CAVITATIONAL DAMAGE AT FRANCIS TURBINE RUNNERS

Gheorghe BĂRAN[1], Cătălin TILEA[2], Gabriela OPRINA[3], Florentina BUNEA[4]

On the basis of data from literature, laboratory researches and measurements performed with a Francis runner having the rapidity n_s of 200, the values of the parameters indicating the intensity of cavitational damage are analyzed. A method for predicting the cavitational damage is also proposed.

Keywords: cavitation, cavitational damage, Francis turbines

1. Introduction

The research concerning the cavitational damage started in 1921 (Föttinger) [1], had a "peak" between 60s and 70s and continues nowadays. In this research field in Romania PhD thesis [2-4] and books have been published [5-6], and solutions for diminishing the cavitational damage have been explored [7]. The new aspects of the cavitational damage treated in [8] show the complexity and the difficulty of the cavitation issue, which is often left to be solved in hydropower plants operation.

Generally, it is more or less explicitly assumed that the turbines operate with cavitation and there are regulations concerning guarantees for cavitational damage [9]. An important issue in turbine operation consist in predicting the intensity of the cavitational damage; this paper proposes a solution for this issue.

2. Parameters indicating the intensity of the cavitational damage

The intensity of the cavitational damage I and of erosion/scouring respectively is evaluated by the following parameters [6], [10]:

- the ratio between the volume of the scoured material ΔV and the period of operation with cavitation τ

$$I_v = \Delta v / \tau ; \tag{1}$$

[1] Prof., Hydraulic and Hydraulic Machineries Department, University "Politehnica" Bucharest, Romania,
[2] PhD. Eng., Hidroelectrica, S.H. Târgu Jiu, Romania,
[3,4] PhD. Eng., INCDIE ICPE-CA Bucharest, Romania.

- the mass of scoured material Δm during the period τ

$$I_m = \Delta m / \tau ; \tag{2}$$

- the maximum depth of the scouring Δh during the period τ

$$I_h = \Delta h / \tau ; \tag{3}$$

- the area Δs scoured during the period τ

$$I_s = \Delta s / \tau . \tag{4}$$

When accurate information is lacking, all these overall parameters can be used in the informative evaluation/prediction of the cavitation. A comparison among these parameters is shown in figure 1. The data are obtained on a Kaplan turbine after 7000 hours of operation; the runner diameter of the turbine is D_1 = 4200 mm, the power is P = 57 MW, the head is 55 m and the speed is 187.5 rpm; the blades are made from stainless steel. With the reservation concerning the measurement of the cavitational damage depths accuracy (10^{-6} m), it is found that in the range (70÷100%)P the parameters I_v and I_s have close values.

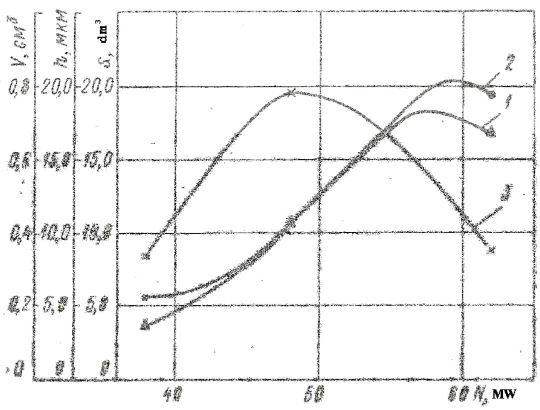

Fig. 1. The dependence of the cavitational damage of blades on power; 1- scoured volume, 2- scoured area, 3- scour depth. [12, p. 224]

3. Laboratory researches

The mechanical resistance of different materials at cavitational damage is studied in laboratory. The equipments used for experiments have different working principles and consequently, the results that have been obtained are different (fig. 2).

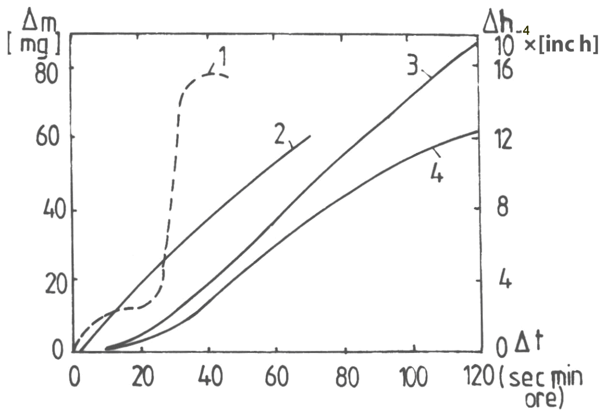

Fig. 2. Characteristic curves of cavitational damage

The curves in figure 2 correspond to the equipments from table 1.

