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Method for prediction of cavitation erosion performance in hydro-turbines based on the two-parameter phenomenological model

Abstract
Two-parameter phenomenological model for quantification of the cavitation damage process in its initial — incubation stage inspired by Förster energy migration theory is presented in the paper. The model built was supplemented with functional relationships between calculation parameters and strength parameters of the materials derived for chosen cavitation loading conditions. Experiments at the rotating disk set-up have been carried out in order to obtain necessary experimental data. The values of calculation parameters have been determined by adjusting the theoretical erosion curve to experimental one. Preliminary experimental verification of the model soundness consisted in comparing theoretical to experimental results obtained from both the ICET program and the experimental investigations of the cavitation erosion at Banki-Michel turbine blades. Reliability as well as the sources of inaccuracy and uncertainties were also discussed. The far-reaching aim of the work is to create the calculation tool for prediction of cavitation erosion performance in hydro-turbines during their operating cycle.
Keywords: cavitation erosion, materials performance, performance evaluation, wear, random process modelling.

1. Introduction

1.1. Core issue

Core issue of the present work is to built up a simple two-parameter phenomenological model for quantification of the cavitation damage process and its particular phenomenological implementation. Numerical implementation of the model supplemented with functional relationships between computational parameters and the strength parameters of the material at chosen loading conditions may serve as a tool for prediction of the cavitation erosion performance. On the other hand the course of conduct presented in the paper provides the method for completing and improving the tool on the base of various other experimental data.

1.2. Cavitation erosion

Cavitation erosion is recognised as surface damage of material placed within the reach of the forces arising from bubble implosions, as micro-jets or shock waves are generated (Hickling, Plesset, 1964). The process depends on the type and spatial distribution of the loadings, dynamics and amplitude of acting forces, probability distribution of pulses, surface morphology of the material, its microstructure, phase and chemical composition, residual stresses in the material and the resulting strength parameters.

The influence of various determinants on the process performance was investigated, e.g. in (Gireń, Szkodo, Steller, 1999; Gireń, 2004; Thiruvengadam, Waring, 1966; Zhang, Li, Hammitt, 1989).

In case of metal alloys the rate of material disintegration occurs as inter-grain or intra-grain cracking and depends on the grains size, their bias to plastic deformations and the rate of plastic zones formation, as well as probability of the structural barriers occurrence (Kocańda, Szala, 1997). Specific stages of the erosion may be recorded: energy accumulation stage followed by consecutively the weight loss acceleration and stabilization or quasi-stabilisation stages (Heymann, 1967). The latter is featured by constant or cyclically changing rate of damage. During the initial stage of the erosion the internal stresses and deformations are accumulated without substantial volume loss. Due to plastic deformations in the surface layer easily discernible indentations are formed. The process is prior to cracking and, subsequently is followed by extracting the solid pieces. Random nature of the process results from time and space randomness of the loadings (e.g. Morozov, 1969), as well as randomness of both microstructure and initial conditions. Initial properties of the target may be of paramount importance in the incubation period of the erosion. The process may perform along one of the damage regimes: fatigue or hardening regime (Gireń, Noińska-Macińska, 2016), however, opinion on predominant meaning of the fatigue regime was inferred i.e. from strong correlation between cavitation damage and fatigue strength of the material (Bedkowski et al., 1999; Richman, McNaughton, 1990).

1.3. Applications to practice

Applications to practice Cavitation erosion happens to be a vital problem in liquid-flow systems, such as ship propellers, hydraulic turbines or valves, being a reason of major concern for equipment users and designers (e.g. Antonini, Giadrossi, 1981; Bellet et al., 1997). Defects occurring due to cavitation action result in decreasing the efficiency of operating machines and cause the frequent maintenance and repairs are necessary. Among prospective benefits of using the tool for prediction of the erosion one can point to reduction of the costs of designing, prototyping, maintenance and repair of the turbines or other machines. Moreover, the exploitation risk may be significantly reduced too. Identification and quantification of the problems dealt with in present work may be of major significance for risk assessment or designing the diagnostics procedures.

