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ГИДРОФОРУМ

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на тему

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A Simplified Approach to Predict Some Cavitation Effects at the Axial Runner Vanes

A single bubble model is used to predict cavitation erosion zones at an axial runner vane under field conditions and to derive a scaling law on cavitation erosion rate.

1. Introduction

Numerous reports on model tests of hydraulic machinery [1, 2, 3] indicate at an unsteady cavitation cloud consisting of a multitude of small cavities as an especially common form of cavitation at the runner vanes. It is quite obvious that this form of cavitation is responsible for most of blade erosion and contributes significantly to machine vibration and some fatigue fractures of the vanes. Significant progress has been recently made in our understanding of the phenomenon. This is due both to the experimental research on cavitation cloud structure [4] and dynamics [5] and to some theoretical efforts in this respect [6, 7, 8]. However, there is still lack of a reliable method that would allow to predict various aspects of bubble cavitation in a hydraulic machine. A lot of cavitation prediction work as well as many research efforts aiming to correlate selected cavitation aspects with operating conditions and the geometry of a hydraulic machine (or a ship propeller) are still based on single bubble evolution models [9, 10]. Despite of rather rough approximations, these models often prove to be unexpectedly efficient.

Recently, one of the authors developed a simplified model of single bubble evolution — originally proposed by A. D. Pernik [11] — in order to predict cavitation erosion zones at the blade sections of hydraulic machines [12, 13]. Theoretical results showed satisfactory agreement with experiment and the results of an inspection under field conditions. A single bubble model was also used later on to derive a scaling law concerning cavitation erosion of Kaplan runner vanes [14]. A critical summarization of the *hitherto obtained results is given in the present report.*

2. Cavitation Extent Prediction by Means of a Simplified Model of Single Bubble Evolution

The model used in this paper has been already discussed in detail in Ref. [12] and [13]. The basic idea consists in dividing the bubble evolution process into three stages, that is the rise in the region of local pressure p, being lower than the saturated vapour pressure p_v, the rise in the region of local pressure being higher than the saturated vapour pressure and the collapse of the bubble. In each of the stages the realistic pressure distribution is replaced by its mean value (Fig. 1). The position s_1 of the bubble at the end of the first stage is determined by the equality $p = p_v$. The positions s_2 and s_3, at the end of the second and the third stage, respectively, can be found from the simplified solutions of the Rayleigh equation [11] and the assumption of no slip between the bubble and surrounding liquid [12, 13]. Both the bubble radii and respective bubble positions for a fixed flow pattern and a given cavitation number appear to be proportional to the characteristic dimension of the flow system (e.g. blade section chord or tip diameter of the runner).

The method has been applied successfully for cavitation prediction under laboratory conditions and at the guide vanes of a pump-turbine in Żydowo Pumped Storage Power Plant in Pomerania (Poland) [12, 13]. Recently, it was also used to predict cavitation erosion zones at the runner vanes of a Kaplan turbine at the Bergheim Power Plant, arranged in a cascade of four river power plants at the German Danube (Fig. 2 [15]). The Bergheim Plant consists of three units of tip diameter $D = 5.35$ m and rated capacity $P = 8.25$ MW, operating under rated head $H = 5.97$ m. Rated suction head — taken as the runner exit height above the tailwater level — amounts $H_s = 1.15$ m. Rotation speed, $n = 76.9$ rpm, is compatible with $f = 16\ 2/3$ Hz frequency of the West German railroad traction grid. The varying power demand of the traction grid requires sometimes an off-design point of operation with head rising up to 8.5 m and the tail water level falling even 1.5 m below its standard level.

