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exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machinery

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ГИДРОФОРУМ

НАУЧНО-ТЕХНИЧЕСКАЯ КОНФЕРЕНЦИЯ

на тему

ПРОБЛЕМЫ ГИДРАВЛИЧЕСКИХ ТУРБОМАШИН

Гданьск-Владыславово, 24-27 сентября 1985 г.

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Detection and Assessment of Flow Cavitation Intensity

Research methods used in the Department of Fluid Dynamics of the Institute of Fluid-Flow Machinery, Polish Academy of Sciences, in Gdańsk and serving for detection and assessment of the degree of cavitation development in hydraulic machines and systems have been briefly reviewed.

1. Introduction

Diagnostic methods used to detect and assess the intensity of cavitation consist either in directly examining the cavitation phenomenon i.e. observing cavitation development and destabilization of flow or in observing (recording) signs accompanying cavitation — especially performance effects, impingement on the flow confining walls, vibration, noise and cavitation erosion. These methods allow to identify the phenomenon experimentally.

Cavitation development can also be assessed by means of analytic methods.

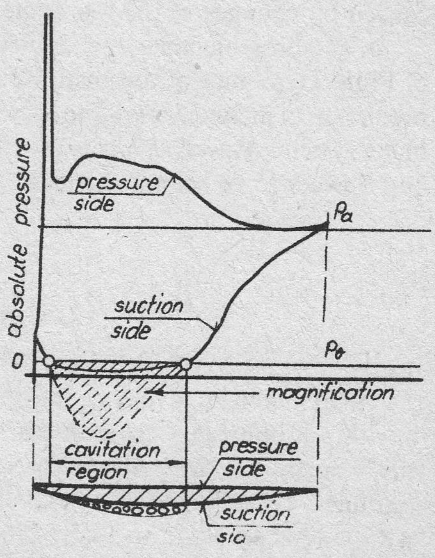

Fig. 1. Pressure distribution over a hydrofoil during cavitation [1]

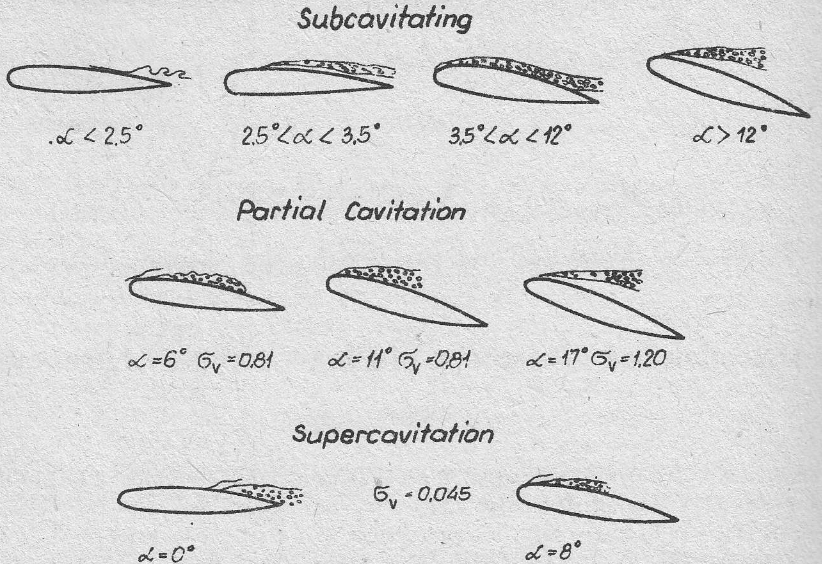

Fig. 2. Different cavitation forms over the NACA 16-012 foil for $Re = 10^6$, different angles of inci
and diversified cavitation index σ_v values

$\sigma_v = \frac{(p_0 + \rho g h) - p_v}{(1/2)v^2}$ (where p_0 — pressure above the free surface, p_v — saturated vapour pressure, ρ — density, g — acceleration of
h — hydrofoil immersion depth, v — liquid velocity)

Assessment of the degree of cavitation development, or rather prediction of ca
tion on the grounds of theoretical premises, is based first of all on calculations
analysis of pressure distribution in the flow. If pressure decreases below the satu
vapour pressure at a given temperature in any place of the flow (inside a hyd
machine), then it is assumed that cavitation may occur in that place (Fig. 1).

Cavitation can take different forms. They depend on the place and conditions
occurrence of the phenomenon. Fig. 2 shows variation of cavitation form on a
caused by changes of the foil angle of incidence and flow parameters.

In the present paper the results of investigations carried out in the Depar
of Fluid Dynamics of the Institute of Fluid-Flow Machinery in Gdańsk, conce
prediction of incipient cavitation and zones of developed cavitation in two-dimens
blade systems as well as assessment of the intensity of cavitation in fluid-flow mac
and devices have been presented.

2. Theoretical Predictions [3]

A cavitation zone may be formed by a single cavity or by a cloud consisting of
cavitation bubbles. One may assess the extent of a single cavity by solving a
problem by the method of iteration. The extent of bubbly cavitation is usually
termined by solving the Rayleigh equation for a bubble moving along a blade
with a velocity equal to that of the ambient liquid.

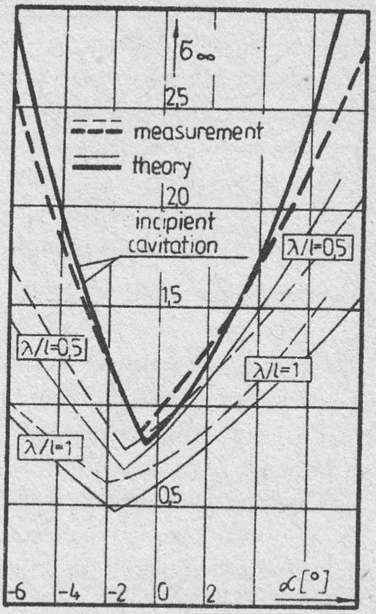

Fig. 3. Cavitation sensitivity of the NACA 2418 foil (comparison of theoretical calculations with an experiment)

σ_∞ cavitation index at the inflow, α hydrofoil angle of incidence, λ cavitation cloud length, l – hydrofoil length

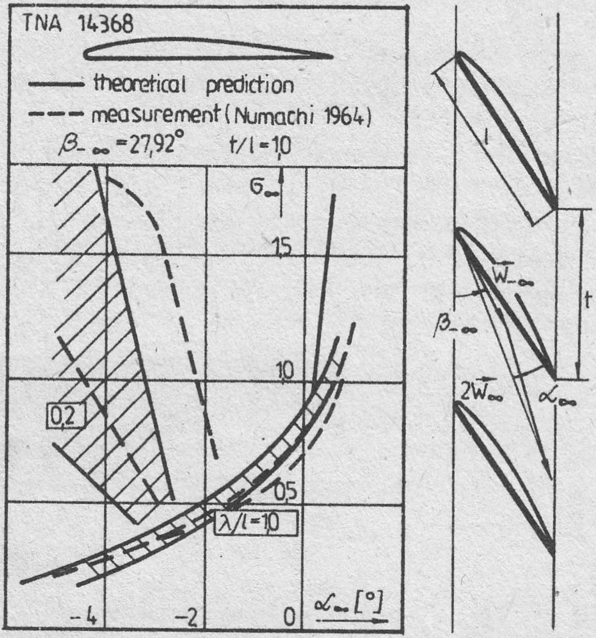

Fig. 4. Cavitation extent in TNA 14368 blade cascade (test results [25])

For some time a simplified routine has been used in the Department of Fluid Dynamics of the IF-FM. It consists in applying a model of a single bubble evolution to assess the extent of cavitation at a blade surface and in replacing the actual pressure distribution over the blade section with a rectangular one. Under these assumptions

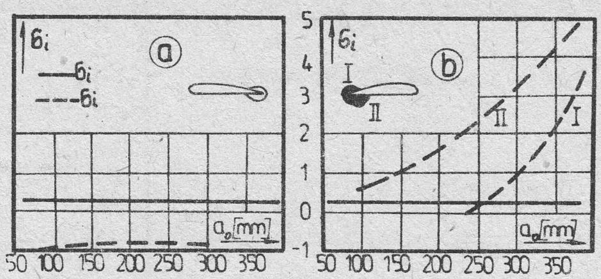

Fig. 5. Cavitation prediction in a reversible machine guide-ring a) turbine operation, b) pumping operation

the problem is reduced to that of solving a system of nonlinear algebraic equations. The results of testing of the NACA 2418 aerofoil can be an example of such routine. In Fig. 3 a comparison of the results of calculations and experiments is presented. A satisfactory conformity of the predicted and actual sensitivity to cavitation of the aerofoil tested is shown. A little worse conformity was obtained for a cascade of blades (Fig. 4). The disregard of the phenomenon of boundary layer separation in the pressure distribution around profiles seems to be the reason of the above. In a new formulation this fact could be taken into consideration together with experimental data concerning the connection of incipient cavitation with the phenomena occurring in the boundary layer.

