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KAPLAN HYDRAULIC TURBINE RUNNER HUB STRUCTURAL DESIGN

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Abstract. *In this work, a theoretical review is done in order to provide theoretical basis for the project to study the viability of implementing an improvement that would replace the material of the runner hub of a cast carbon steel (ASTM A 216 Gr.WCC) by a cast aluminum alloy (A 201.0), and analyzed the advantages and disadvantages of this modification. It's necessary using the Finite Element Method for calculating the runner hub of a Kaplan hydraulic turbine. Design, calculation and execution are crucial to the design of this component. For this, it is developed a case study that includes step by step, the methodology used. The analysis of the runner hub of a Kaplan hydraulic turbine be used in the case study.*

Keywords: *hydraulic turbine, finite element, runner, kaplan, cast aluminum alloy.*

1. INTRODUCTION

The importance of this work is to analyze the mechanical components of the runner of a Kaplan hydraulic turbine, used in hydro power plants projects, furthermore, in addition to mechanical calculation of the components that compose the turbine runner is analyzed the viability of the substitution of material runner hub of a cast carbon steel by a cast aluminum alloy with the purpose of turbine weight reduction and improvement for the project.

When using certain components in equipment that are not series, it is interesting the execution of an project in order to obtain a structure that presents gains mass (less mass), cost (higher profit) and operation (increased security).

The main objective of this work is the study of weight reduction in runner hub by replacing the material hub. For this, through the Finite Element Method, the calculations of mechanical components are performed to determine the level of stresses acting and verify which are the most critical points to calculate, as well as to study possible design improvements. This study supports the designer, allowing to obtain better design through structural analysis.

In Figure 1 shows a section of the runner of a Kaplan turbine with all its components inside for a better understanding of the elements necessary for the operation of a turbine.

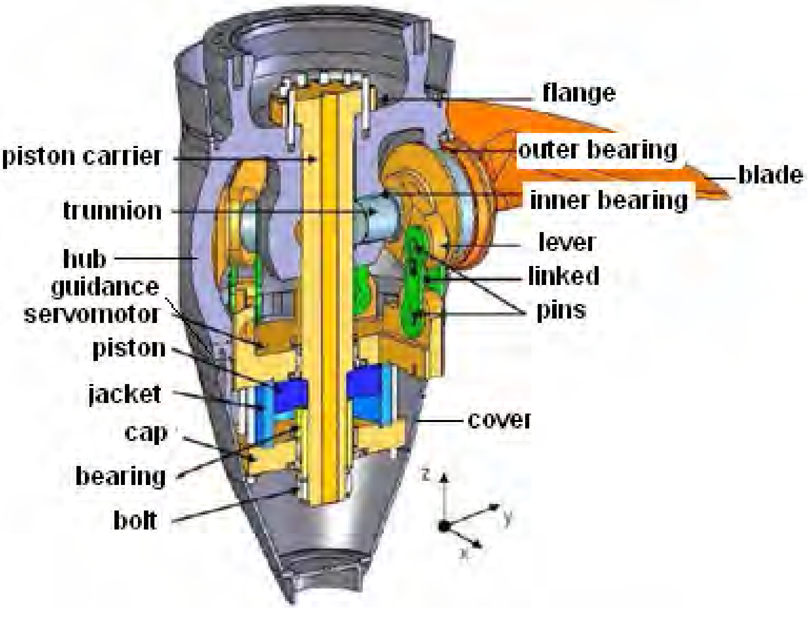


Figure 1 – View of a Kaplan turbine runner with its internal components.

For a project, the geometric parameters must necessarily be varied in a certain range of values, in order to achieve the desired result to find the optimal solutions. This result can be based on project cost (less time of design), manufacturing costs (lower cycle, lower energy, easy manufacturing, reduction of raw material). Generally, the desired results should provide greater reliability of the final product, with good performance of the equipment in operation and customer satisfaction.

2. THEORETICAL BASIS

As one of the goals of this work is the study of weight reduction in the runner hub, it is necessary to analyze other materials aiming at substitution of runner hub material that is currently the cast carbon steel, so that it has the necessary rigidity for the project linked to the lowest possible weight. For the rigidity of the component to be enhanced without great increase in your weight, it is essential to have lightweight materials and high modulus of elasticity.

To selecting properly these materials, the diagram most suitable is which shows these two properties simultaneously, as can be seen in Figure 2.