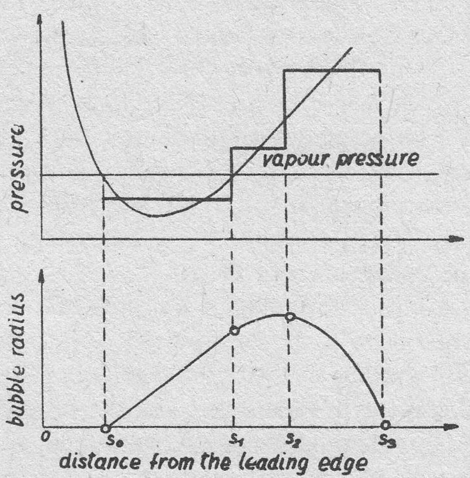

Fig. 1. The realistic and the simplified pressure distribution at a foil section

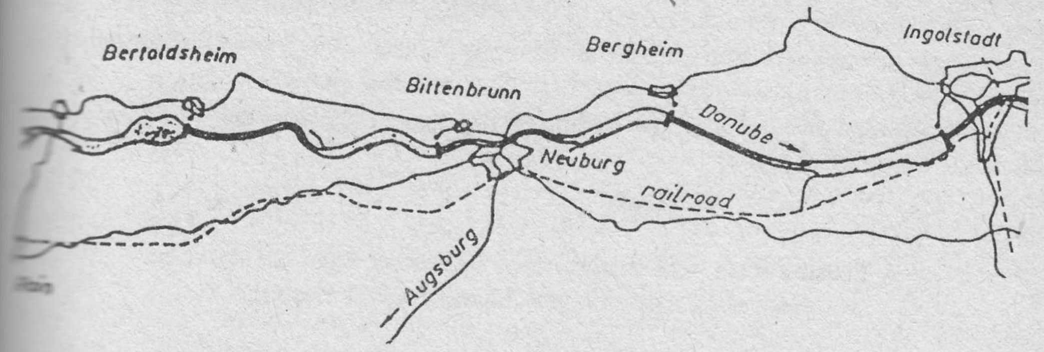

Fig. 2. Cascade of four river plants at the German Danube (after [15])

During a period of 48 500 hours of operation the suction face of 4 runner vanes showed a remarkable pitting area, especially at the cylindrical section of 95% of runner tip diameter. This is attributed to 12 800 hours of swell operation, in particular at $H = 8.5$ m head, $Q = 106.2$ m^3/s flow rate and an angle of $\varphi = 16°$, the chord of 0.95 D cylindrical blade section makes with the circumference. Velocity distribution round this blade section has been calculated by means of the Schlichting's singularity method [16] at the Technical University of Munich. Operation point and the blade geometry data have been delivered by the power plant owner (Rhein-Main-Donau AG) and the turbine producer (J. M. Voith GmbH), respectively.

Cavitation inception number, σ_i, has been calculated from the formula [17]

$$\sigma_i = \lambda_{\max}\frac{w_1^2}{2gH} + \eta_s\frac{c_m^2}{2gH} \tag{1}$$

where w_1 and c_m are the relative and the absolute meridional velocity at the runner outlet, respectively, g is the acceleration of gravity and η_s — the draft tube efficiency. The pressure coefficient, λ, can be found from the distribution of the relative velocity w, using the formula

$$\lambda = (w/w_1)^2 - 1 - K_0 \tag{2}$$

where K_0 denotes a coefficient accounting for the height of the actual point above the runner outlet 1, and the respective runner losses [14]. Installation sigma.

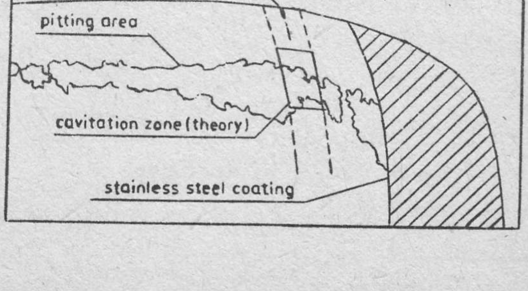

Fig. 3. Predicted and realistic erosion zone at the Kaplan runner vane in Bergheim Power Plant (after a photograph by Rhein-Main-Donau AG)

$$\sigma = \mathrm{NPSH}/H \tag{3}$$

proved to be smaller than cavitation inception number σ_i, which indicated that cavitation should have been expected. In fact erosion zone calculation by means of the simplified model of single bubble evolution coincided well with the results of field inspection (Fig. 3).

3. Erosion Rate — a Scaling Law Following from the Analogy Between Cavitation and Liquid Impact Damage

We shall assume further on that cavitation damage is due to the collapse of individual bubbles travelling with the velocity of surrounding liquid and not interacting one with another. The number of cavities or cavitation nuclei in a unit mass of fluid will be considered constant. All the supercritical nuclei will be assumed equivalent, that is having equal gas content and following Rayleigh equation without viscosity, surface tension and gas diffusion terms. For simplicity, we shall assume the isothermal gas convertion inside a bubble with R_0 being the bubble radius corresponding to the partial gas pressure Δp_0 under steady-state conditions.