Also computer programs for prediction of cavitation in machines that have been worked out at the Institute of Fluid-Flow Machinery, P.A.Sci. are worth of notice. They were used, among others, for prediction of cavitation in guide apparatuses of reversible machines installed in the pumped-storage water power plant at Żydowo [5] and in the Kaplan runner at the Bergheim Hydro-Electric Power Plant [6].

Fig. 5 presents results of numerical calculations allowing to infer about the possibility of cavitation development (σ_i) in a guide apparatus during turbine operation (50 MW) and pump operation (67 MW) at the rated head of 81.0 m and the maximum

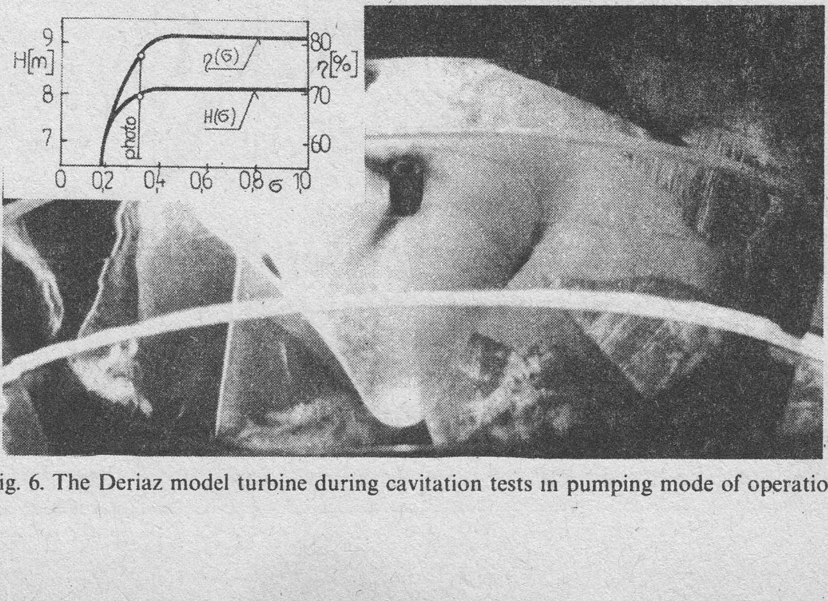

Fig. 6. The Deriaz model turbine during cavitation tests in pumping mode of operation

total head of 83.7 m, respectively. It is easy to notice that cavitation should not occur in turbine mode of operation ($\sigma > \sigma_i$) whereas one can expect it on guide vane edges in pumping mode of operation ($\sigma < \sigma_i$). The curve showing the cavitation development measured by $\Delta\sigma = \sigma_i - \sigma$ suggests that the intensity of erosion increases with increasing opening of the guide apparatus a_0. An inspection of the guide apparatus confirmed the predictions. Cavitation pitting found on the blade edges reached the depth of 4 mm after 10 000 hrs of machine operation.

3. Empirical Methods

3.1. Direct methods

Direct methods allow to follow the cavitation phenomenon in different stages of its development. They consist first of all in visual observations and in making films and photographs of zones threatened with cavitation. Their use is limited almost entirely to laboratory conditions, especially to testing models of machines and hydraulic devices. Though information got in this way is incomplete, it is nonetheless fairly reliable as far as detection of cavitation, location cavitation-covered zones and learning the cavitating flow pattern are concerned. The photograph in Fig. 6 is an example.

Formation and existence of cavitation in hydraulic machines are determined also by performance parameters, especially the Net Positive Suction Head:

$$\mathrm{NPSH} = \sigma H = \frac{p_s - p_v}{\gamma} + \frac{c_s^2}{2g}.$$

In this equation: σ — Thoma cavitation index, H — head, p_s and c_s — pressure and absolute velocity of liquid at the draft tube outlet, p_v — pressure of liquid evaporation, — specific weight of liquid, g — acceleration of gravity.

As already mentioned in section 2, the value of σ index is often considered a measure

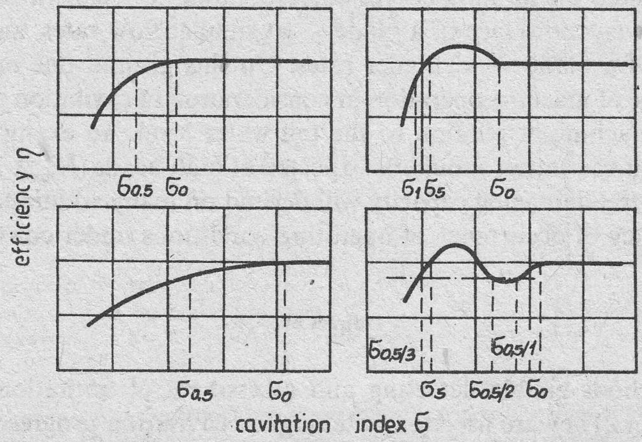

Fig. 7. Distortion of impeller pumps efficiency characteristics resulting from cavitation

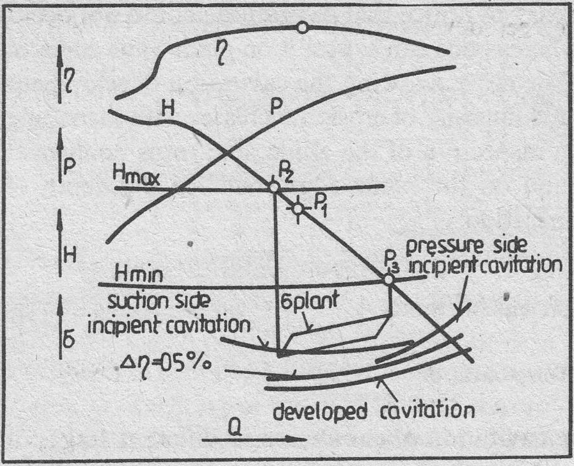

Fig. 8. Cavitation characteristic of a re-versible machine during pumping
P_1 — optimum working point, P_2 — working point H_{max}, Q_{min}, P_3 — working point H_{min}, A_{max}

of cavitation development. It serves as a criterion of danger of cavitation inception inside a machine (σ_i), indicates the permissible degree of development of the phenomenon (σ_{perm}) and determines its intensity. In the case of developed cavitation inside a machine a break-down in the performance characteristics occurs. Fig. 7 presents typical characteristics $\eta(\sigma)$ illustrating the effect of degree of cavitation development on the efficiency of impeller pumps. Different shape of $\eta(\sigma)$ curves results, among others, from different design features and specific speed of the machines tested.

Cavitation tests of a model hydraulic machine give some information about its behaviour within the desired range of variability of H and Q and indicate the required suction head defined by the inequality:

$$h_s < h_a - h_v - \sigma_{perm} H;$$

where h_a means the atmospheric pressure head measured at the tail water free surface and h_v is the saturated vapour pressure.