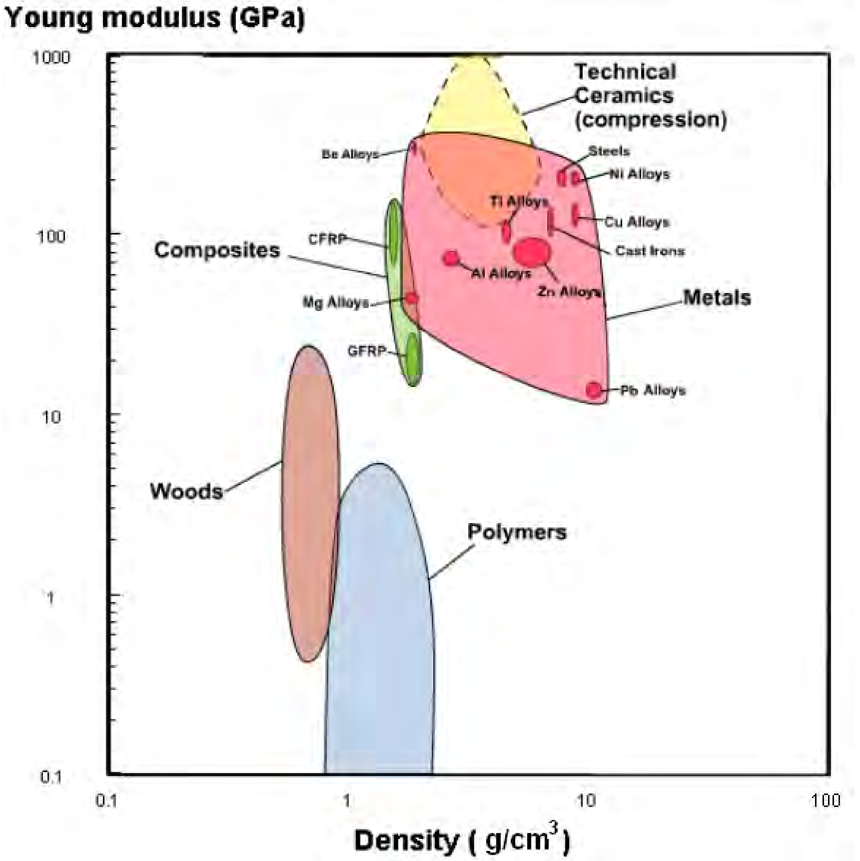


Figure 2. Diagram showing the value of the elasticity modulus versus density for different classes of materials and for some metals and alloys (Heck, 2012).

On the basis of Figure 2 it may be noted that aluminum alloys have good relation between elasticity module and density, since they have lower density than steel, thus contributing to reduced weight of the runner. In this case, because the aluminum alloy has lower elasticity module than steel, which must be calculated the impacts of this change and may to be viable in order to study in reducing weight and meet the necessity of the component stiffness. Therefore, there is need to study the properties of aluminum alloys and check what type of alloy more appropriate to replace the cast carbon steel of the runner hub.

2.1 Aluminum Alloys

The aluminum commercially pure is a metal that combines a series of expressive properties - light weight, high ductility, good corrosion resistance and excellent thermal and electrical conductivities. However, pure aluminum has a low mechanical strength for structural applications and therefore, the majority of aluminum products are obtained from an alloy in order to achieve the desired properties.

One of the aspects that make aluminum alloys as attractive as building materials mechanics is the fact that aluminum can be combined with most engineering metals, known as alloying elements, and from this combination can be adjusted to obtain a technical according to the application of the final product. Of course, a alloy can't combine all optimal properties for each application, it is necessary to know the advantages and limitations of each so you can make the best selection. The large range of alloys offers the industry a wide variety of combinations of mechanical strength, resistance to corrosion and attack by chemical substances, electrical conductivity, machinability, ductility, formability.

The cast alloys are those whose products are obtained by leaking the liquid metal into a mold to get the desired shape. Likewise workable alloy which also uses a system of four digits for identifying the aluminum in molten form. The first digit indicates the group of the alloy, as shown in Table 1, as follows:

Table 1 – Designation of cast alloys by groups (NBR 6834, 2000).