Under these assumptions, the Rayleigh model yields the following formula for the bubble collapse rate [18]

$$\dot{R}^2 = \frac{2\Delta p}{3\rho}\left[\left(\frac{R_a}{R}\right)^3 - 1\right] - \frac{2\Delta p_0}{\rho}\left(\frac{R_0}{R}\right)^3 \ln\frac{R_a}{R} \tag{4}$$

where $\Delta p = p - p_v$ and the subscript a corresponds to the start of the collapse. The local pressure p, is assumed to be kept constant during the collapse. It follows easily from Eq. (4) that the maximum collapse rate, corresponding to the bubble radius

$$R_i = R_0 \sqrt[3]{\Delta p_0/\Delta p} = R_0 \sqrt[3]{(2\Delta p_0/\rho w_1^2)/(K_1 - \lambda)} \tag{5}$$

can be calculated from the formula

$$\dot{R}_i^2 = \frac{2\Delta p}{3\rho}\left(\frac{\Delta p R_a^3}{\Delta p_0 R_0^3} - 1 - \ln\frac{\Delta p R_a^3}{\Delta p_0 R_0^3}\right) \tag{6}$$

where parameter K_1 in Eq. (5) denotes cavitation index,

$$K_1 = (p_1 - p_v)/(0.5\rho w_1^2) \tag{7}$$

defined by pressure p_1, and relative velocity w_1, at the runner outlet. Disregarding the last two terms in the parantheses in Eq. (6) yields

$$\dot{R}_i = \Delta p \sqrt{\frac{2R_a^3}{3\rho \Delta p_0 R_0^3}} = 0.5 w_1^2 (K_1 - \lambda) \sqrt{\frac{2\rho R_a^3}{3\Delta p_0 R_0^3}}. \tag{8}$$

The corresponding kinetic energy of the liquid around the collapsing bubble becomes, according to Rayleigh

$$E_{\mathrm{kin.}} = 2\pi\rho R_1^3 \dot{R}_i^2 = (2\pi/3)\rho w_1^2 R_a^3 (K_1 - \lambda_i). \tag{9}$$

In fact, the Rayleigh model used above assumes spherical symmetry. On the other hand side, cavitation pitting is generally acknowledged nowadays to be mainly due to the cumulative jets forming during bubble collapses close to a solid wall. The energy delivered to the wall by a cavitation microjet is a fraction of the total kinetic energy of the liquid surrounding the collapsing bubble. No serious error seems to be done by assuming this energy to be proportional to the energy calculated from Eq. (9). In the same way we shall assume the average realistic "effective" microjet velocity to be proportional to the maximum collapse rate as calculated from Eq. (8).

The energy needed for cavitation erosion of ΔV volume of the wall material is given by equation

$$\Delta E = \mathcal{R}_{cav} \Delta V \tag{10}$$

where $\mathcal{R}_{cav}$ denotes the so called cavitation resistance. In general, $\mathcal{R}_{cav}$ depends both on the structure of cavitation pulses and on the physical and chemical features of a material which change significantly in course of cavitation attack [19]. It follows from the considerations of F. G. Hammitt et al [20] that the initial value of cavitation resistance is usually close to the ultimate resilience

$$UR = 0.5\sigma_R{}^2/\xi \tag{11}$$

where σ_R denotes the tensile strength and ξ is the Young modulus of the material. This result coincides with the result of theoretical considerations presented in Ref. [14] under assumption of a rather special erosion mechanism.

The average volume loosened by a single collapse can be thus expressed as

$$V = \eta E_{\text{kin}}/\mathcal{R}_{cav} \tag{12}$$

with η being the proportionality coefficient between energy delivered to the solid and the energy following from Eq. (9). Under assumptions made before there are

$$\Delta N = \Delta b \Delta t \int_0^\infty \mathcal{N} w \, dn \tag{13}$$

bubble collapses to be expected in a time interval Δt over a blade strip of Δb width. The symbol $\mathcal{N}$ in Eq. (13) denotes the volume concentration of the supercritical nuclei. Integration is carried out at any point of the blade surface upstream of the cavitation zone in the direction normal to this surface. Volume concentration $\mathcal{N}$ decreases very rapidly with growing distance from the solid wall and Eq. (13) can be replaced by an approximate relationship

$$\Delta N = \kappa \mathcal{N}_0 w_1 \Delta b D \Delta t \tag{14}$$

where $\mathcal{N}_0$ is the concentration of the supercritical nuclei at the streamline coinciding with the blade section contour and D is a characteristic dimension of the machine (e.g. tip diameter). The proportionality coefficient κ is assumed to depend exclusively on the velocity field pattern.

Taking into account relationships (9), (10), (12) and (14) we can write down th volume loss per time unit as

$$\Delta V/\Delta t \propto (2\pi/3)\,(\Delta b/D)\,(K_1-\lambda)\kappa\eta\mathscr{N}_0\rho w_1{}^3D^2R_a{}^3/\mathscr{R}_{cav} \propto \mathscr{N}_0 w_1{}^3D^2R_a{}^3/\mathscr{R}_{cav} \tag{15}$$

In fact, erosion intensity depends often on a much higher power of relati velocity than that appearing in formula (15). A reasonable result can be obtaine by making use of the analogy between the liquid impact and cavitation erosio mechanisms.