Fig. 8 illustrates operating conditions of the machine in pumping regime. One can distinguish here the limiting curves corresponding to incipient cavitation occurring on the back (suction) face of a blade — at smaller flow rates, and on the active (pressure) face of a blade — at higher rates. On this ground one may indicate the permissible range of machine operation in consideration of cavitation and recommend placing of the machine in relation to the tail water level. An example presented in Fig. 8 shows, that cavitation should be expected at high heads (H_{max}). It will be moderate but its material-damaging capacity will depend on many additional factors, including the frequency of occurrence of operating conditions under consideration.

3.2. Indirect methods

Indirect methods enable detecting and assessment of cavitation intensity with different accuracy. They are used for watching the cavitation progress in machines as well as for determining the permissible parameters of machine operation.

The following indirect methods have been developed* at the Institute of Fluid-Flow Machinery, P.A.Sci., in Gdańsk:

- optical (measurement of light beam attenuation, recording changes of intensity of a γ-ray beam, application of laser techniques),
- electric (measurement of liquid resistance),
- acoustic (measurement of cavitation noise),
- vibrative (measurement of acceleration and vibration amplitude),
- hydrodynamic (measurement of pressure pulsation and cavitation impingement),
- destructive (measurement of loss of material).

Below selected results of investigations carried out at the Institute and some results of investigations conducted by others using above mentioned methods are presented.

3.2.1. Optical methods

The essence of detecting and observing cavitation development through measurement of light beam attenuation consists in dispersion of a light beam crossing a liquid with bubbles. Attenuation of light intensity depends on its wavelength, concentration and sizes of bubbles and the index of refraction.

At the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences measurement of attenuation of light intensity is carried out with a probe designed by S. Mackiewicz [10]. It consists of two pieces of a metal pipe. Inside a longer pipe section there is a movable insert with a light bulb (3 V), inside a shorter section — a photoresistor. Both sections of the pipe with lenses mounted on the ends are joined with fixing bars and a small tube with photoresistor leads. Current intensity (i) in the photoresistor circuit is measured by a microammeter of class 0.5.

Fig. 9 shows an example of attenuation of light as a function $i/i_0 = f(\sigma)$, where

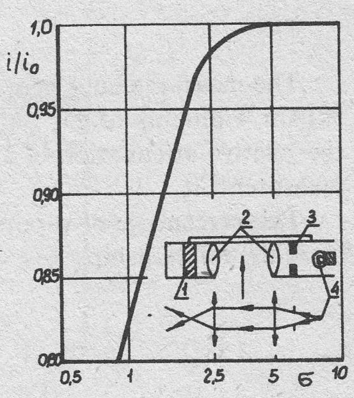

Fig. 9. Dependence of the relative attenuation of a white light beam (i/i_0) on the cavitation index (σ)
1 – photoresistance, 2 – lens, 3 – diaphragm, 4 – light source

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* Apart from the mentioned methods measurements of luminescence (first of all of sonoluminescence [illegible]), measurements of stresses in machinery components and changes of intensity of ultrasonic radiation beam [9] are worth of notice.

i_0 means the current intensity in cavitation free flow. The results indicate that a distin attenuation of light beam occurred at $\sigma \cong 2$. This value can be accepted as a critica value corresponding to incipient cavitation. It was confirmed by visual observations.

One should notice that optical probes are very sensitive to any variations in th flow and they register different disturbance including the disturbance caused b cavitation. However the detection of cavitation can be done without particula difficulties.

Optical methods may be used to assess cavitation cloud structure. Conception o "structure" concerns the form of the cloud, its constitution and oscillation in differen stages of cavitation development. Fig. 10 shows lines of equal gas phase contents in a cloud close to an aerofoil NACA 2418.

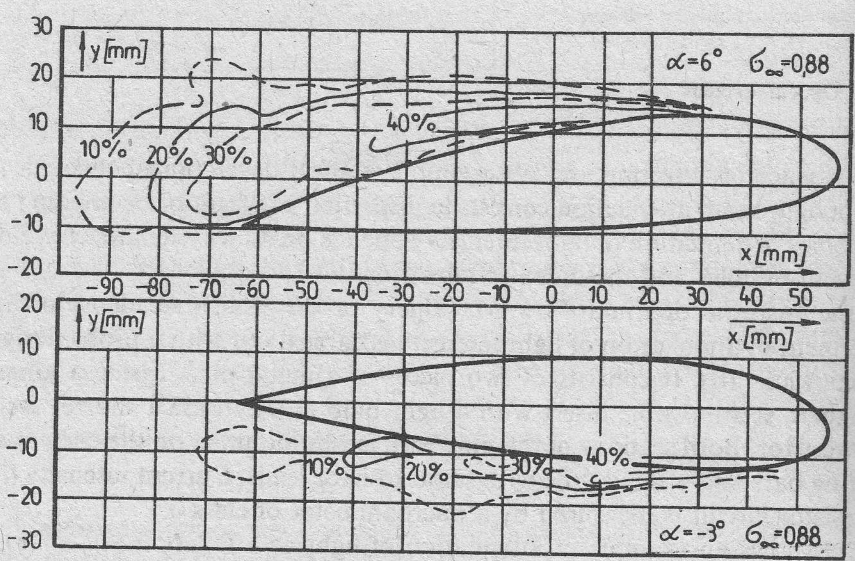


Fig. 10. Lines of equal gas phase contents around the NACA 2418 in a cavitating flow (α — hydro setting angle, $\sigma = 0.88 = \text{const}$)

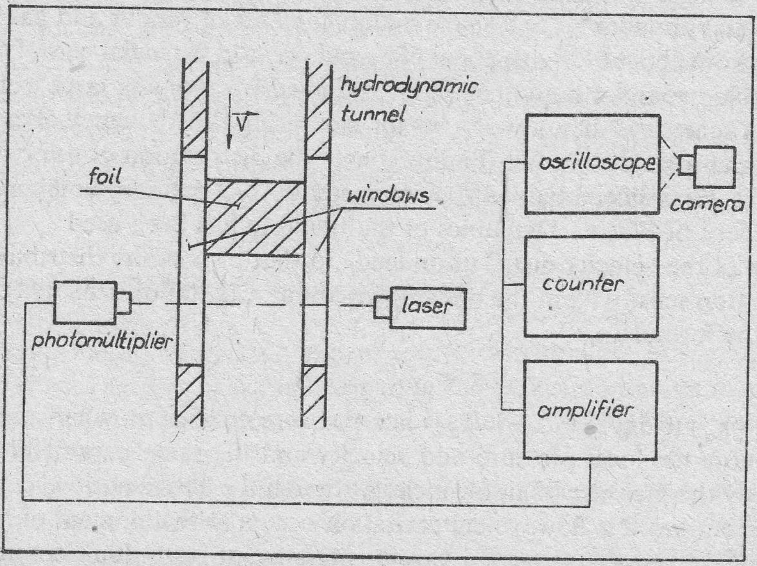
The measurements were carried out by means of beam of γ radiation emitted b $^{241}_{95}$Am. Contents of gas phase (vapour and gas mixture) were calculated based o the relative attenuation of a radiation beam of 1 mm diameter crossing the zone o measurement.

