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Experimental approach to rotor-stator interactions in a steam turbine using hydraulic analogy.

Summary:

The first stage blade assemblies in a steam turbine are very heavily loaded by instationnary forces, essentially due to control by partial steam injection, which is used in order to adapt the turbine to the power demand. The resulting thermal gradients also contribute to the high loads sustained by these blades. These instationnary loads are difficult, if not impossible to obtain by direct measurement. A steam turbine first stage model allows us to simulate operation in partial or total injection mode. The turbine operates in water. Its internal flow is of free surface type. A wheel blade equipped with capacitive gauges allows us to measure the instantaneous water heights on the blade assembly and it is, therefore, possible to deduce instationnary pressure values on the blade.
This paper presents the experimental results pertaining to four guide vane assembly/wheel geometries.

Abstract:

In a steam turbine, the blades of the first stage are very highly stressed by unsteady forces due to the partial injection used to adapt the turbomachinery to the power demand. Thermal gradients which result from it also participate in the important stresses sustained by these blades. The direct measurement of these unsteady forces is delicate, or even impossible. A model of a steam turbine stage allows us to simulate functioning in partial or total injection. The turbine works in water, and internal flow is in free surface flow. A rotor blade, equipped with capacitive gauges, measures the instantaneous height of water on the blade, and then it becomes possible to deduct instantaneous pressure repartition on the blade surface. In this paper, are presented the experimental results relating four rotorstator geometries.

1) Introduction.

The instationnarities which result from mutual interactions between two rows of blades or vanes in relative rotational movement are found in any turbomachine. In the particular case of steam turbines, the first stage blades are subject to very high instationnary loads essentially due to adjustment by partial steam injection which is used in order to adapt the turbine to the power demand. These loads are obviously linked with the operating conditions (pressure, rotational speed, temperature, etc.) but also to the blade assembly geometry. A better knowledge of these loads would allow us to optimise the turbine blade design while reducing the risk of fatigue failure (alternate loads).

CETIM is conducting an essentially experimental research work jointly with the CNAM and the French manufacturers of such machines.

A steam turbine first stage model (figure 1) allows us to simulate operations in partial or total injection mode. The turbine operates in water. Its internal flow is of free surface type. A wheel blade, equipped with capacitive gauges (figure 4), measures the instantaneous water heights on the blade assembly and it is, therefore, possible to deduce instationnary pressure values on the blade.

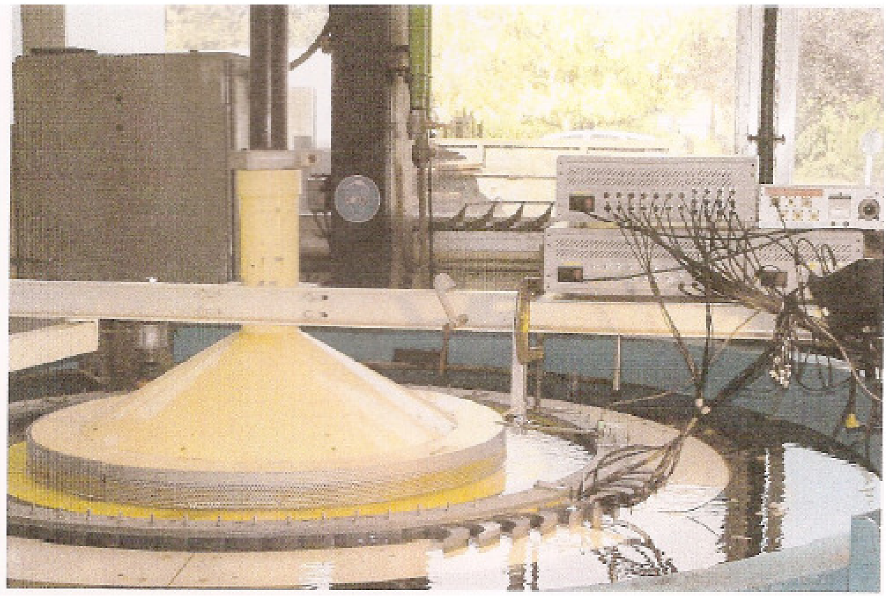

Fig 1: Steam turbine stage model.