According to F. J. Heymann [21] the mean volume loss during a liquid impac test can be expressed as

$$\Delta V_{li} = k'_{li}\,\Delta N v^{4.26} \tag{16}$$

where ΔN is the number of impacts, v — liquid jet velocity and k'_{li} — a coefficie depending on material and jet parameters. Eq. (16) can be rewritten as

$$\Delta V/\Delta t = k''_{li}v^{1.26}E_{\text{kin}}\mathscr{R}_{li} \tag{17}$$

where k''_{li} is a coefficient assumed constant for a definite facility and liquid use $E_{\text{kin}} = 0.5\pi r^2\rho v^3$ is the kinetic energy of a single liquid impact of duration $\tau = \Delta t/\Delta$ r — radius of the liquid jet and $\mathscr{R}_{li}$ — material resistance against liquid impa erosion defined by a formula analogous to Eq. (10). Liquid compressibility and vis cosity as well as the liquid impact device size seem to be the basic parameters affe ting the k''_{li} coefficient. A simple consideration based on the dimensional analy methods yields

$$\Delta V/\Delta t = k_{li}(cD/\nu)\,(v/c)^{1.26}\,E_{\text{kin}}/\mathscr{R}_{li} \tag{18}$$

where c and ν denote the sound celerity and viscosity of the liquid, respecti D is the characteristic size of the facility and k_{li} — a dimensionless paramete pending on the facility design, liquid impact kinematics and the "Reynolds numb $Re_c = cD/\nu$. Although the precise form of the k_{li} coefficient dependence on the parameter is closely linked to the test device design, the physical intuition (ero rate fall with increasing liquid compressibility and viscosity) suggests that k_{li} sh rise with growing Re_c at least as steeply as $Re_c{}^{0.26}$.

It can be easily seen from Eq. (18) that the efficiency of energy transfer material appears proportional to $v^{1.26}$. Making use of previous assumptions the analogy between the jet impact in a liquid impact test device and the cavit microjet impact onto a solid wall, we can assume the coefficient η in Eq. (12 be proportional to $\dot{R}_i{}^{1.26}$. Taking Eq. (18) into account we obtain

$$\eta = k_{cav}\left[0.5(K_1-\lambda)\sqrt{\frac{2\rho R_a{}^3c^2}{3\Delta p_0R_0{}^3}}\right]^{1.26}\left(\frac{w_1}{c}\right)^{2.52}$$

where k_{cav} is a dimensionless coefficient depending on the $2cr/\nu$ parameter with noting the microjet radius. Disregarding, in the first approximation, the r de dence on the cavity and ambient liquid parameters we obtain k_{cav} = const. H relationship (15) takes the form

$$\left(\frac{\Delta V}{\Delta t}\right)_{cav} \propto k_{cav}\mathcal{N}_0(K_1-\lambda)^{2.26}\left(\frac{2\rho c^2 R_a{}^3}{3\Delta p_0 R_0{}^3}\right)^{0.63}\cdot\left(\frac{w_1}{c}\right)^{2.52}\rho w_1{}^3 D^2 R_a{}^3/\mathcal{R}_{cav} =$$

$$= k'_{cav}\mathcal{N}_0(K_1-\lambda)^{2.26} R_a{}^{1.89} w_1{}^{5.52} D^2/\mathcal{R}_{cav} \tag{20}$$

where

$$k'_{cav} = 0.775\, k_{cav}\,\rho^{1.63}/(c^2\Delta p_0 R_0{}^3)^{0.63}.$$

Relationship (20) is valid only for kinematically similar flows which means

$$w_1 \propto c_1 \propto Q/D^2 \propto \sqrt{gH},$$

$$K_i - \lambda \propto \Delta\sigma = \sigma_i - \sigma$$

and therefore

$$(\Delta V/\Delta t)_{cav} \propto k''_{cav}\,\Delta\sigma^{2.26}\mathcal{N}_0 R_a{}^{4.89} D^2 H^{2.76}/\mathcal{R}_{cav} \tag{21}$$

where

$$k''_{cav} = g^{2.76}\,k'_{cav}.$$

The scaling laws (20) and (21) require certain comments.