On account of application needs the development of simple tool for prediction of erosion performance is of major importance. Basic charge of the model should include determination of the erosion curves in the initial period of the erosion.

1.4. Models developed to solve the problem

Previous efforts to model the cavitation erosion process have been reported, e.g. in (Berchiche, Franc, Michel, 2000; Gireń, Frączak, 2016; Gireń, Steller, 2009; Hammit, De, 1979; Karimi, Leo, 1987; Pereira, Avellan, Dupont, 1998), however, bearing the deficiency the formulations obtained were very simplified and did not account various aspects and incentives. Some contemporary works model cavitation impingements on the solid surface, confining its applicability to the incubation period of the erosion, e.g. in (Fortes-Patella, Reboud, 1998; Robinson, Blake, Kodama, Shima, Tomita, 2001). Some attempts to predict cavitation erosion efficiency by finding scaling or similarity laws were reported too, e.g. in (Choi, Jayaprakash, Chahine, 2012; Hickling, Plesset, 1964; Stinebring, Arndt, Holl, 1977). Semi-empirical formulas applicable in scaling can be found i.e. in the papers: (Rao, Buckley, 1984) and are mostly valid in the incubation period of the erosion. An issue, important from the practical point of view is that precise prediction of cavitation erosion is difficult due to high sensitivity of the process. Enormous scatter of the volume loss in conditions differing only by type/quality of the loadings was observed (*International Cavitation Erosion Test, Experimental rigs*).

1.5. Model approach to the problem resolution

The problem consists in assessing the volume loss in the initial period of the process. It was assumed that prediction of the process performance is to be based on phenomenological kinetic model.

Both the space resolution of the loadings and damage topography were not taken into account. By assumption, the model employs parameters arbitrarily referred to loading conditions and target specifications, as energy threshold level and efficiency of energy absorption of a single impulse. Physically, their values decide on the increase in energy trapping points density in the material. Both parameters act as computation parameters and are not known a priori. Energy trapping points in the material were assumed to constitute the effectiveness of the erosion performance: the probability of the material disintegration under external forces is related to the temporal density of the energy trapping points within the surface layer of the solid body. Energy threshold level and efficiency of energy absorption of a single impulse were assumed to be related to physical/strength parameters of the material by functional dependencies. Therefore, in order to make the model usable, it should be completed with functional relationships between computation parameters and material parameters.

Under assumption the material is extracted layer by layer, an integral of erosion probability over the time may be regarded approximately proportional to the volume loss. The formula for probability has been adopted from excitation energy migration theory, developed i.e. in (Bojarski, Grabowska, Kułak, Kuśba, 1991). The formula includes constant parameters. Their relationships with measurable parameters, as material or strength parameters are to be inferred in phenomenological way, by appropriate adjustments of series of experimentally revealed erosion curves. Having the relationships found, the erosion process of any known material in any known loading conditions could be determined.

1.6. The aim and the scope of the work

The aim of the work is to built up a two-parameter phenomenological model for quantification of the cavitation damage process in its initial stage with the use of the Förster (1949) energy migration theory. Moreover, the model built is to be supplemented with functional relationships between calculation parameters and strength parameters of the materials, derived for chosen cavitation loading conditions. The far-reaching aim is to find the dependencies of the derived relationships on the loading intensity and thus to create the calculation tool for prediction of cavitation erosion performance in optional conditions. The scope of the work covers the presentation of the method as well as preliminary experimental verification of the simulating capabilities, including verification of the convergence of calculated and measured volume loss of the material. Moreover, reliability and sources of inaccuracy and uncertainties are discussed.