Alloy ABNT (NBR 6834)	Principal Chemical Element Alloy
1XX.X	Non-alloy aluminum (99% purity)
2XX.X	Copper
3XX.X	Silicon with addition of Copper and/or Magnesium
4XX.X	Silicon
5XX.X	Magnesium
6XX.X	Series unused
7XX.X	Zinc
8XX.X	Tin
9XX.X	Other Elements

The alloy heat treated high strength, which contain copper or zinc as the main alloying elements are as tough as steel structure, but require surface protection. These alloys are used when greater relative strength / weight is the main consideration, as in aviation. In this paper, this type of aluminum-copper alloy is the most interesting to be analyzed due to the need for the project to meet the ratio weight / resistance.

The Al-Cu alloys may have different kinds of alloying elements added for various purposes, which can cause the formation of several different phases. In general the Al-Cu alloys have high mechanical strength after heat treatment of precipitation hardening. The higher levels of hardness are obtained for copper levels of the order of 4 to 6% depending on the influence of other alloying elements present.

The Table 2 shows typical values of mechanical properties that can be obtained for the Al-Cu alloy castings.

Table 2 – Mechanical Properties of Al-Cu alloy castings (NBR 6834, 2000).

Alloy	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%) in 50mm	Brinell Hardness (MPa)
201.0 (T6)	448	379	8,0	130
208.0 (F)	145	97	2,5	55
213.0 (F)	165	103	1,5	70
222.0 (T62)	421	331	4,0	115
224.0 (T571)	380	276	10,0	123
240.0 (F)	235	200	1,0	90
242.0 (T571)	221	207	0,5	85
295.0 (T6)	250	165	5,0	75

With knowledge of the advantages of using aluminum-copper alloys, one can by Table 2 perform a comparison of various Cu-Al alloys that exist and in the case the 201.0 alloy (T6) has the mechanical properties (yield strength and tensile strength) needed to replace the cast carbon steel (ASTM A 216 Gr.WCC).

The temperas are classified according to ABNT NBR 6835 and in accordance with the processes they shall be submitted. The code (T6) means that the aluminum alloy applies to products that suffer thermal treatment, with or without plastic deformation which produces stable physical properties. The letter "T" must be followed by one or more digits that indicate the sequence of the basic processes performed: heat treatments or plastic deformations.

3. METHODOLOGY

In a study of finite elements is always recommended from simplified models and if there is need, incrementing the details that are important. The goal is to have a simple model and reliable results, because the time that demand for modeling and solving the finite element calculation is considerable in the process.

In this case, the input data required for this work are not hypothetical, they are real data from a project that is in the design phase, the Santo Antônio do Jari hydroelectric plant and is expected to be completed in 2014.

This section presents all the information needed to design the finite element calculation, obtained from the hydraulic test of the reduced model and general technical data of the Santo Antônio do Jari hydroelectric plant.

3.1 Input Data

Turbine type:	Kaplan
Orientation of axis:	Vertical
Direction of rotation (viewed from the generator):	Horary
Rotation speed in synchronism:	90 rpm
Rotation speed in load rejection:	144 rpm
Rotation speed in runaway:	219,4 rpm
Minimum aperture of blades:	8,0 º
Maximum aperture of blades:	37,2 º
Stroke of aperture of blades:	29,2 º
Head maximum net:	29,35 m
Head nominal net:	24,4 m
Rated power at maximum head:	132,35 MW
Runner diameter:	7800,0 mm
Hub diameter:	3328,0 mm
Number of blades:	5
Specific speed:	682
Weight the runner hub (ASTM A216 Gr.WCC):	40,5 ton
Weight the runner hub (A 201.0 T6):	14,3 ton

3.2 Finite Element Model

The Figure 2 illustrates the complete runner that was modeled in the software Pro-Engineer, allowing not only a study more adequate of assembly and operation of the parts of the runner and identify possible interference, but also a better visualization of details of each component in together.