2) Analysing instationnary flows in the turbine. Turbine stage geometry.

Literature [1], [2], [3], demonstrated the influence of a turbomachine stage geometry on the dynamic loads on the blades. The amplitude and instationnary nature of these loads are a direct driver for blade dimensioning. The geometry of a turbine stage (figure 2) can be characterised by a significant parameter determined by:

θ = stator assembly pitch / mean length of the wheel channel = P/L
Zs = number of vanes in the guide vane assembly
Zr = number of blades on the wheel
j = gap (wheel / guide vane assembly clearance)
C = cord
P = pitch
L = wheel channel length.

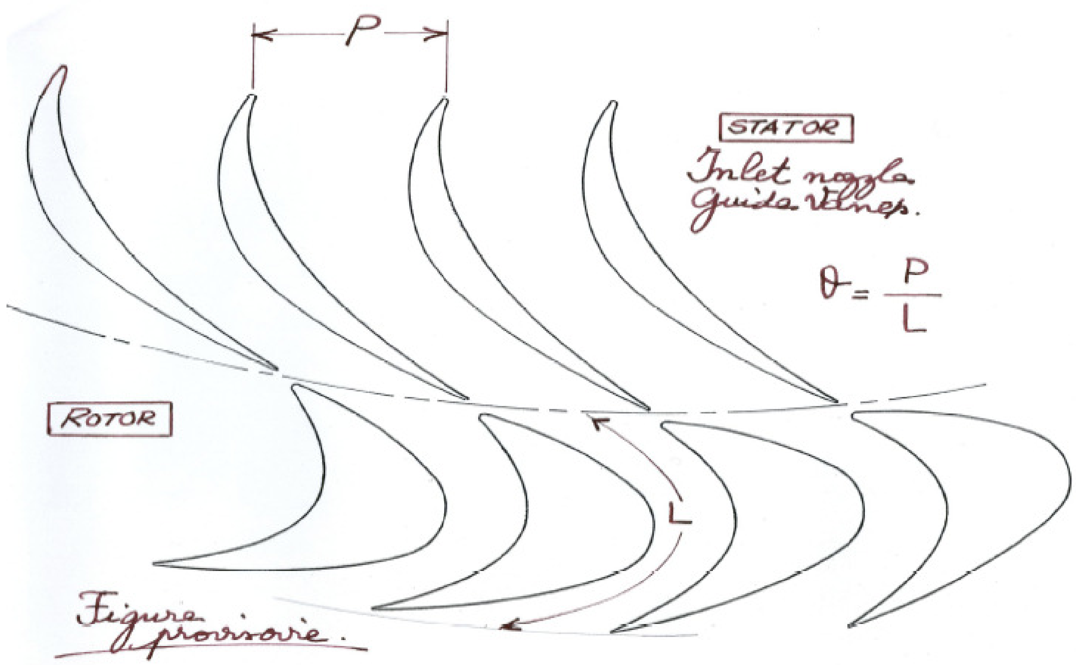

Fig 2: Steam turbine stage geometry.

3) Experimental study.

3.1) Test bench description.

As shown in figure 3 above, the experimental bench is comprised of a concrete block on which the guide vane assembly, the rotor wheel and the water height adjustment devices are mounted. The radial flow is maintained in closed circuit by a pump, which delivers the required output flow for the experiments. For obvious experimental convenience, the rotor blades are fixed and the guide vane assembly, which is partially blank in order to simulate operating conditions in partial injection mode, rotates around the wheel blade assembly.
The water is asymmetrically delivered into the stage by means of a central diffuser equipped with a filter which stabilises a chosen value of water height at the at guide vane assembly input. The rotary guide vane assembly is driven by a variable rotational speed roller.