Table 1

Equipments for studying the cavitational damage

Current no.	Type of equipment	Cavitational damage measurement		Period of test
		Scoured mass	Scour depth	
1.	Ultrasound	–	Inch	minutes
2.	Hydrodynamic tunnel	mg	–	hours
3.	Magnetostriction	mg	–	minutes
4.	Jet	mg	–	seconds

Table 2

The diameter and the maximum depth of the cavities

Steel mark	Period of test (hours)	Stream velocity (m/s)	Cavitation coefficient σ	Diameter max-min	Maximum depth (mm)	Scoured volume (mm^3)
FB-50AK	100	27.5	0.65	2-3	2.1	5.0
17-M13	100	27.5	0.65	2-3	2.0	4.7
OL38ABK	100	27.5	0.65	4	2.8	11.7

The experimental researches performed in a lab of Politehnica University of Bucharest in a hydrodynamic tunnel show the evolution of the cavitational damage for three different types of steel (table 2 [6]).

The cavitation coefficient σ is computed with the relation given by Thoma

$$\sigma = 2\left(p_{am} - p_v\left(t°C\right)\right) / \rho v^2 . \quad (5)$$

The parameters mentioned in §2 can be computed with the values from table 2. It obtains:

$$I_h = (2-2,8)10^{-2} \quad \text{mm/h}$$
$$I_v = (5-11,7)10^{-2} \quad \text{mm}^3\text{/h} . \tag{6}$$

For a test period of 60 hours (for a similar equipment) from figure 2 results a scoured material of about 60 mg; for $\Delta m = \rho \Delta V$ and ρ = 8000 kg/m^3 results the following parameter I_v

$$I_v = 60/8000 \cdot 60 = 1,25 \cdot 10^{-2} \text{ mm}^3\text{/h.} \tag{7}$$

This result is in a good agreement with the results computed previously.

4. Safety coefficients for cavitation

The cavitation coefficient of a hydropower plant is defined by the relation

$$\sigma_{inst} = \{[(p_{at} - p_v)/\gamma] \mp H_s\}, \tag{8}$$

where p_{at} is the atmospheric pressure, p_v – vaporization pressure, $\gamma = \rho g$ – specific weight, $\mp H_s$ – suction height, H – head (at best efficiency point, BEP, used in calculations); the atmospheric pressure varies with the altitude after the following relation

$$p_{at}/\gamma = 10.33 - \nabla/900, \tag{9}$$

wher ∇ is the level of water downstream the hydropower plant.

The cavitation coefficient of turbine σ_T is obtained from laboratory tests on model and is given by the relation (10)

$$\sigma_T = K_1 K_2 \sigma_m \tag{10}$$

where σ_m is the value obtained on, K_1 = 1,05÷1,10 is a coefficient for scale correction and K_2 = 1,2÷2,5 express the influence of the flowrate at other values than the best efficiency point [5].

Statistical formulae can be used for computing the coefficient σ_T, where $\sigma_T = f(n_s)$, with n_s the rapidity of turbine

$$\sigma_T = 6.065 \cdot 10^{-5} {n_s}^{1.41} \tag{a}$$

$$\sigma_T = 0.018\left\{0.48 - 0.222\left[(n_s - 150)/100\right]^2 + \exp 0.07 n_s + 0.0017(n_s/100)^5\right\} \tag{b}$$

$$\sigma_T = 1.113\times10^{-4} n_s^{1.25} / \left[(64/n_s) + 0.78\right]^4 + 4\times10^{-3}(n_s/100)^2 + 0.03 \tag{c}$$

$$\sigma_T = 3.9 \cdot 10^{-6} n_s^2 - 1.25 \cdot 10^{-4} n_s + 0.0265 \tag{d}$$

$$\sigma_T = 0.043(n_s/100)^2 \tag{e}$$

$$\sigma_T = 0.0348(n_s/100)^{1.283} \tag{f}$$

Some laboratories/companies introduce safety coefficients for cavitation, such as:

$$K_{\sigma si} = \sigma_{inst} / \sigma_{Ti}; \quad K_{\sigma sx} = \sigma_{inst} / \sigma_{Tx}, \tag{11}$$

where $K_{\sigma si}$ represents the safety coefficient for incipient cavitation and $K_{\sigma sx}$ corresponds to the flowrate Q_x and depends on the material of the runner – for low alloy steel $K_{\sigma sx}$ = 2÷2.22 and for high alloy steel $K_{\sigma sx}$ = 1.1÷2 [5]. Values of the cavitational damage depth for 4 types of runners are given in table 3 [5], [11-12].