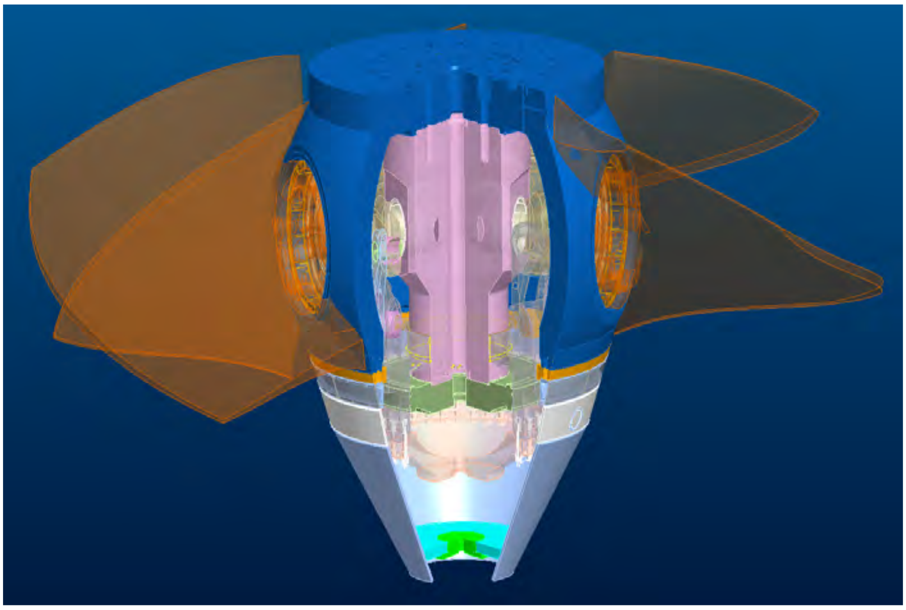


Figure 2 – Runner.

The Figure 3 illustrate the model that shows 320323 nodes and 184872 elements as considered for the finite element calculation, which 1/5 of the model geometry due to its symmetry, it has caused reduction by approximately 80% the number of elements and nodes of the model, significantly reducing the time to calculation resolution.

It was used the MESH200 element for all components that constitute the model. The element can have any spatial orientation, and allows plasticity, fluidity, resistance to stress, large deflection, and a large strain capacity.

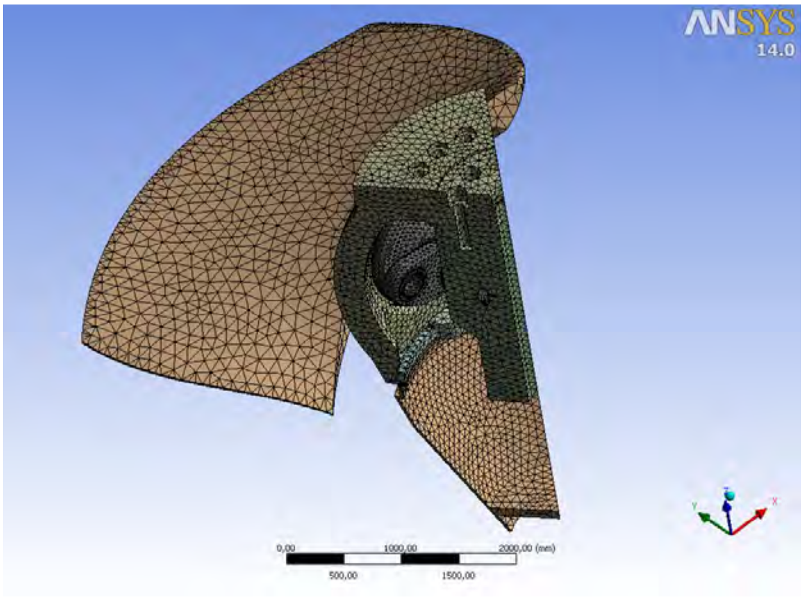


Figure 3 – Finite Element Model.

3.3 Materials applied in the project

The Table 3 shows information about the materials used and the mechanical properties for each component existing in the project. In the model 1 is used as the material for the runner hub the cast carbon steel and in the model 2 is used the cast aluminum alloy to make the comparison between the two models.

Table 3 – Specification of materials.

		Yield Strength	Tensile Strength
Component	Material	S_Y [MPa]	S_U [MPa]
Blade	A 743 CA6NM	550	755
Runner Hub	ASTM A216 Gr.WCC	275	485
Piston Carrier			
Guidance			
Runner Hub	A 201.0 T6	379	448
Lever	ASTM A148 Gr 80-50	345	550
Cover	S275 J0 N	265	410
Pins blade/trunnion	SAE 4340	880	1080
Rods			
Bolts blade/trunnion			

The Table 4 shows the other mechanical properties depending on the type of material under analysis.