The percentage of vapour and gas mixture in the cavitation zone was calculate from the relationship:

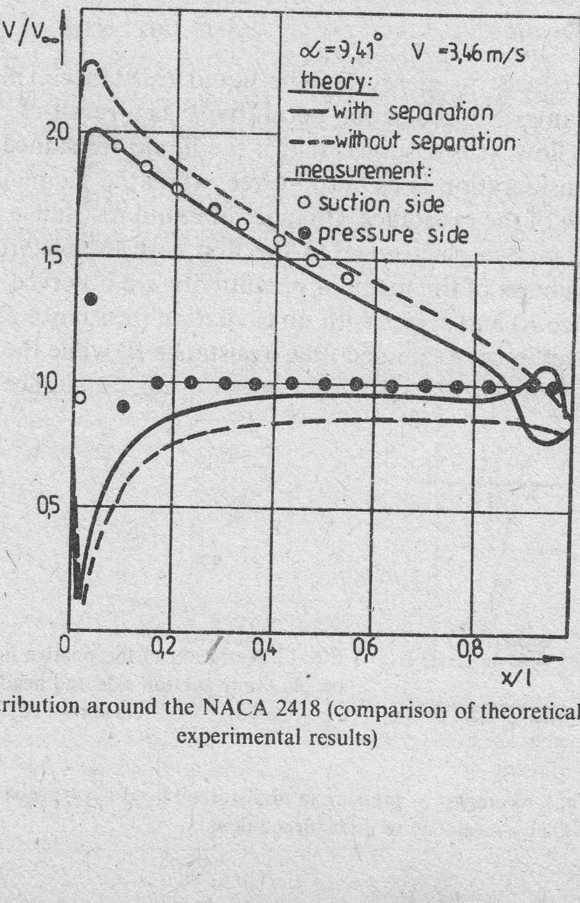
$$\varphi = \frac{\ln(I_{w/a}/I_w)}{\ln(I_a/I_w)} \cdot 100\%$$

where $I_{w/a}$, I_w and I_a are the intensity of beam after crossing the cavitation zone after crossing a chamber filled with water and after crossing an empty chambe respectively.

Measurements carried out in tap water at a temperature of 20°C revealed that a



ig. 11. Schematic diagram of the set for measuring the cavitation cloud pulsation frequency using the optical method



ig. 12. Velocity distribution around the NACA 2418 (comparison of theoretical calculations with experimental results)

the value of cavitation index* $\sigma = 0.88$ maximum contents of vapour and gas mixture are of the value from about 61.5% to about 66% and occur in the initial part of the zone.

Flow of liquid around a body may be investigated by applying laser techniques. Fig. 11 shows a schematic diagram of a set for measuring the frequency of cavitation cloud pulsation at a single aerofoil. To investigate the distribution of velocity round the aerofoil (Fig. 12) a differential laser anemometer RAL-2 designed and constructed at the Department of Plasma Dynamics of the Institute has been used.

Knowledge of the velocity distribution leads to that of pressure distribution and hence to cavitation sensitivity of the body flown about. Cavitation sensitivity may be expressed by the formula:

$$\sigma_i = -c_{p\min}$$

where $c_p = (p - p_\infty)/(0.5\rho v_\infty^2) = 1 - (v/v_\infty)^2$ is a pressure coefficient, whereas p, v, and p_∞ and v_∞ denote the local pressure and velocity and the same parameters in flow not disturbed by the presence of an obstacle. Although the above notions concern an inviscid and incompressible flow, where cavitation occurs at the moment of reduction of the local pressure to the saturated vapour pressure, still we don't commit a big mistake using them for detection of cavitation under realistic conditions.

3.2.2. Electric methods

Electric methods consist in measuring the liquid resistance. These methods are based [11] on the change of the medium permittivity as a result of presence of cavitation bubbles in the flow. It is assumed that if the liquid resistance is low, the flow in the zone under consideration is cavitation free, while the incipience of cavitation is indicated by growth of the resistance. Changes of liquid resistance may be detected with the help of one or two electrodes. In the first case the electrode is set in the examined flow and changes of the medium permittivity are observed in different cavitation stages (resistance R) and stages with no cavitation (resistance R_0). In the second case one electrode is set in the examined flow (resistance R) while the second one is in another place of the flow where cavitation doesn't occur (resistance R_0).

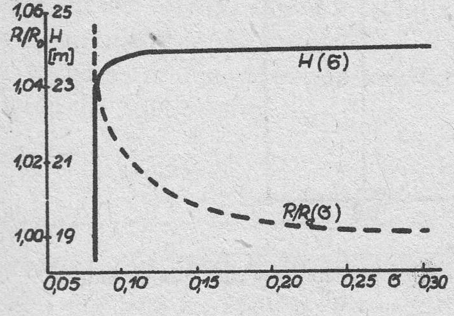


Fig. 13. Variation of the relative liquid resistance R/R_0 on the pump suction side and head H vs. the cavitation index σ [12]

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* $\sigma = (p_\infty - p_v)/(0.5\rho v_\infty^2)$, where: p_∞ — pressure in undisturbed flow, p_v — pressure of liquid evaporation, ρ — density of liquid, v_∞ — velocity of undisturbed flow.

Fig. 13 shows the change of liquid resistance and the total head of an impeller pump as functions of the cavitation index σ. Electrodes were set up on an inner circumference of the pump suction nozzle, just upstream of the impeller inlet. From both curves conclusions can be drawn that a change of liquid occurs before the break of curves $H(\sigma)$ revealing cavitation in an early stage of development. This observation was confirmed by visual observations and control tests performed in the cavitation tunnel of the IF-FM P.A.Sci. designed for testing ship propellers.

3.2.3. Acoustic methods

Acoustic methods, making use of conversion of flow energy disturbing into acoustic wave energy, consist in measuring the acoustic pressure in the air (outside the machine) and in the liquid (inside the machine). Microphones and hydrophones are the basic instruments.

Most often sound level meters consisting of a microphone and a measuring amplifier, showing acoustic pressure in decibels, are employed for noise measurements. More discerning assessment of noise measurement results consists in performing spectroanalysis of sound.

Cavitation noise is an often measured parameter. Random acoustic signals of ultrasonic frequency (above 16 kHz) and continuous spectrum are concerned. Noise measurements are carried out mainly in the range of frequency from 10^5 to 10^8 Hz.

Figs 14-17 present some results of investigations carried out at the IF-FM as well as at other laboratories. The possibility of detection and observation of cavitation on the basis of acoustic pressure change is evident. Figs 14 and 15 (the authors' own investigations) and Fig. 16 (investigations carried out by others) indicate close relationship between acoustic pressure and cavitation development: while the value of σ index is decreasing the acoustic signal increases independently of the measuring transducer art and situation. This increase occurs up to a certain threshold corres-

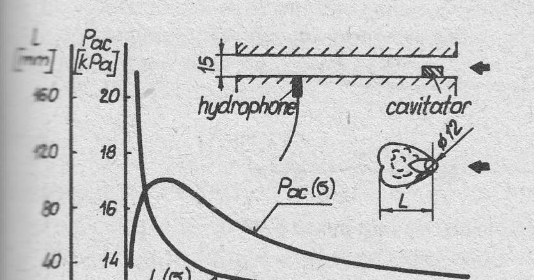


Fig. 14. The influence of cavitation index σ change on the cavitation cloud length L behind a cylindrical bolt and on the hydroacoustic pressure change p_{ac} [13]

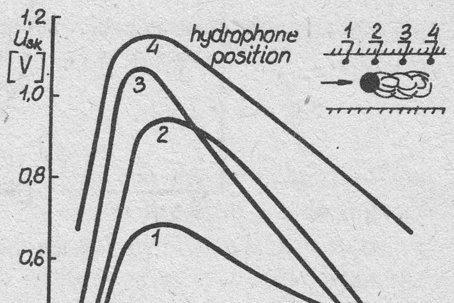


Fig. 15. The influence of hydrophone position and cavitation development degree σ on the acoustic pressure u_{sk} value [15]