2. Two-parameter phenomenological model

2.1. Initial assumptions

In order to build a model up, the following assumptions have been taken:

1. Present quantification of the process is valid in the incubation period of the material damage.
2. Mass loss rate during the process depends functionally on the temporal density of the energy trapping points and the rate of energy accumulation — effectiveness of reaching the critical level resulting in crack inception.
3. Mass loss rate during the process is proportional to average intensity of cavitation loading.
4. Target material and space distribution of the impulses are considered statistically homogenous.
5. Effectiveness of the process is driven by the value of cavitation loading (1), fraction of impulse energy being absorbed in the trapping point — as energy linked to hysteresis loop (2), threshold energy for crack inception (3) and decrease in fraction of impulse energy absorbed versus amount of energy accumulated — reinforcement of the material under mechanical loadings (4).
6. In mathematical formulation, the specified values are represented by the loading parameter and two independent parameters, which are assumed constant for given material. Under that simplification particular values of the parameters could be determined off given erosion curve.
7. Volume loss of the material proceeds by extraction of debris until the whole layer is removed.

There could be found some conformities between the present system of impulse energy absorption and transfer and excitation energy transfer from donors to acceptors in multi-molecular systems, determined by Förster (Bellet et al., 1997).

2.2. Model for quantifying the process

Probability function of extraction of the unit of the material surface layer under cavitation loadings can be expressed by the following formula:

$$\Phi(n) = \sqrt{\pi}\, n \exp\left(n^2\right)\left(1-\mathrm{erf}\left(0,n\right)\right) \tag{2.1}$$

where *n* stand for the average density of the energy trapping points within the layer, thus the formula (2.1) is getting more exact if the thickness of the layer is being decreased.

Volume loss of the material (x) is to be described as an integral:

$$x(t) = \int_0^t x(\tau)\Phi(t-\tau)\,d\tau$$

In case of very thin layer, the following simplification is acceptable:

$$\int_0^t x(\tau)¦\,(t-\tau)\,d\tau \approx \int_0^t ¦\,(\tau)\,d\tau$$

Thus, an integral of probability function over time may be proportional to the volume loss of the material.

Attaining the value $n = 1$ means the layer is removed in total. It happens, if n is equal about 6 in formula (2.1) n is a function of time. In present paper considerations are performed within the exposition time interval confined by the condition: $n < 6$. It approximately equals the incubation time of the erosion.

In present paper n was arbitrarily defined by two parameters w and s:

$$n = 6\left(t / s\right)^{w} \tag{2.2}$$

where t means time, w and s play the role of computation parameters.

Volume loss of the material in the initial stage of the erosion is proportional to the time integral of function n. Coefficient of proportionality depends on the energy delivered to the layer. Scaling of its value for computational purposes is carried out in the course of phenomenological procedure: adjusting the numerically derived curves to the experimental curves having regard to the loading the latter have been obtained under.

2.3. Phenomenological way for providing the parameters values

Values of calculation parameters w and s are derived by adjusting the theoretical erosion curve to experimental one. Approximation is carried out by selection of the parameters, which are gradually modified until the experimental curve is imposed with acceptable accuracy. The parameters obtained concern the particular experimental curve and refer to defined loading conditions and material characteristics. Due to poor repeatability of experimental curves, the mean results should be taken of numerous experimental cases. Sets of calculation parameters taken of various materials eroded under same conditions can be referred to strength parameters of the materials enabling the adequate relationships to establish.

3. Experimental sources of the data

Experimental tests have been conducted with the use of the rotating disk facility in The Szewalski Institute of Fluid Flow Machinery Polish Academy of Sciences in Gdańsk. Detailed description of the device has been presented in (Gireń, Steller, 2014).

Data on cavitation erosion for six materials: (a) determined numerically on base of the presented model and (b) measured at experimental runs are shown in Table 1. The materials chosen were: yellow brass, aluminium magnesium alloy: hardened and not hardened, chromium non-resistant steel rolled without heat processing and after heat treatment, acid resistant steel and two-phase corrosion resistant steel depicted according Polish Norms correspondingly M58, BA1032, BA1032-U, 2H13, 2H13-U, 1H18N9T, and DUPLEX 2205 with strength parameters presented in Table 2.

Table 1.