Table 4 – General properties used in finite element analysis.

Material	Modulus of elasticity [MPa]	Density [kg/mm^3]	Poisson's ratio
Carbono steel	210000	$7{,}85.10^{-6}$	0,3
Aluminum-copper	71000	$2{,}77.10^{-6}$	0,33
Bronze	98000	$8{,}2.10^{-6}$	0,35

3.4 Allowable stresses for materials

The allowable stresses for all components of the runner must be met according to the ASME Code (2010), as observed in table 5.

Table 5 – Stress categories.

Primary			Secondary Membrane plus Bending (Q)	Peak (F)
General Membrane (Pm)	Local Membrane (Pl)	Bending (Pb)		
Average primary stress across solid section. Excludes discontinuities and concentrations. Produced only by mechanical loads.	Average primary stress across any solid section. Considers discontinuities but not concentrations. Produced only by mechanical loads.	Component of primary stress proportional to distance from centroid of solid section. Excludes discontinuities and concentrations. Produced by mechanical loads.	Self-equilibrating stress necessary to satisfy continuity of structure. Occurs at structural discontinuities. Can be caused by mechanical loa dor by differential thermal expansion. Excludes local stress concentrations.	- Increment added to primary or secondary stress by a concentration. - Certain thermal stresses which may cause fatigue but not distortion of vessel shape.

For each component has allowable stresses values in Table 6, according to the type of stress to be analyzed in the finite element model.

Table 6 – Allowable stresses.

Component	Normal Operation and Exceptional		
	P_m [MPa]	$P_l + P_b$ [MPa]	$P_l + P_b + Q$ [MPa]
Runner Hub (A216 Gr.WCC)	183,3	275,0	550,0
Runner Hub (A 201.0 T6)	186,7	280,0	560,0
Piston Carrier	183,3	275,0	550,0
Lever	229,2	343,8	690,0
Blade	314,6	471,9	943,8
Cover	170,8	256,3	530,0
Guidance	183,3	275,0	550,0

3.5 Determination of the loads acting on the model

To determine which of the loads that are applied to the model, require to have the results from the hydrostatic test of the reduced model. Once known such unit values (for machines 1 m head and 1 CV of net power), just transpose these values to the actual dimensions of the prototype and apply the Pro-Engineer model.

The Figure 4 shows the platform of hydraulic test of reduced model with all the hydraulic circuit to obtain the hydraulic efforts necessary for cases of turbine operation of Santo Antônio do Jari.

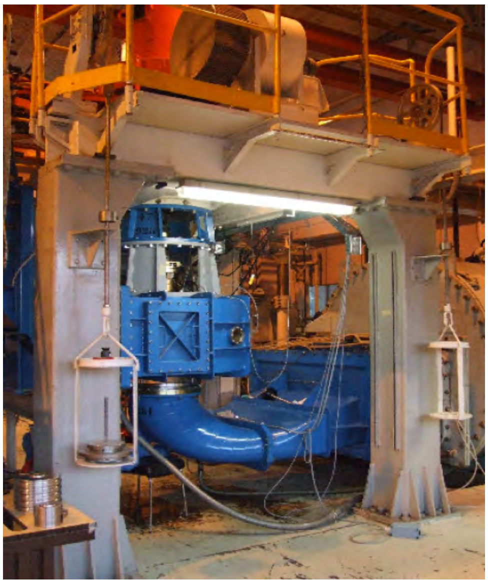


Figure 4 – Reduced model for hydraulic tests.

Practically no great hydraulic project, such as a hydroelectric plant, are designed without detailed studies on various types of mathematical models and reduced.

The construction of physical models at reduced scales, it was only possible after the discovery of the Theory of Similarity Mechanics by Isaac Newton, this also results in time savings, since it provides possible problems or solve them, thus avoiding major problems during execution.

The load cases are analyzed for which the models are:

Normal case:

- Case 1 - Synchronism - 8°
- Case 2 - Synchronism - 31,6°

Exceptional case:

- Case 3 - Runaway - 8°
- Case 4 - Runaway - 37°

The synchronization condition is the normal operating mode of the machine, so the rotation axis and generated power are to their respective nominal values cited.

The runaway condition is an exceptional case, because it is a consequence of a load rejection, either by external faults such as loss transmission line, faulty operation in substation, generation failure in power conductor, or due to internal faults as performance security system due to faulty equipment. It is a condition that because the machine can not be connected to the generator, the rotation speed of the shaft increases until reaching its limit.

