 20 guiding vanes were studied, but, by reason of space limitations in the article, five guiding vanes were taken into consideration for analysis as they presented the most significant results for a further evaluation. Results of average torque and load for distributor's guide vanes are presented on Table 1.



(a) **(b)**

Figure 4. Diagram of load on shear pin of blades 1(a) and 4 (b)



(a) **(b)**

Figure 5. Load acting on shear pin of blade 9 (a) and 11 (b)

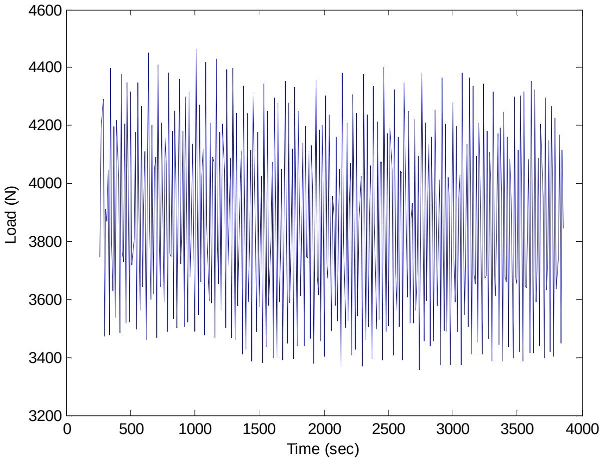


Figure 7. Load acting on shear pin of blade 13

Table 1. Results of average torque and load for wicket gate's guiding vanes

Vane	Average Torque [N.m]	Average Load [N]
1	7199,7	16318,4
2	6331,6	14350,9
3	2957,2	6702,6
4	-8299	-18810,1
5	3185,4	7219,9
6	5967,1	13524,7
7	5032,5	11406,4
8	4540,1	10290,3
9	1706,2	3867,2
10	3757	8515,4
11	287,08	650,7
12	4526,7	10260,0
13	1846,7	4185,6
14	4974,9	11275,8
15	3133,8	7102,9
16	5330,9	12082,7
17	4381,8	9931,6
18	6139,9	13916,4
19	5271	11947,0
20	6632,6	15033,1

Figures 4, 5, 6 and 7 show the results for the load on each shear pin calculated by equation 10. It is evident the irregular behavior of the load on each pin from the corresponding vane. Observing Figures 4 to 7, it is possible to notice the difference between the characteristics of transient load that each pin is submitted. The mean value of the load amplitude fluctuates from 0.6507kN to 18.8101kN according to table 1. Other important variation is related to the period of load application on each blade, which is evident on the curves obtained on the time domain graphics.

The highest loading values are present on shear pins from blades numbers 1 and 4, with loads of the order of 16kN and 18kN respectively. According to table 1, the shear pin of the crank-rod set from blade 4 is under a negative loading value. This is consequence of the negative torque associated to that blade, which means that the torque signal has a different sign compared to the convention adopted as pattern on the CFD study. Physically, it means that the blade has an opening tendency, differently from the other 19 blades. According to the study of Azevedo et al (2009), the shear pins supports a pure shear load of 108kN before fracture. However, an important remark in the same reference is the one concerning the admissible loading on shear pins considering spurious bending loads. In this particular case, the maximum admissible load for the shear pin to fail by shear is 53kN. If there is the presence of a bending spurious load associated with cyclic load, this condition would lead to a significant decrease in the shear load, which would induce a failure by fatigue, reaching a value of 14kN. As the loads generated by the flow induce to a dynamic loading on shear pins, it is evident by Figures 4 (a) and (b) that the loads on the pins correspondent to blades 1 and 4 are the order of 16 to 18 kN respectively, what may be a cause of shear pins fatigue failure if there is a bending force acting together with the cyclic loading caused by the flow on these components.

Table 2. Results of peak to peak average torque and load for wicket gate's guiding vanes

Vanes	**Peak- to- peak average torque [N.m]**	**Peak- to- peak average load [N]**
1	91.1	206,8
2	46,0	104,5
3	39,4	89,5
4	67,1	152,3
5	23,1	52,6
6	37,6	85,4
7	24,1	54,5
8	79,7	180,9
9	486,9	1104,2
10	267,4	606,4
11	654,4	1484,1
12	348,3	789,9
13	536,4	1216,5
14	259,1	587,3
15	94,4	214,1
16	170,1	385,8
17	246,9	560,0
18	221,3	501,9
19	273,5	620,3
20	156,7	355,4

Table 2 shows the peak to peak average torques and loads that every 20 vanes are submitted to. It is evident the irregular pattern of loading amplitude acting on the vanes. The most significant variation is located on vane 13 and the lowest one is acting on vane 5. The distinct amplitude of forces acting on guiding vanes is not desirable, as the main purpose of wicket gate hydrodynamical design is to ensure that the flow will be uniform within the whole assembly. Nevertheless, the complexity of the flow does not ensure that condition, and the amplitude difference on loading applicable on each vane may be a cause of spurious stresses on its structures.