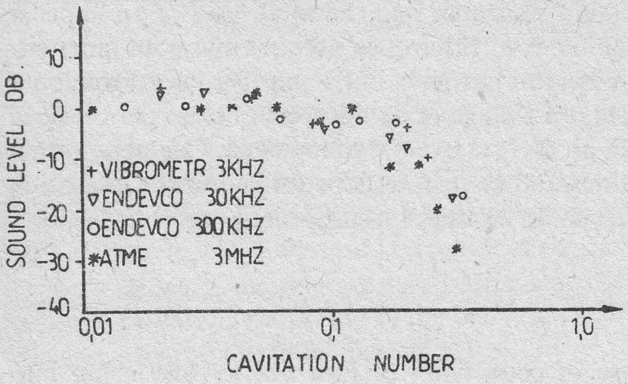


Fig. 16. Sound level variation (dB) depending on the cavitation index σ, recorded with different measuring instruments (from [14])

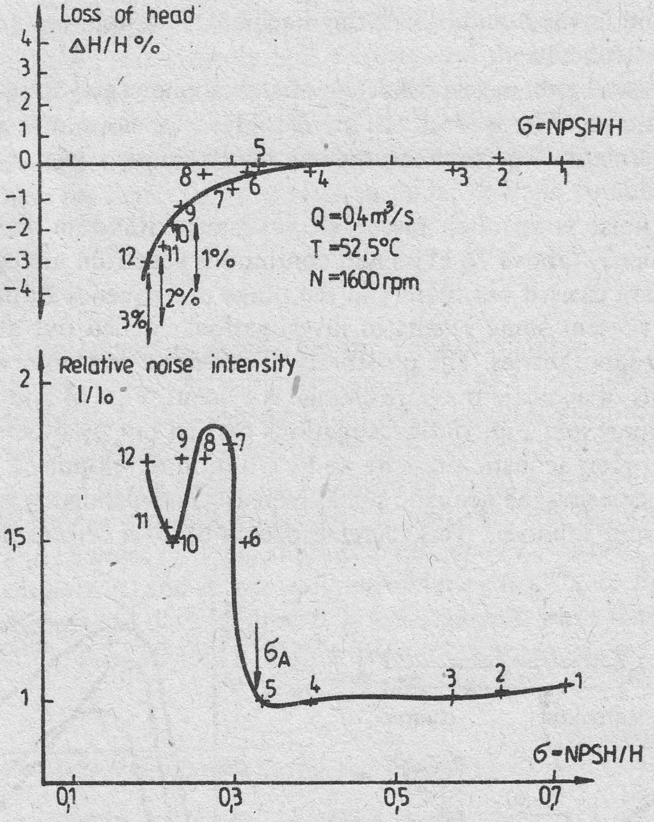
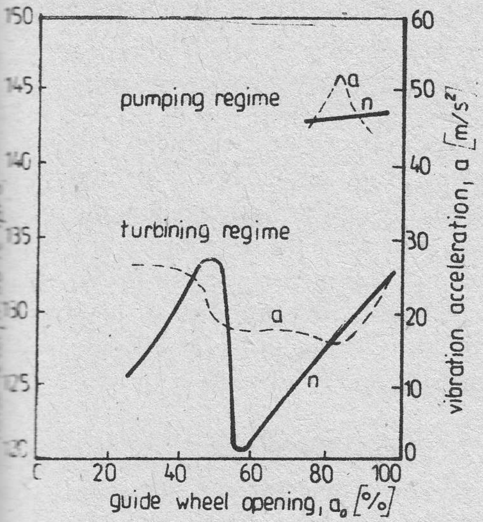


Fig. 17. Test results on Superphenix 1 pump model [24]

ponding to strongly developed cavitation. The level of the recorded signal decre under supercavitation conditions.

A similar pattern of acoustic pressure changes is observed when testing hydrau machines in the cavitation regime. The highest sound (noise) level occurs befor simultaneously with the bending of the performance characteristics (Fig. 17). Af hat the sound level decreases in general, which is connected with a state in which avitation fills a significant part of space between the blades.

Acoustic methods are used in cavitation diagnosis of large hydraulic machines orking in water power plants. The results of the authors' own investigations shown Fig. 18 are an example. This drawing shows hydroacoustic noise variation under e runner of a reversible machine versus opening of the guide-ring during pumping power of 67 MW) and turbine operation (power of 50 MW). Also accelerations of vibrating cover of the draft tube scuttle are presented in this figure. The cover acts s a membrane of a kind, sensitive to dynamic effects occurring under the runner. From e form of the curves it is easy to infer that the most beneficial cavitation conditions ccur during the turbine operation, at the guide-ring opening from 50 to 80% nd that during pumping the influence of cavitation on the surroundings is most ntense.



g. 18. Hydroacoustic noise emission and accele-tion of vibrating draft tube of a reversible ma-chine vs. the guide-ring opening [19]

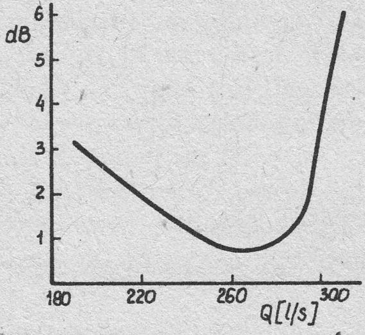


Fig. 19. Cavitation noise emission vs. pump discharge [17]

Fig. 19 is another example indicating usefulness of the acoustic method for ssessment of cavitation hazard to a machine. This figure presents the change of vitation noise level as a function of the liquid flow rate through a pump. The curve orms not only about different intensities of the phenomenon, but also about the owable range of pump operation.

Worth mentioning here are the observations made by various investigators, including the authors, that it is advisable to use higher frequency transducers (> 100 kHz) measure the acoustic pressure in flow with cavitation. One may recommend Brüel Kjaer hydrophones and Piezotronics pressure transducers of high sensitivity (on e order of several μV/Pa) and small diameter (several mm).

3.2.4. Vibrational methods

As vibrational method one understands diagnostic methods based on measurement and analysis of vibrations (displacement, velocity or acceleration) of a machine and equipment parts exposed to cavitation. The point in question concerns vibrations which are caused by implosion and collision of cavitation bubbles and by cavitation clouds pulsation.

Usually the spectrum of vibration frequency is contained in the band from several to a dozen or so (several tens) kHz. When accelerations of vibrating machine components are measured, the most significant part of process energy is concentrated within the range of the highest measured frequencies, in the case of vibration velocity the process energy is distributed evenly in the spectrum, in the case of displacement — it is concentrated at the lowest frequencies.

The progress of vibration depends, of course, on the degree of cavitation development. The vibration level increases owing to decrease of cavitation index reaching maximum for developed cavitation. For strongly developed cavitation the intensity of vibration decreases.

Increase of the vibration level caused by cavitation occurrence in the flow is not always distinct. On this account and also because of the random character of vibration process, by observing a characteristics of machine vibration one can only roughly indicate these operating parameters for which cavitation appears and reaches the highest dynamic intensity. Fig. 20 may be an example. It presents the dependence of vibrative displacements in a body of a Kaplan turbine on the generating set power. As results from audiovisual observations cavitation in a bubbly form appears at the power of about 9 MW. At the power of about 12 MW it is strongly developed (intense sheet cavitation) generating noise of moderate intensity, and from 13 MW on it is a cause of louder clicks and of unrhytmic din.