Material M58 brass			Material 1H18N9T steel			Material BA1032 bronze		
time [min]	volume loss [mm^3]		time [min]	volume loss [mm^3]		time [min]	volume loss [mm^3]	
	experiment	calculation		experiment	calculation		experiment	calculation
0	0	0	0	0	0	0		0
10	0.162	0.170	11	0.003	0.007	10	0.096	0
14	0.424	0.511	15	0.026	0.035	15	0.119	0
20	0.678	1.052	21	0.050	0.082	20	0.146	0
30	2.972	2.442	30	0.285	0.322	30	0.148	0.033
40	3.818	3.851	39	0.675	0.807	45	0.304	0.126
			45	1.292	1.116	60	0.997	0.518
			60	2.733	2.861	70	1.054	1.055
			70	4.090	4.074	90	2.811	2.928
			90	6.273	7.083			
Material 2H13 steel			**Material 2H13 hardened steel**			**Material DUPLEX 2205 steel**		
time [min]	volume loss [mm^3]		time [min]	volume loss [mm^3]		time [min]	volume loss [mm^3]	
	experiment	calculation		experiment	calculation		experiment	calculation
0	0	0	0	0	0	0	0	0
11	0.027	0	15	0	0	10	0	0
15	0.081	0.039	20	0.026	0	20	0	0
20	0.567	0.224	30	0.057	0.042	30	0.030	0
29	0.764	0.848	40	0.569	0.208	40	0.397	0.108
40	2.169	1.915	45	0.876	0.348	60	1.002	0.744
60	5.412	4.752	60	1.735	1.082	70	1.282	1.446
69	8.941	6.135	70	1.857	1.958	90	3.400	3.661
			90	5.270	4.285			

Table 2. Mechanical properties of the material tested

	Density [g/cm^3]	Vickers hardness *HV10*	Tensile strength R_m [MPa]	Yield strength R_e [MPa]	Fatigue strength S_f [MPa]	Hardening exponent [—]	Young's modulus E [GPa]
M58	8.4	119	457	165	140	0.35	96
1H18N9T	7.88	191	605	225	465	0.73	200
2H13	7.75	192	863	432	271	0.49	200
2H13-U	7.75	244	1116	658	275	0.47	200

	Density [g/cm³]	Vickers hardness *HV10*	Tensile strength R_m [MPa]	Yield strength R_e [MPa]	Fatigue strength S_f [MPa]	Hardening exponent [—]	Young's modulus *E* [GPa]
Duplex	7.82	310	763	496	530	0.52	200
BA	7.51	202	730	240	255	0.57	115

4. Evaluation of the computation parameters

Values of computation parameters have been derived from Table 1. Relationships between computation parameters *w* and *s* to the strength parameters product [$(S_f/E + R_m/E)*HV$] have been obtained (Fig. 1 and 2).

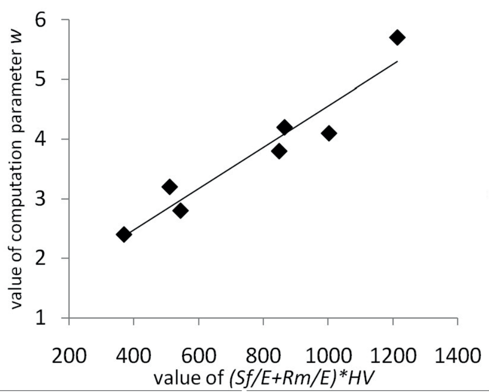

Fig. 1. Graph presentation of the *w* value vs. the *HV*, R_m, *E* and S_f parameters product. Continuous trend line is depicted

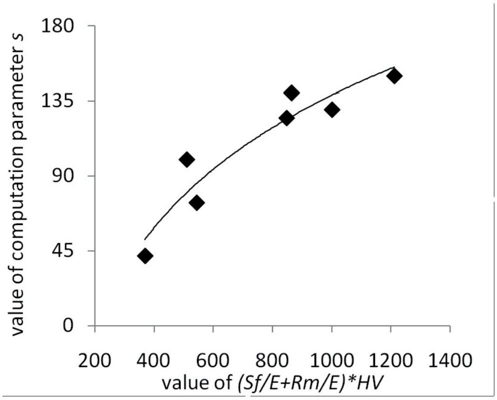

Fig. 2. Graph presentation of the *s* value vs. the *HV*, R_m, *E* and S_f parameters product. Continuous trend line is depicted

Parameter *w* is dimensionless. Parameter *s* is to be expressed in time units [min]. It follows from the measurement results that monotonic, unambiguous relationships have been obtained for same experimental conditions.