The angles 8°, 31,6° and 37° are the respective opening angles of the rotor blade, conditions most critical in terms of loading for the dimensioning of the rotor blade.

The Table 7 represent forces applied in the finite element model for the calculation.

Table 7 – Forces applied on the prototype.

Load case	Hydraulic moment (N.mm)	Tangential force (N)	Hydraulic thrust (N)	Guidance force (N)	Servomotor force (N)
1	$-2,7578.10^{8}$	$2,4554.10^{5}$	$1,8036.10^{6}$	$-3,9920.10^{5}$	$-1,2706.10^{6}$
2	$-2,3399.10^{8}$	$2,4554.10^{5}$	$1,8036.10^{6}$	$5,3012.10^{5}$	$1,6017.10^{6}$
3	$-1,6211.10^{9}$	0	$1,7775.10^{6}$	$-7,1573.10^{5}$	$-2,2782.10^{6}$
4	$-2,7990.10^{8}$	0	$1,7775.10^{6}$	$7,3188.10^{5}$	$2,3941.10^{6}$

4. RESULTS AND DISCUSSION

This item presents the results related to static analysis. In this case, the results are presented in figure 5 only in case 1, however, in Table 8 presents the results for all load cases.

The displacements of the runner hub are shown as compared with the material used for calculation and design that is cast carbon steel in model 1 and the proposed use of a new material that would be the aluminum-copper A 201.0 in model 2.