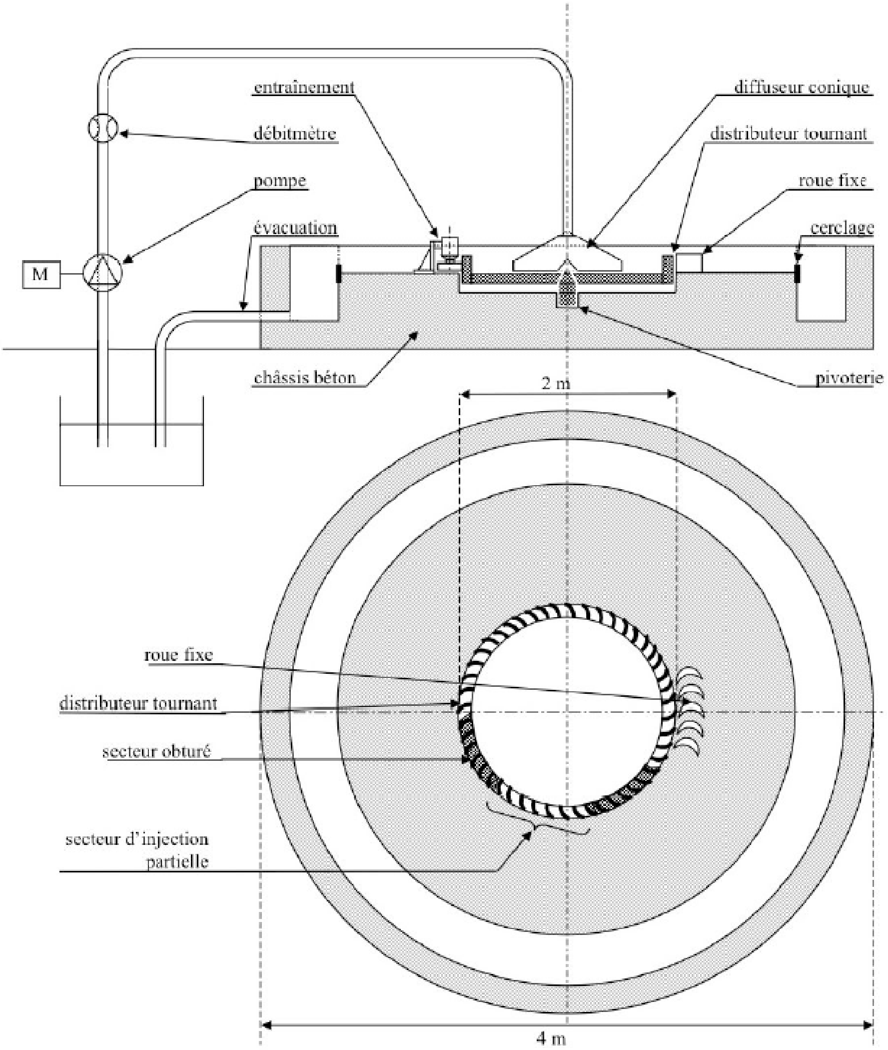

Fig 3: Water table Steam turbine stage model.

3.2) Hydraulic analogy

Bases equations: Hydraulic analogy between the supersonic flow of a compressible fluid and the flow of a free surface liquid layer running in a channel whose bottom is horizontal, was described by Joukowski and Prandtl and developed by Jouguet, Riabouchinsky and Preiswerk. [4] The gas density variations (hence the variation of its pressure) induce height variations of the liquid layer in hydraulic analogy. It can be demonstrated that this analogy is expressed:

Any discontinuity caused, for example by a shockwave, will result in a surge of the free surface load.

3.3) Measurement Methodology

3.3.1) In a first experimental campaign, we implemented an inter blade channel of the wheel meshed by enamelled copper wires. This allowed us to calculate by interpolation the water heights on blade's pressure face and suction face. The results of these preliminary works have been presented in 1998 [2].

3.3.2) This paper presents the continuation of these works based on instationnary water height measurement on the pressure and suction faces of a wheel blade; this blade is parietally equipped with capacitive gauges housed in the thickness of the blade. Figure 4 shows a view of the wheel with instrumented blade detail.