5. Preliminary verification of the method

5.1. Testing of the method using the International Cavitation Erosion Test results

In order to verify the usability of the model the control calculations have been carried out for cavitation erosion cases obtained under International Cavitation Erosion Test (Steller, 1999). Particular results obtained at the vibratory rigs in China Ship Scientific Research Center (CSSRC) and Hiroshima University (HIRO) laboratories are presented in Fig. 3 and 4. Average values of density of energy flux determined by Steller fractional method were approximately 90.6 W/cm² and 101.3 W/cm². Corresponding theoretical curves (continuous lines), resulting from model calculations are displayed.

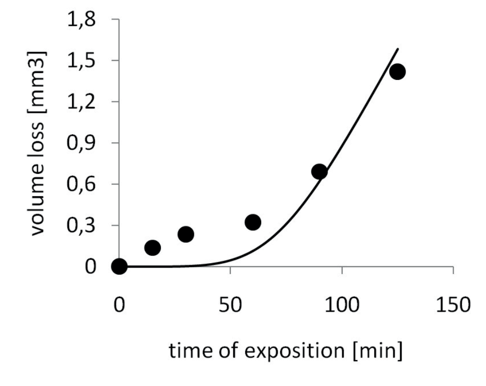

Fig. 3. Experimental results of the erosion of the 45 steel (discernible points) at the vibratory rig in CSSRC Lab. and theoretical curve determined by computation (continuous line)

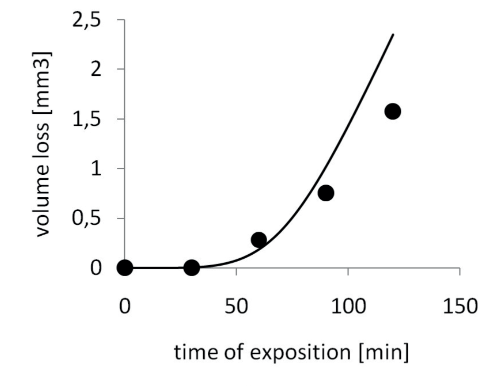

Fig. 4. Experimental results of the erosion of the 45 steel (discernible points) at the vibratory rig in HIRO Lab. and theoretical curve determined by computation (continuous line)

5.2. Testing of the method using data on cavitation erosion occurrence at Banki-Michel turbine

Moreover, the calculations have been carried out for cavitation erosion occurred at the blades of the Banki-Michel turbine during its exploitation for 438 days. Parameters and operating conditions of the turbine were in the ranges: height 13 m, volume flow 0.07–1.5 m^3/s, power 5–200 kW, dynamic specific speed n_{sn} = 114 (Reymann, 1993). Investigations have been carried out in hydro-power plant in Jeziorany (Poland) (Gireń, Noińska-Macińska, 2014; Gireń, Wasilewski, Janicki, 2012). An appearance of cavitation is expected as cavitation clouds within the diffusion zone over the surface of the blades and jets containing the cavitation bubbles, developed in the vortex cores. Jags and depressions created due to cavitating jets action may be locally noticeably deep — up to 2–3 mm. An exemplary effects are presented in Fig. 5 and 6. In order to trace the erosion since the beginning the chosen blades have been restored by the method of electrode cladding. Convex surfaces and areas adjoin to the leading edge of the remain blades have been covered with welding electrode material EB-150 (the trade name). Annealing processing has not been performed. Three areas of 2 cm^2 each on the convex surface of each blade were chosen for quantification analysis. Total time of turbine operation stand for 10,520 hours.