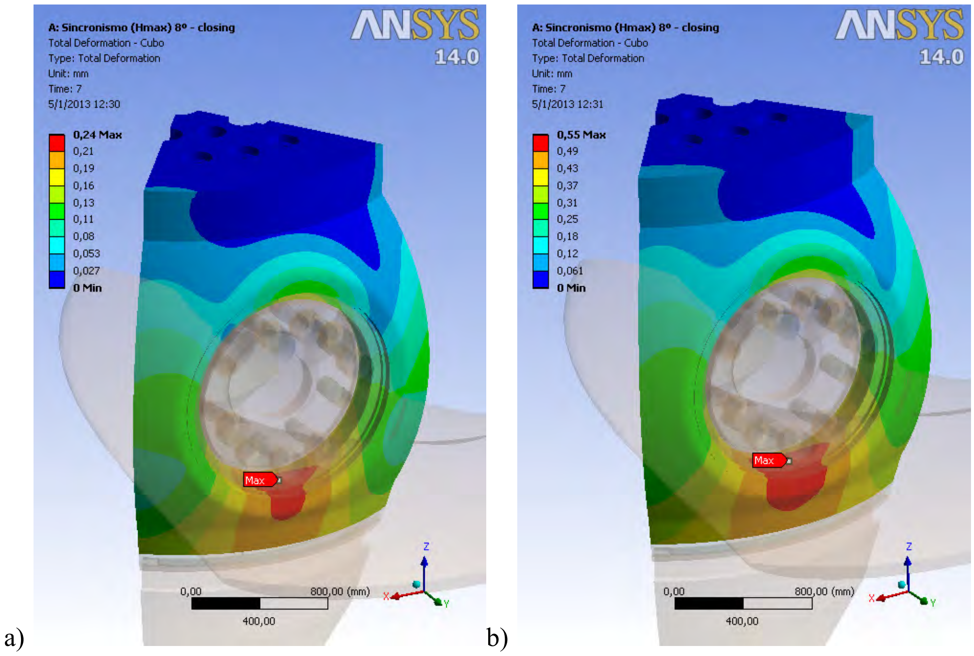


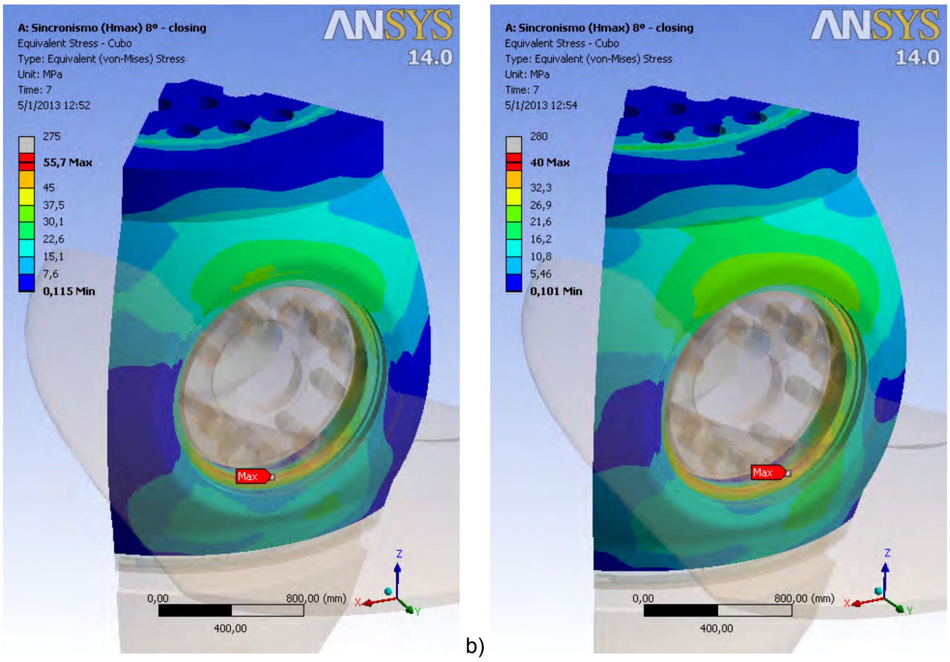
Figure 5 – Total displacement of the hub: (a) Results obtained for model 1; (b) Results obtained for model 2.

The Table 8 presents the results for all load cases of displacement of the hub in its main directions, radial and axial, both the maximum as the minimum, being of great relevance to calculate the clearances assembly design between the runner and band.

Table 8 – Resume of displacement results of the runner hub.

Load case	Material of runner hub	Displacement of the hub [mm]				
		Total	Maximum radial	Minimum radial	Maximum axial	Minimum axial
1	ASTM A216 Gr.WCC	0,24	0,16	-0,08	0,08	-0,23
	Alloy Al-Cu	0,55	0,38	-0,17	0,18	-0,53
2	ASTM A216 Gr.WCC	0,36	0,12	-0,12	0,03	-0,34
	Alloy Al-Cu	0,82	0,31	-0,23	0,09	-0,78
3	ASTM A216 Gr.WCC	1,18	0,99	-0,05	0,83	-0,06
	Alloy Al-Cu	2,56	2,15	-0,09	1,64	-0,11
4	ASTM A216 Gr.WCC	1,04	0,92	-0,09	0,52	-0,02
	Alloy Al-Cu	2,20	2,00	-0,15	1,07	-0,07

This item presents the results related to static analysis. The von Mises equivalent tensions of the runner hub are shown as compared with the material used for calculation and design. In this case, the results are presented in Figure 6 only the case 1, however, in Table 9 presents the results for all load cases.



a) b)

Figure 6 – von Mises equivalent stress of the hub: (a) Results obtained for model 1; (b) Results obtained for model 2.

The Table 9 presents the results for all loading cases of the level of stresses acting on each component of the model in study are of fundamental importance to ensure that the results obtained are below the allowable stresses as shown in Table 6.

Table 9 – Resume of equivalent stress results of the runner hub.

Load case	Material of runner hub	von Mises equivalent stress [MPa]					
		Hub	Piston Carrier	Cover	Lever	Guidance	Blade
1	ASTM A216 Gr.WCC	55,7	46,6	26,9	103,2	53,3	299,0
	Alloy Al-Cu	40,0	47,1	34,7	104,6	60,8	298,0
2	ASTM A216 Gr.WCC	60,5	49,0	28,1	124,2	51,1	221,3
	Alloy Al-Cu	48,5	47,0	35,6	130,8	56,4	221,8
3	ASTM A216 Gr.WCC	216,6	88,5	59,0	203,3	122,2	426,4
	Alloy Al-Cu	161,1	88,3	106,9	205,0	175,3	426,8
4	ASTM A216 Gr.WCC	211,4	52,0	52,4	402,9	129,3	437,2
	Alloy Al-Cu	155,4	52,9	88,5	394,9	175,0	435,4

4.1 Analysis of results

In this paper two models were studied with changing the material of the runner hub in order to study the feasibility of reducing the weight of the component structure. The results obtained are important for the practical visualization of the influence of changed parameters.