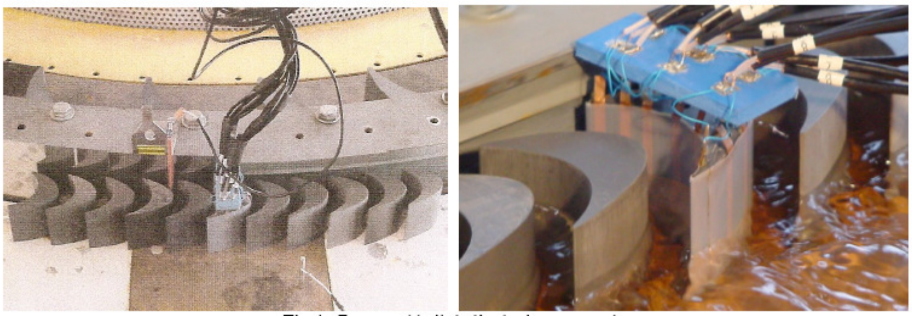

Fig 4!: Wheel and instrumented wheel blade detail.

3.3.3) Acquisition mode.
The capacity of each "electrode blade" is proportional to its "wet" height. A circuit which integrates this capacity delivers a voltage which is also proportional to the water height. By calibration of the 22 (large blades) or 14 (small blades) electrodes, we obtain an accurate measurement of the parietal water height values on the entire blade. It is, therefore, possible to compute the radio static pressure as well as the elementary force on the capacity blade’s surface elements. By integration, we obtain the resultant force applied on the blade:

$$F(t) = \sum dF_{intrados} - \sum dF_{extrados}$$

intrados = high pressure face
extrados = low pressure face

We can then calculate:

F_{mean} = mean load
F_{RMS} = root mean square value of the instationnary load
DF95 = 95 % of the instationnary load, peak to peak

Finally, we obtain the properties for each flow configuration by averaging between these loads over 10 tests.

Remark concerning partial injection.

The partial injection operating case is more intricate to analyse: the wheel which enters into an injection arc is filled with a rotary "static" fluid; the jet from the guide vane assembly must, therefore, set it into motion. This causes disturbances and a shockwave likely to move back into the guide vane assembly. Likewise, while leaving the injection arc, the fluid is abruptly slowed thereby causing expansion waves which propagate in the channels. Therefore, the injection arc input and output generate alternate loads which add themselves to those caused by the wakes, and alter the cyclic nature of fatigue loading on the blades[5].

For calculation of partial injection loads taking into account these effects, we only integrate, in the F_{mean} 5 channels of the wheel out of the 7 injected channels, as shown in figure 5 opposite.

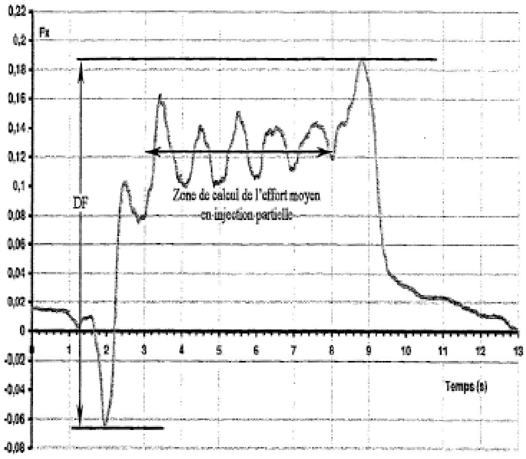

Fig 5: Mean load calculation zone in partial injection mode

3.4) Studied geometries.

The studied geometries are described and one of them is shown in figure (6).