The results obtained are presented in Fig. 7. Discernible points refer to the experimental results, and continuous lines are derived from model computations, executed for two values of cavitation loadings: 150 W/cm^2 and 350 W/cm^2. Intensity of cavitation over turbine blades in relevant conditions has been assessed as comprised in the interval of values: <150; 350> W/cm^2 (Gireń, Wasilewski, Janicki, 2013).

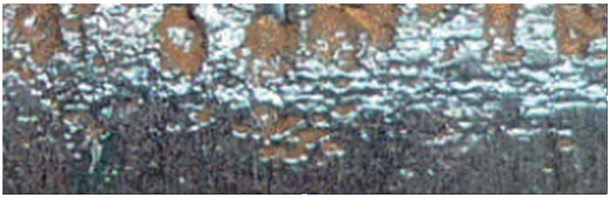

Fig. 5.

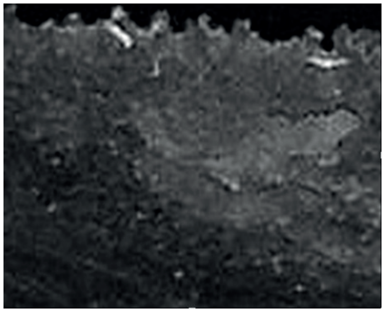

Fig. 6.

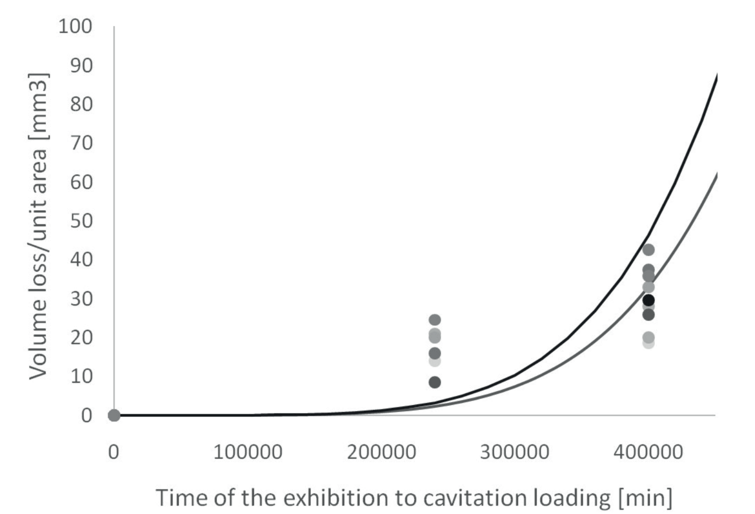

Fig. 7. Volume of the material lost from the surface area of 1 cm^2 of the blade restored with EB-150

5. Discussion on the results

Cavitation erosion in the incubation stage is featured by as quality as remarkable variety of the detected volume loss due to the random nature of the process, hence the poor repeatability of the results. This empowers one to apply the simple two-parameter model to quantification of the process in its initial stage.

The consistency between erosion curves derived using the methodology described and the experimental erosion curves is acceptable in most cases. The discrepancies observed are primarily caused by: (1) insufficiently precise formulas for dependencies between parameters, i.e. computational parameters derived from the formulas may deviate from the average computational parameters determined by adjusting the experimental curves; (2) the lack of consistency of the experimental erosion curves providing the basis for determining the calculation parameters. Calculation parameters derived by adjusting the experimental curves of the same material may be noticeably different due to randomness of the loading conditions and material properties. The essential source of that deficiency is very limited number of experimental runs to establish the relationships; (3) model imperfections — an assumption on the independence of the calculation parameters on the loadings, which implies that calculation parameters referring to various loadings may be considerably different. Inaccuracy in measurement results and uncertainty linked to stochastic nature of the process may be reduced by employing more experimental erosion curves as well as employing more materials of different properties.

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