In order to illustrate the action of incident hydrodynamic loads on each vane of the distributor, a polar graphic was built, and is shown on Figure 8, taking into consideration average load values. It allows the evaluation of load distribution throughout the whole distributor's assembly. Considering Figure 8, it is clear that the load distribution on the wicket gates is not uniform. Some neighbor vanes receive a more severe load coming from the flow than others. There is a considerable variation on loads applied on vanes 20 to 5 (clockwise), submitting these elements to a more complex load distribution and consequently, leading its elements (shear pins among them) to more severe operational conditions. These variations are due to the flow characteristics on the wicket gate intake, which have been directly influenced by the action of the fixed palettes of the pre distributor.

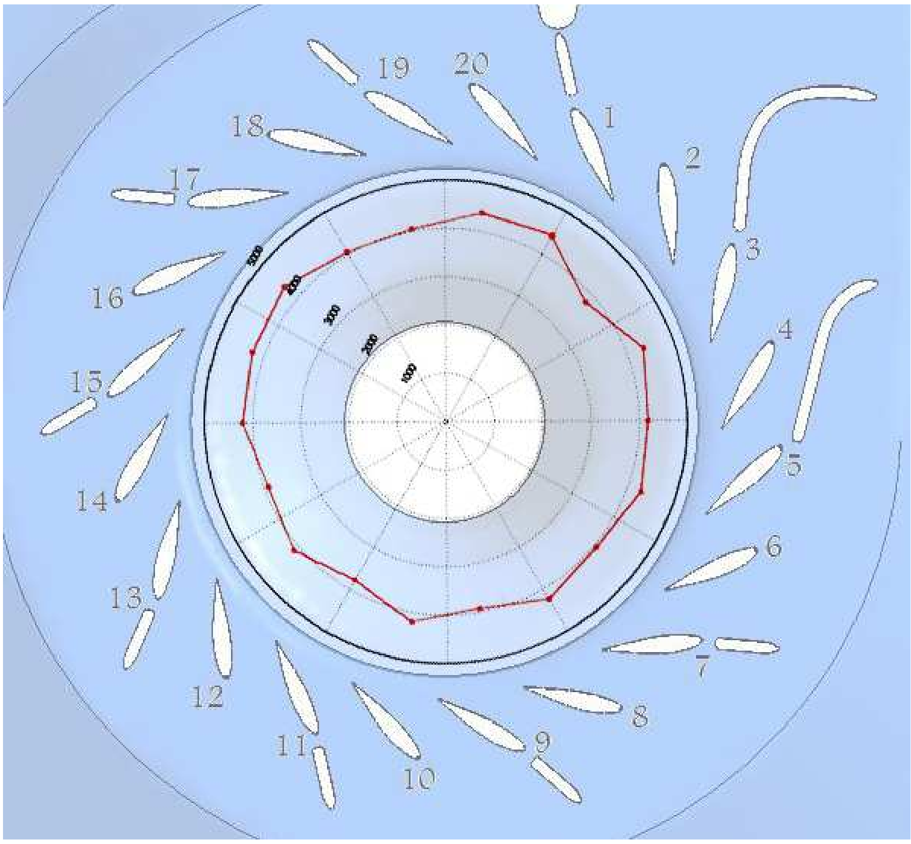


Figure 8. Load distribution on wicket gates

Even with the whole project of the spiral case to guarantee a homogeneous flow when it reaches the rotor blades, it is remarkable the difference among the loads on the shear pins located in different guiding vanes. It is due to the fact that some wicket gates receive the flow with a pressure difference, what determines the torque on the blade and consequently the load applied on the shear pin. This fact determines that dynamic loads in some vanes will be more significant than in others.

4. CONCLUSIONS

A methodology to estimate the load transmission from directing vanes to the shear pins was performed. From torque signals obtained by CFD studies, it was possible to estimate the loads acting on shear pins with a hydrodynamic origin. From that analysis, it was possible to verify that these hydrodynamic loads have a time variation and act differently on each blade. Moreover, the study permitted conclude that, considering shear loads only and with no alignment issues, the dynamic loads generated by the flow passage through the distributor's vanes per se are not sufficient to cause shear pins failures. However, in presence of bending, there is the possibility that the cyclic loads, to which shear pins are submitted, may produce loads superiors to that designated as the limit of resistance of the pins' material and may suffer fatigue failure. To prove that phenomenon it is necessary further analysis to investigate the presence of bending acting on the shear pins.

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