Table 3

The depth of the cavitational damage (scour) for runners from steel 30L

Runner type	Period of operation [hours]	Scour depth [mm]	$K_{\sigma sx}$	$I_h\,10^4$ [mm/h]
RO211	35000	2	2-3	0.57
RO123	11000	7	1.3	6.36
RO211	22000	30	1.15	13.63
RO82	5000	6	1.1	12

From table 3 it can be seen that for low safety coefficients (1.1÷1.15) the parameter I_h differs as order of magnitude in comparison with the case of high coefficients; concurrently, there is not a coherent relation between the parameter

I_h and the operation period of the turbine. In comparison with the values obtained in laboratory, the values of I_h from table 3 are different as order of magnitude.

5. Case study

During 2002 and 2008 operating repairs have been accomplished at a vertical Francis turbine having the characteristics shown in table 4.

Table 4

Technical characteristics of turbines

Label	Measurement unit	Value
Turbine type	–	FVM 31.5 – 182
Net head max/min	m	210/139
Head at BEP	m	182
Flowrate at BEP	m^3/s	19.8
Suction height	m	-11.6
Characteristic diameter	mm	1250
Revolution at BEP	rot/min	750
Power at BEP	KW	31500
Number of runner blades	–	14
Number of guide vanes	–	16
Height of wicket gates	mm	250

At best efficiency point, the rapidity is n_s = 200. For a water level $\nabla = 470$ m and H_s = -11.6 m σ_{inst} is given by the relation (12)

$$\sigma_{inst} = 21.077 / H = 0.1158 . \quad (12)$$

The coefficient σ_T is evaluated with a statistical formula selected among the formulae presented above. Applying this formula for verifying H_s, values close to the ones from the project are obtained:

$$\sigma_T = 6.065 \cdot 10^{-5} n_s^{1.41} = 0.1158 . \quad (13)$$

It results the safety coefficient at best efficiency point K_{sn} = 1.087 – a low value, considering that for Francis turbine $K_{\sigma sx}$ = 1.01÷1.6 [5, p. 412], so the runner is exposed to cavitation.

In the case of the analyzed turbine the following findings arose:

- at the wicket gate were found small cavities, uniformly distributed on the lower camber of the blades (on the rings);

- same situation was found on the runner blades in 2002, but in 2008 an important damage was discovered on one of the blades; this damage consists in 6÷8 mm depth cavities, disposed on the exit edge of the blade (fig. 3). For about 10000 hours of operation the parameter I_h is

$$I_h = (6 \div 8) \cdot 10^{-4} \text{ mm/h}, \tag{14}$$

a value comparable with the values from table 3.

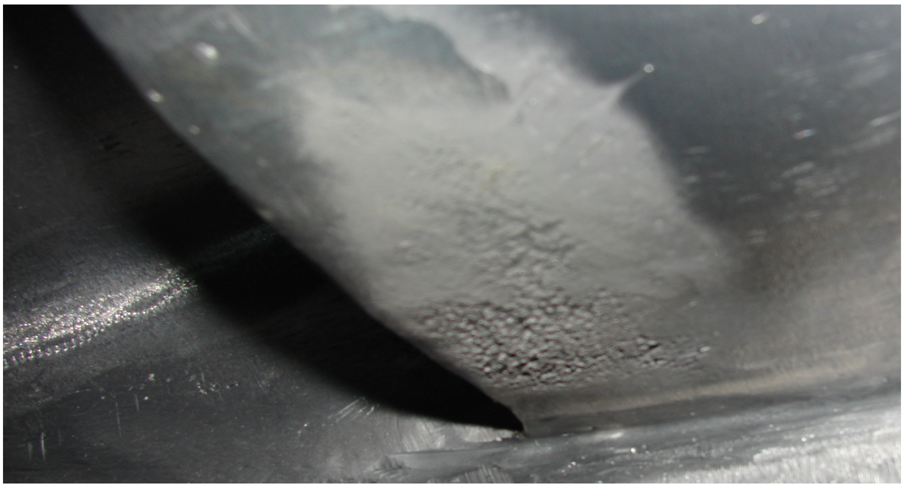

Fig. 3. Cavitational damage at blades for the analyzed runner

The standards regarding the evaluation of the cavitational damage establish the values Δh in function of the runner diameter; in these standards the values Δh are noted with s [mm]. Thus, for D = 1.25 m [9] the cavitational damage is