In this process, it was possible to verify the influence of the material aluminum alloy, since elasticity module of aluminum is 69000 MPa, whereas the addition of other metals does not change considerably this value, which can reach about 73000 MPa. Thus, elasticity module for aluminum and its alloys is approximately one-third of the steel, which is very important with regard to stiffness.

Due to the fact that it presents a lower elasticity module, as expected, observed in Table 8 the results for the displacement of the runner hub in the model 2 of calculation (hub material of aluminum alloy) were higher in the order of magnitude of 2,5 times compared to model 1 (hub material of cast carbon steel). Because the variation of the elasticity module it is a linear magnitude, the difference is not exactly three times higher because of the existence of the centripetal force, so due to reduction of the mass of the runner hub, this influences directly in the reduction of hub displacement.

In this case, by presenting higher radial displacement of the hub, this implies a necessity to pay attention to the radial clearance between the turbine runner and the band, since when designing a machine with mechanical clearance little larger, as has been consequence of a lower hydraulic efficiency. However, the variation of the maximum radial displacement of the hub in the case of runaway around 1,0 mm for a machine with a runner diameter of 7800 mm, not influence significantly the hydraulic efficiency to be considered a disadvantage the use of aluminum alloy.

The low elasticity module has the advantage of giving the aluminum alloy structure a high capacity for greater deformation as well as reducing the stresses produced, as can be seen in Table 9, in which the hub shows a reduction of approximately 25% the value of von Mises equivalent stress when using the aluminum alloy in the runner hub. This is interesting for projects that want to reduce the levels of stresses acting in the hub. For other turbine components, replacement of the material of the hub does not change significantly the von Mises equivalent stress.

Another very important and advantageous of aluminum alloy is lightweight, being one of the main characteristics of aluminum. Its specific weight is approximately 2,70 g/cm^3, about 35% of the steel weight and 30% of the copper weight. This characteristic combined with the increase of mechanical resistance by the addition of alloying elements / heat treatment makes the aluminum metal of choice for the aviation and transport industry.

For the Santo Antônio do Jari project, the replacement of cast carbon steel by cast aluminum alloy causes a reduction of 26,2 tons in total weight of the runner hub, this means a considerable gain for the project as a whole, since that the cost to transport these components from manufacturing until the site is predominant. In addition, the weight reduction results in a lower inertia moment, one important requirement for pieces with linear or rotational movements and rapid acceleration and deceleration which is the case of the turbine runner.

Another advantage of the turbine weight reduction is associated with the shaft coupling the turbine to the generator, since it has as one of its purposes support the entire weight of the turbine. With reduced weight, tension effort on the shaft reduces, allowing resize the shaft and coupling rods between the runner hub and shaft.

With respect to corrosion when the liquid aluminum is exposed to the atmosphere, it forms immediately a thin oxide layer and invisible which protects the metal from after oxidation. This characteristic of self-protection gives a high aluminum corrosion resistance.

5. CONCLUSIONS

In relation to the use of cast aluminum alloy rather than carbon steel, despite the technical advantages mentioned, there is a necessity to make a detailed study of economic viability, since a cast aluminum alloy cost is approximately twice that cast carbon steel. With the reduction in turbine weight, the costs of transportation reduction added to the dimensioning of the components that belong to the turbine runner also results in considerable gains. In addition, with the increasing growth of the use of aluminum, nothing prevents that in the near future the cost of aluminum is more and more competitive compared to carbon steel.

Another important point is the necessity to perform hydraulic tests demonstrating the capability of the runner hub of aluminum alloy to resist the hydraulic effects such as corrosion, abrasion and cavitation in a way that does not harm their operation over the years in a hydroelectric power plant and presents an efficiency equal or superior to that currently used is carbon steel cast. In this case, it is recommended to investigate the possibility of a surface treatment, such as surface painting of the runner hub of cast aluminum alloy.

The use of finite element calculation as a tool able to determine a geometry near an ideal solution allows that programs that operating with finite elements decrease the possibility of uncertainties. Therefore, it can be stated which are obtained a final product greater reliability with lower costs for rework due to errors during the process, improved equipment performance and result in customer satisfaction.

This paper contributes to the academic area and industrial it gives a calculation method with the knowledge required to design a turbine and analyze the feasibility of implementing improvements in the design of a Kaplan turbine.

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