The influence of cavitation intensity and the angular velocity ω of a diagonal pump

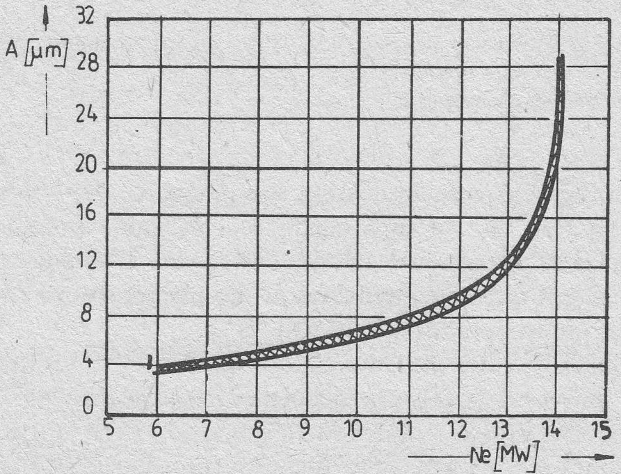


Fig. 20. Dependence of Kaplan turbine body vibration amplitude on turbine set power

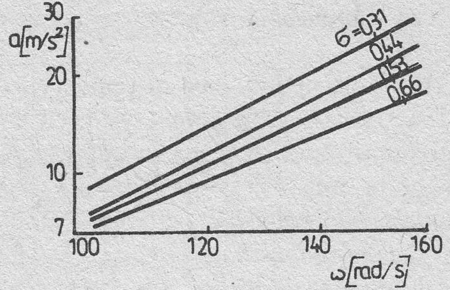


Fig. 21. Dependence of the pump body vibration acceleration a on the impeller angular velocity ω and cavitation index σ for the discharge coefficient $\varphi^* = \varphi/\varphi_{\text{opt}} = 1.22$ [18]

impeller on the level of the pump body vibration is presented in Fig. 21. From empirical data it appears that vibrative acceleration may be expressed by the equation

$$a = c\omega^n,$$

where c is a function of the discharge coefficient φ and cavitation index σ while the value of the exponent n is contained within the bounds from 2.4 to 3.1. One should mention that this quantitative relationship concerns a definite case, so it is characteristic for this particular case only and can't be a basis for generalization.

One should point out the fact that except cavitation there exist also other forces causing vibration of flow limiting walls. Separation of "cavitation free" runs comes up against serious difficulties. The same takes place also during noise measurements. Received results may be disturbed also by reverberations, interferences, resonanse, aberrations and so on.

3.2.5. Hydrodynamic methods

Hydrodynamic methods consist in observing pressure pulsations produced by cavitation and in measuring the flux of energy delivered by cavitation impulses to a transducer set up in the cavitation zone.

An example of a spectrum of cavitation pressure pulsation in a diagonal pump is presented in Fig. 22. The lowest frequencies, on the order of a few Hz, are caused by pressure micropulsations in the whole pumping system. They are the effect of a feedback between the cavitation zone sizes and the pumping discharge under conditions of strongly developed cavitation. Frequencies from tens to several hundred kHz are an effect of cavitation cloud pulsation. These are usually pulsations of high amplitude. Pressure pulsations caused by motion and development of cavitation bubbles are contained in the band of frequencies from several to a dozen or so kHz. The highest frequencies in the range of tens, hundreds or even thousands kHz are the result of pulsations caused by cavitation bubble implosion.

The flux of impact energy per unit of surface may be described as follows:

$$\hat{E} = n_1\hat{e}_1 + n_2\hat{e}_2 + \dots + n_k\hat{e}_k,$$

where n_1, n_2, ... are numbers of pressure impulses at a mean energy level $\hat{e}_1$, $\hat{e}_2$, ... Histograms of pressure impulses received for different cavitation intensities in a flow

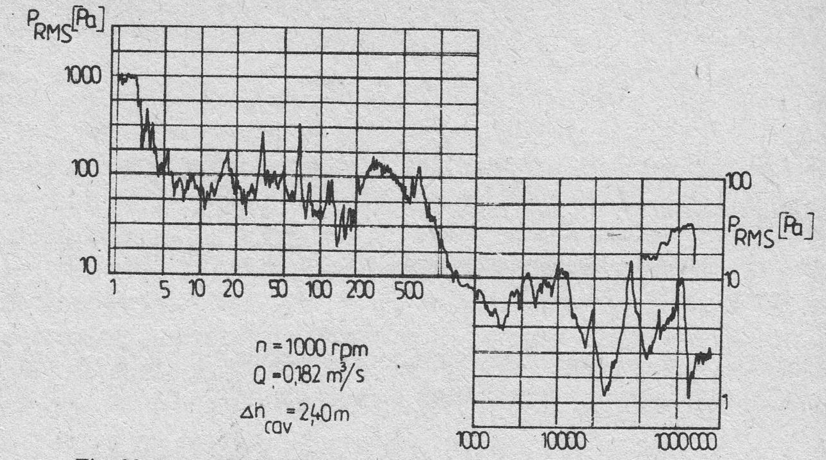


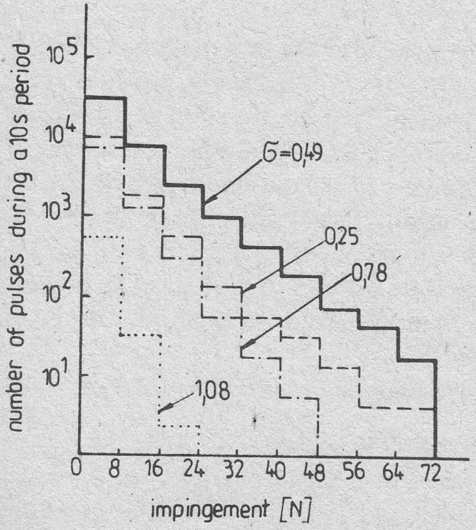
Fig. 22. Spectrum of cavitation pressure pulsation in a diagonal pump

are presented in Fig. 23. The transducer for pressure impulses measurements (PC Piezotronics transducer with a sensivity of 0.145 mV/kPa, resolution of 1.4 kPa, re- sonant frequency 500 kHz, membrane diameter — 5 mm, fitted for max. pressu of 100 MPa) was installed in the region of direct cavitation action. One should pa attention to variability of the number of impulses depending on the value of σ inde and to the fact, that impulses reach their maximum values for a certain defined cavitation number (this result is known from experimental and theoretical investigations

Assuming that the energy of a single impulse is defined by power emitted b a collapsing bubble and that the density of this power figures:

$$e = p^2/\rho c$$

(where p is the impact pressure, and c is the speed of sound in a medium of density



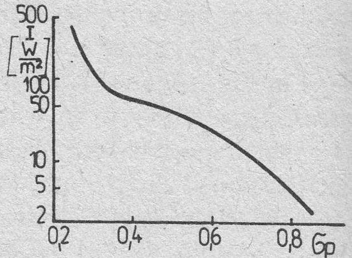


Fig. 24. Dynamic index of cavitation intensity I as a function of cavitation index σ of a diagonal pump for the angular velocity $\omega = 157$ rad/s and discharge coefficient $\varphi^* = \varphi/\varphi_{\text{opt}} = 1.22$

Fig. 23. Histograms of cavitation pulses [2

the expression:

$$\hat{E} \propto ME = \frac{1}{T}\sum_{i=1}^{i=k} n_i p_i^2$$

can be a measure of cavitation intensity. Fig. 24 presents the change of the energy flux density $I = 2.5 \cdot 10^{-5}\, ME/\rho c$ in relation to cavitation index $\sigma_p = \mathrm{NPSH}(u^2/2g)^{-1}$ for a diagonal pump. Worth noting are large changes of the cavitation intensity indicating high erosion hazard for small values of σ_p.

As it follows from the experience of the Department of Fluid Dynamics of the IF-FM, Pol. Acad. Sci., measurements of energy of pressure impulses are the best way of assessing the influence of cavitation on a flow confining wall, and thus assessing the cavitation intensity, forming a basis for prediction of erosion damage.