$$\Delta h = s = (4 \div 6) D^{0.4} = (4.373 \div 6.56) \text{ mm}. \tag{15}$$

The values of Δh depends on operation regime, water quality, material quality, refurbishment etc. For a hydropower plant operating 3000 hours/year results a parameter I_h of $(0.1457 \div 0.2186) \cdot 10^{-4}$ mm/h; these values are smaller than the values encountered in practice. Looking into perspective, we can consider these values realistic taking into consideration the novelty (2005) of the legislation (regarding the cavitational damage) we referring to and the progress attained in materials quality.

For the analyzed turbine the safety coefficient is

$$K_{s\sigma x} = \frac{\sigma_{inst}}{\sigma_{Tx}} = \frac{21.077}{H} \cdot 1/0.065 \cdot 10^{-5} \left[n \left(P^{1/2} / H^{5.4} \right) \right]^{1.41} = 30.7 \frac{H^{0.7625}}{P^{0.705}} . \qquad (16)$$

Knowing the head and the power of the turbine and using the data from table 3, the operation regime in cavitation can be determined.

6. Conclusions

1. The analysis of the data from literature concerning the cavitational damage at Francis runners showed that the main factor determining the intensity of the damage is the safety coefficient $K_{s\sigma x}$.

2. For the case study analyzed in this paper the safety coefficient is given by relation (16).

3. In order to roughly predict the evolution of the damage, the following stages are proposed in this paper:

- damage can be neglected for $I_h < 0.5 \cdot 10^{-4}$ mm/h;
- low damage for $I_h = (0.5 \div 1.5) \cdot 10^{-4}$ mm/h;
- average damage for $I_h = (2 \div 8\text{-}9) \cdot 10^{-4}$ mm/h;
- heavy damage for $I_h > 10^{-4}$ mm/h.

REFERENCES

[1] *R. Knapp, J. Daily, F. Hammit*, Cavitation, Mc Graw Hill, New York, 1970.

[2] *Gh. Băran*, Teză de doctorat, I.P.B., 1976.

[3] *I. Bordeaşu*, Teză de doctorat, Universitatea Politehnica Timişoara, 1997.

[4] *L. Ciocan*, Teză de doctorat, Insitutul Politehnic Iaşi, 1985.

[5] *I. Anton*, Cavitația (Cavitation), **V. II**, Ed. Academiei, Bucureşti, 1985.

[6] *Gh. Băran, A. Ciocănea*, Curgeri cavitaționale şi abrazive (Cavitational and abrasive flows), Ed. Printech, Buc., 2005, ISBN 973-718-267-7.

[7] *** Studiu privind reducerea cavitației la rotoarele HA de la CHE Motru (Study regarding the diminishing of the cavitation at the turbine runners from Motru Hydropower Plant), ICEMENERG-UPB, 2003.

[8] *S.C. Li*, A New Type Of Cavitation (Damage) Identified From Three Gorges Turbines, IAHR 24th Symposium On Hydraulic Machinery And Systems, October 27-31 2008, Brasil, paper 06.

[9] SR EN 60.609-1, Evaluarea eroziunii datorită cavitației la turbine, pompe de acumulare şi turbine-pompe (The evaluation of the erosion due to cavitation at turbines, accumulation pumps and turbines-pumps), P. I, dec. 2005, Ed. 1.

[10] *J.M. Darcy, A. Verry, P. Grison*, Une meilleure maitrise de la cavitation, Épure, no. 25, Electricité de France, pp. 13-21, 1990

[11] *V.I. Karelin*, Iznos lopastnîh ghidravliceskih mesin ot cavitatii i nanosov, Izd. Masinostroenie, Moskva, 1970.

[12] *N.I. Pîlaev, I.U. Edeli*, Kavitatia v ghidroturbina Izd. Masinostroenia, Leningrad, 1974.