Proportionality between R_a and the runner diameter leads — in general — to overprediction of the size effect. In fact, such a proportionality may be assumed only in case of very small $\mathcal{N}_0$ and negligible interaction between cavitation bubbles. No erosion tests are carried out under such conditions. Furthermore, simple stereometrical consideration indicates [12] that the maximum bubble radius should not be expected to overstep the value

$$R_{\max} = 0.72/\sqrt[3]{\mathcal{N}_0}.$$

This result has been confirmed by the experimental data of S. Måckiewicz [4] showing the volume concentration of vapour in a cavitation cloud over a NACA 2418 foil to be always smaller than 65%.

The above consideration suggests that the size effect depends in general on supercritical cavitation nuclei content. Erosion rate seems to be a very steeply growing function of size D and concentration $\mathcal{N}_0$ for small nuclei contents and to grow only proportionally to D^2 and decrease slightly with growing $\mathcal{N}_0$ for high nuclei contents. Numerous experimental data suggest the power exponent of the runner diameter D to range between 3 and 5 [22] which is a sort of compromise between both tendencies. On the other hand side, the scaling laws of N. I. Pylaev, Y. U. Edel' [23] and A. S. Lashkov [24] as well as recent results of K. Steller [19] indicate the values between 2 and 3 as most realistic.

The erosion rate dependence on the 5.5 power of velocity w_1 in relationship (20) seems to be a reasonable result in view of the data of R. T. Knapp [18] and other authors. However, it should be stressed that severe deviations in the value of the velocity power exponent are reported [19]. At least some of these deviations can be explained by the effect of the supercritical nuclei content $\mathcal{N}_0$. In fact $\mathcal{N}_0$ depends on the critical nuclei radius

$$R_{cr} = 2s/(p_v - p_{\min}) \tag{22}$$

where $p_v - p_{\min} = 0.5\rho w_1{}^2(K_1 - \lambda) = \Delta\sigma\rho g H$, $p_{\min}$ is the minimum pressure at the blade section contour and s denotes the surface tension coefficient. It is quite evident that the function $\mathcal{N}_0 = \mathcal{N}_0(R_{cr})$ can be replaced by a function of relative velocity w_1 or total head H. The course of these functions is defined by the cavitation nuclei spectra which usually differ between different test facilities.

4. Conclusions

Despite of far reaching simplifications, the model of single bubble evolution as described in Ref. [13] proved a reliable tool for prediction of cavitation erosion zones under field conditions.

Single bubble model and some data from the liquid impact erosion tests were used in Ref. [14] and the present report to derive a scaling law on cavitation erosion. The result is close to that of other authors although size effect seems to depend essentially on the cavitation nuclei spectra. Experimental verification of this statement is needed.

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Uproszczone metody przewidywania niektórych efektów kawitacyjnych na łopatkach wirników osiowych

Streszczenie

Praca stanowi przegląd dwóch uproszczonych metod rozwiniętych ostatnio przez obu autorów, celem oceny różnych aspektów kawitacji w wirnikach maszyn hydraulicznych. Podano podstawowe założenia uproszczonego modelu ewolucji pojedynczego pęcherzyka, opisanego szczegółowo w poprzednich pracach. Stosowalność tego modelu do przewidywania strat erozji na profilach łopatkowych zilustrowano na przykładzie turbiny Kaplana w Elektrowni Wodnej Bergheim na niemieckim odcinku Dunaju. Następnie, posługując się podobnymi założeniami a także pewnymi wynikami badań erozji uderzającą strugą, wyprowadzono prawo skalowania erozji kawitacyjnej. Wynik jest podobny do uzyskanego poprzednio innymi metodami przez innych autorów, chociaż wpływ rozmiaru maszyny wydaje się mocno zależeć od widma jąder kawitacyjnych. Konieczna jest doświadczalna weryfikacja tego stwierdzenia.

Упрощённые методы предвидывания некоторых кавитационных эффектов на лопатках осевых роторов

Резюме

Реферат является просмотром двух упрощённых методов, развитых за последнее время обома авторами, в целью оценки аспектов кавитации в роторах гидравлических машин. Представлены основные предположения упрощённой модели эволюции одиночного пузырька, подробно описанной в предыдущих трудах. Применяемость этой модели для предвидывания эрозионных зон на лопаточных профилях иллюстрируется на примере турбины Каплана в Гидроэлектростанции Берггейм на германском участке Дуная. Затем, пользуясь похожими предположениями, а также некоторыми результатами исследований эрозии ударяющей струей, выводится закон калибровки кавитационной эрозии. Результат похож на достигнутый раньше другими методами другими авторами, хотя влияние размера машины кажется быть сильно зависящим от сектора кавитационных ядер. Необходима экспериментальная верификация этого обнаружения.