3.2.6. Destructive methods

Destructive methods consist in recording changes which occur under the influence of cavitation acting on structural materials of machines and models and test samples of material inlayed in a flow confining wall. The recording may concern observation of surface changes, a measurement of mass or volume loss or medium depth of cavitation pitting. Observations allow first of all to detect places exposed to cavitation attack. To this end one may use coatings sensitive to cavitation activity. On coatings of low durability marks of destructive action of cavitation occur already at small intensities of the phenomenon. Marks of damage occurring on a model runner of a turbine may be an example (Fig. 25). In the case of cavitation intensity assessment one may use erosion tests of appropriate specimens of materials or inspection of machines after some time of operation. For instance one may use for tests: two

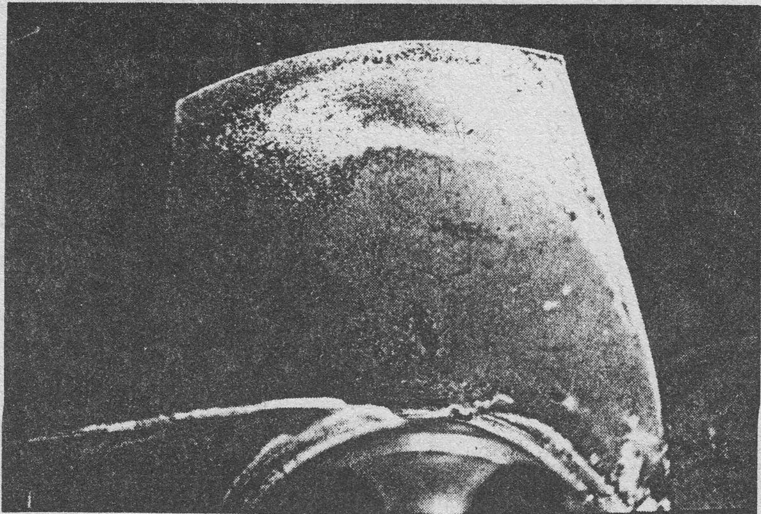


Fig. 25. Effects of cavitation on a model impeller

specimens made of the same material: a standard one (M) put to cavitation of known intensity (ME_M) and a test sample (P) set in flow with cavitation of unknown intensity (ME_P). Comparing medium durability $\bar{\delta}$ [min/mm^3] of both pieces (δ_P and δ_M) after the same time of cavitation activity one may infer about erosion and cavitation intensity in a given place of flow. As proved in earlier works (for instance [23]) we may write roughly that:

$$\frac{\delta_P}{\delta_M} = \frac{R_{\mathrm{cav},P}\,(\eta ME)_M}{R_{\mathrm{cav},M}\,(\eta ME)_P},$$

or assuming the same cavitation resistance of the standard and test sample ($R_{\mathrm{cav},M} = R_{\mathrm{cav},P}$) and similar efficiency of energy absorption by the material ($\eta_M = \eta_P$),

$$\frac{\delta_P}{\delta_M} = \frac{ME_M}{ME_P}.$$

On the ground of the above we may estimate the actual cavitation intensity level for which the factor ME will be

$$ME_P = ME_M \frac{\delta_M}{\delta_P}.$$

Also incubation (initiation) period and maximum damage penetration rate $MDPR$ may be applied as measures allowing to assess the cavitation intensity. One should explain here that some authors [26] stress the relationship between the value of $MDPR$ and the acoustic power of a point (monopolar) source $W(R)$. This relation is as follows:

$$MDPR = C[W(R)]^{1/n}$$

in which C means a constant while power $W(R)$ may be reckoned from the equation:

$$W(R) = \int_{(S)} I\,ds,$$

where I means the unit acoustic energy flux emitted by a source set at a distance R, S is the area of a surface which that flux "covers".

Generally one may say that destructive methods serve mostly for revealing the spots exposed to cavitation and assessing the cavitation erosion intensity.

4. Final remarks

It appears from the review of diagnostic methods suitable for detection and observation of cavitation development in hydraulic machines that most of them are not good for use under field conditions. Specifically, power-related and optical methods are suitable first of all for model investigations, while vibroacoustic methods can be used for investigations under natural conditions.

Table 1

Visual observations	1
Power methods*	0.3-0.4
Acoustic methods**	1.05
Vibration methods	0.9
Hydrodynamic methods:	
a) according to energy flux	0.6-0.9
b) according to pressure pulsation	0.25-0.95
Destructive methods	depending on material

* This means distortion of cavitation characteristics by breaking the curves of head, flow intensity, power and efficiency (decrease of values of H, Q, N and η within 1 to 3%)

** concerns spectral analysis of cavitation noise.

One can estimate the efficiency of diagnostic methods by comparing the results of visual observation with the results of measurement of different cavitation signs. Such an analysis was carried out for a radial-flow impeller pump by V. Kercan and F. Schweiger [21]. Similar diagnosis for a diagonal pump was carried out in the Department of Fluid Dynamics of the IF-FM [22]. Listed in Table 1 are some of results of this analysis. Number 1 means occurrence of cavitation in the flow at a stipulated incipient cavitation number $\sigma_{in} = \text{NPSH}/H = 1$. Numbers different from one indicate an earlier or later — in relation to cavitation inception discovered visually — occurrence of particular marks of the phenomenon. And so numbers smaller than one give evidence of given marks appearing at cavitation index smaller than the value of cavitation inception index i.e. $\sigma < \sigma_{in}$, whereas a number larger than one gives evidence of cavitation having been detected earlier than noticed by the observer. Differences between particular values indicate the known fact that particular signs of cavitation do not occur simultaneously.

When assessing the diagnostic methods one should take into account that their evaluation is based on the results of empirical investigations performed under different conditions of machine operation, thus at different speeds of impeller rotation and at different heads. Among others that's why estimations are expressed by an interval of two numbers. Besides, recorded signs of cavitation are disturbed by other phenomena

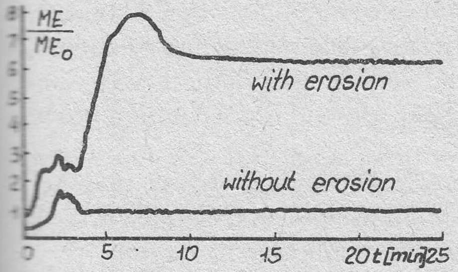


Fig. 26. Variation of the relative density of energy flux ME/ME_0 delivered to the cavitation chamber wall during time t of material damaging [23]

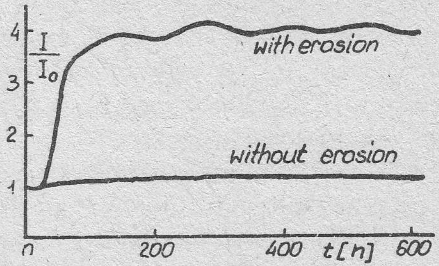


Fig. 27. Relative cavitation noise intensity variation I/I_0 vs. time t of material damaging [24]

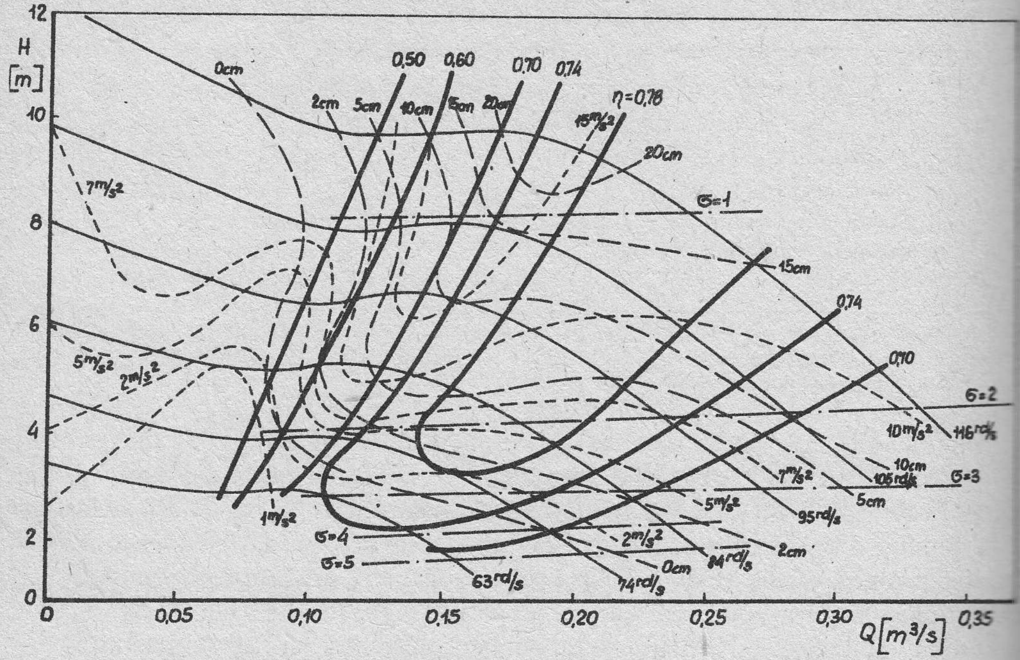


Fig. 28. Complex characteristics of a diagonal pump including curves of throttling *H*(*Q*) , cavitation cloud length *L* , efficiency η = = = = = =, cavitation index σ · · and vibrating body acceleration ...... [19]