	Rotor Wheel			
No.	**Nb of blades**	**Factor**	**Cord**	**Channel L**
1	80	1	116.00	172.69
2	120	1.5	77.33	115.13
3	160	2	58.00	86.35
4	200	2.5	46.40	69.08

	Guide vane assembly			
No.	**Nb of vanes**	**Factor**	**Cord**	**Pitch**
1	80	1	144.00	78.38
2	53	1.5	216.00	118.31
3	40	2	288.00	156.77
4	32	2.5	360.00	195.96

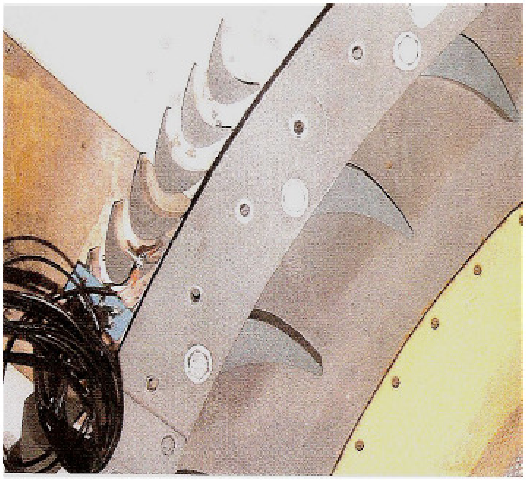

Fig 6: wheel and guide assembly geometries .

The values of parameter θ achievable based on the wheel and guide vane assembly geometries are listed in the table in figure 7.

Theta θ				
Guide vane assembly *Rotor wheel*	1	2	3	4
1	0.454	0.685	0.908	1.135g
2	0.681	1.028	1.362	1.702
3	0.908	1.370	1.816	2.269g
4	1.135p	1.713	2.269p	2.837

Fig 7: Experimented θ parameter .

4) Experimental result analysis.

The test results are shown in figure (8) for total injection and (9) for partial injection. The result from Rieger & Wicks [1] are also added (blue colour).

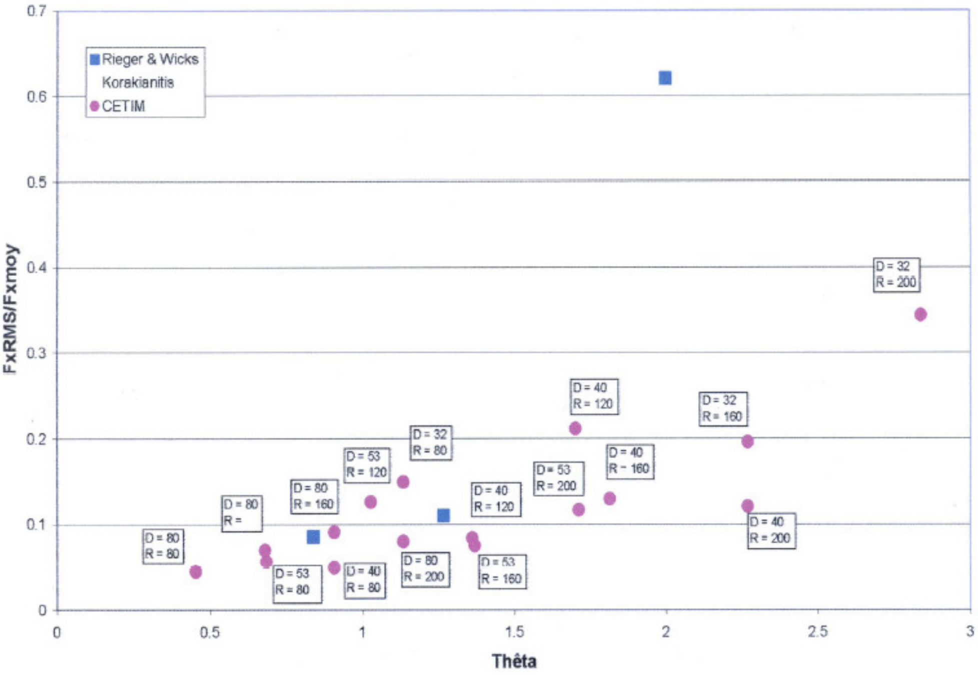

Fig 8: Values of the Frms/Fmean ratio versus parameter θ for total injection tests.

Fig 9: Values of the Frms/Fmean ratio versus parameter θ for partial injection tests.

Comments, Analysis. Draft jointly.

5) Conclusions and perspectives.

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