accompanying operation of the machine tested. This state of the art as well as fluctuations of the measured parameters have an effect on the results obtained. Nonetheless, numerical data indicate that measurements of pressure pulsation in a flow are the most controversial ones (large dispersion of the impulse levels indicating cavitation), while vibroacoustic methods do not arouse distinct reservations (level of impulses generated by cavitation differ only slightly).

Apart from the power-related methods which are standard ones and most often applied during laboratory tests, one should acknowledge the superiority of hydrodynamic methods based on measurement of the flux of "cavitation energy" delivered to the flow confining walls. Hydrodynamic methods may be also acknowledged as especially suitable for inferring about the hazard of cavitation erosion for machines and devices. Fig. 26 may be an example. It presents recorded signals of cavitation impingement in flow without and with material damaging cavitation [23]. Similar curve (Fig. 27) was obtained by P. Courbiere [24] who applied cavitation observation with an acoustic method.

Also vibroacoustic methods give good results. Distinguished here may be an acoustic method consisting in analysing the cavitation noise and suitable first of all for detection of cavitation under natural conditions of machine operation.

Considering different aspects and criteria of assessment of hydraulic machinery qualities it is desirable to know the so-called "complex" characteristics. A characteristics giving information about performance cavitation and vibroacoustic qualities f a machine (Fig. 28) is meant here. Such a characteristics is suitable not only to ssess the product quality but also to determine the rated operating parameters and o predict machine performance under various operation conditions.

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Wykrywanie i ocena natężenia kawitacji przepływowej

Streszczenie

Praca zawiera krótki przegląd metod badawczych stosowanych w Zakładzie Dynamiki Cieczy Instytutu Maszyn Przepływowych PAN w Gdańsku, służących do wykrywania oraz oceny stopnia rozwoju kawitacji w maszynach i urządzeniach hydraulicznych. Przegląd zilustrowano wynikami badań własnych i obcych. Wskazano na efektywność opisanych metod oraz na te metody, które najlepiej nadają się do diagnostyki kawitacji przepływowej.

W szczególności omówiono metody teoretyczne i doświadczalne.

W zakresie metod teoretycznych przedstawiono uproszczoną procedurę polegającą na zastosowaniu do oceny zasięgu kawitacji w palisadach łopatkowych modelu ewolucji pojedynczego pęcherzyka kawitacyjnego oraz niektóre wyniki obliczeń numerycznych, wskazujące na możliwość poprawnego przewidywania kawitacji w kierownicach maszyn odwracalnych (rys. 5).

W zakresie metod doświadczalnych omówiono metody bezpośrednie i pośrednie.

Do metod bezpośrednich zaliczono obserwacje wizualne i fotografowanie stref zagrożonych kawitacją (rys. 6) oraz zniekształcenie charakterystyk energetycznych w przypadku kawitacji rozwiniętej we wnętrzu maszyny. Typowe charakterystyki $\eta(\sigma)$ ilustrujące wpływ stopnia rozwoju kawitacji na sprawność pomp wirowych przedstawiono na rysunku 7, natomiast na rysunku 8 przedstawiono wykres ilustrujący pracę modelowej maszyny odwracalnej w różnych warunkach kawitacyjnych.

Spośród metod pośrednich scharakteryzowano metody następujące:

— optyczne (pomiar osłabienia wiązki światła białego — rys. 9, rejestracja zmiany natężenia wiązki promieniowania γ — rys. 10, zastosowanie anemometrii laserowej — rys. 11 i 12),
— elektryczne (pomiar rezystancji cieczy — rys. 13),
— akustyczne (pomiar szumu względnie hałasu kawitacyjnego — rys. 14 ÷ 19),
— wibracyjne (pomiar przyspieszeń i amplitudy drgań — rys. 18, 20 i 21),
— hydrodynamiczne (pomiar pulsacji ciśnienia i obciążeń kawitacyjnych — rys. 22 ÷ 24),
— niszczące (pomiar ubytków materiału — rys. 25).

Za szczególnie przydatne do wnioskowania o zagrożeniu elementów maszyn erozją kawitacyjną uznano metody hydrodynamiczne, oparte na pomiarze strumienia „energii kawitacyjnej” dostarczonej do ścianek ograniczających przepływ. Podkreślono także dobre własności diagnostyczne metod wibroakustycznych, a zwłaszcza metody polegającej na analizie szumu kawitacyjnego.

Na zakończenie wskazano na celowość znajomości „kompleksowych" charakterystyk maszyn, informujących o ich własnościach energetycznych, kawitacyjnych i wibroakustycznych.

Обнаруживание и оценка интенсивности проточной кавитации

Резюме

В работе дан короткий просмотр методов исследований применяемых в Отделе динамики жидкости Института проточных машин ПАН в Гданьске и служащих обнаруживанию и оценке степени развития кавитации в гидравлических машинах и устройствах. Просмотр иллюстрируется результатами собственных и чужих исследований. Указана эффективность описанных методов, а также те методы, которые особенно пригодны для диагностики проточной кавитации.

В особенности обсуждаются теоретические и экспериментальные методы.

Среди теоретических методов представлены упрощённая процедура основанная на применении для оценки предела кавитации в лопаточных решётках модели одиночного кавитационного пузырька, а также некоторые результаты численных расчётов, показывающие на возможность правильного предусматривания кавитации в направляющих аппаратах обратимых машин (рис. 5).

Среди экспериментальных методов обсуждаются непосредственные и посредственные методы.

К непосредственным методам зачисляются наглядные наблюдения и фотографирование зон угроженных кавитацией (рис. 6), а также деформация энергетических характеристик в случае кавитации развернутой внутри машины. Типичные характеристики $\eta(\sigma)$, иллюстрирующие влияние степени развития кавитации на к.п.д. роторных насосов, представлены на рисунке 7, а на рисунке 8 представлен график иллюстрирующий работу модельной обратимой машины в различных эксплуатационных условиях.

Среди посредственных методов схарактеризованы следующие методы:

— оптические (измерение ослабления пучка белого света — рис. 9, регистрация изменения интенсивности пучка излучения γ — рис. 10, применение лазерной анемометрии — рис. 11 и 12),
— электрические (измерение резистанции жидкости — рис. 13),
— акустические (измерение кавитационного шума — рис. $14 \div 19$),
— вибрационные (измерение ускорений и амплитуд колебаний — рис. 18, 20 и 21),
— гидродинамические (измерение пульсаций давления и кавитационных нагрузок — рис. $22 \div 24$),
— разрушающие (измерение убылей материала — рис. 25).

Особенно пригодными для делания выводов об угрозе кавитационной эрозии относительно элементов машин считаются гидродинамические методы, основанные на измерении потока „кавитационной энергии" доставляемой к стенкам ограничивающим течение. Подчёркиваются также хорошие диагностические свойства виброакустических методов, а особенно метода основанного на анализе кавитационного шума.

В заключении указывается на целесообразность значения „комплексных" характеристик машин, информирующих об их энергетических, кавитационных и виброакустических свойствах.