EXPERIMENTAL INVESTIGATION OF CAVITATION NOISE

BY J. VARGA *
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Introduction

Cavitation phenomena due to shock waves produced by the collapse of bubbles is suitable to make investigations by acoustic methods. Therefore more research institutes would be expected to deal with the noise spectrum of cavitation [1], however, only a few of them performed such experiments up till now.

Under specified conditions, cavitation noise spectrum characteristics render a reliable basis for the evaluation of cavitating flow features and cavitation erosion damage. Led by this consideration, the Department of Fluid Machinery, Technical University Budapest, supported by the Hungarian Academy of Sciences supplemented their current cavitation damage experiments [2], [3], [4] with investigations on cavitation noise spectra.

In the course of these experimental investigations the cavitation noise spectrum has been studied with its visual appearance and with its erosion characteristics. The results of these investigations will be reported in the following paragraphs.

Test equipment

The experiments were performed in a closed circuit hydrodynamic tunnel. There was a 48 mm diameter bronze circular cylinder located horizontally in the working section with the dimensions 48 × 200 mm, perpendicular to the flow direction, and the acoustic behaviour of the cavities produced beyond this cylinder was then studied. One side of the working section was constructed of steel, whereas the other three of plexiglass.

For frequency and sound pressure level measurements there was a Brüel and Kjaer electrostatic microphone mounted normally to the sidewall, displaced with 100 mm from the cylinder end, in the horizontal plane containing the axis of the cylinder. The microphone indications were connected to a Brüel and Kjaer frequency analyzer to study sound pressure level values within the frequency range of from 20 to 20 000 cps. Connecting the frequency analyzer to an automatic level recorder, measurement results could be continuously registered.

Cavitation noise

The noise of cavitation could be observed in a natural auditory manner although, in the course of the joint perception of all sound frequencies, there is a possibility existing that the higher sound pressure level frequencies would suppress the less intensive ones. With some periodical shedding of cavities produced in the system, due to the cavitating flow, the sound pressure level generated along the collapse of bubbles could readily be observed as a vibration occuring at the same time. Model experiments revealed that the shedding of the cavities from the circular cylinder of 48 mm diameter in

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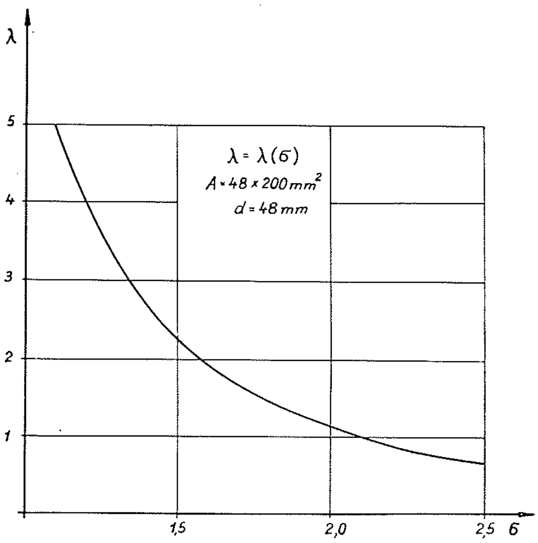
the aforesaid working section begins at a cavitation number of about $\sigma = 2.4, \ldots 2{,}5$. The cavitation number is defined by:

$$\sigma = \frac{P_\infty - P_v}{0{,}5\, v^2_{\infty 0}\, \rho}$$

where P_∞ is the static pressure measured at the sidewall in place of the cylinder, P_v, is the vapour pressure referring to the given liquid temperature, ρ is the liquid density, and $v_{\infty 0}$ indicates the maximum velocity of undisturbed flow.

In case of cavitation numbers exceeding the aforesaid values, only a low whisper will be heard changing into an increasing rumble with the reduction of the cavitation number. The thin vortex filaments visible at the beginning of cavitation change into a staple from of a few mm length, produced along the top and bottom generating line of the cylinder, with the reduction of the cavitation number. By the further reduction of the cavitation number, this will develop into shedding vortices having a visual appearance of short cavitation zones. Reducing the cavitation number even more the cavitation zone increases.

According to the results of the frequency analysis to be presented later, the short cavitation zone $l_z = 1.5\, d$ where l_z indicates cavity length measured by visual observation from the center line of the cylinder generating the highest sound pressure level which will gradually decrease with the increase of the cavity length, that is, with the reduction of the cavitation number. The functional correlation between the relative—nondimensional—cavity length $\lambda = l_z/d$ and the cavitation number (σ) is shown in Figure 1, [5]. Figures 2, 3 and 4 present short exposure time pictures of various cavitation conditions.



1/ Relative cavity length (λ) in function of the cavitation number (σ).
Longueur de poche relative (λ) en fonction du coefficient de cavitation (σ).

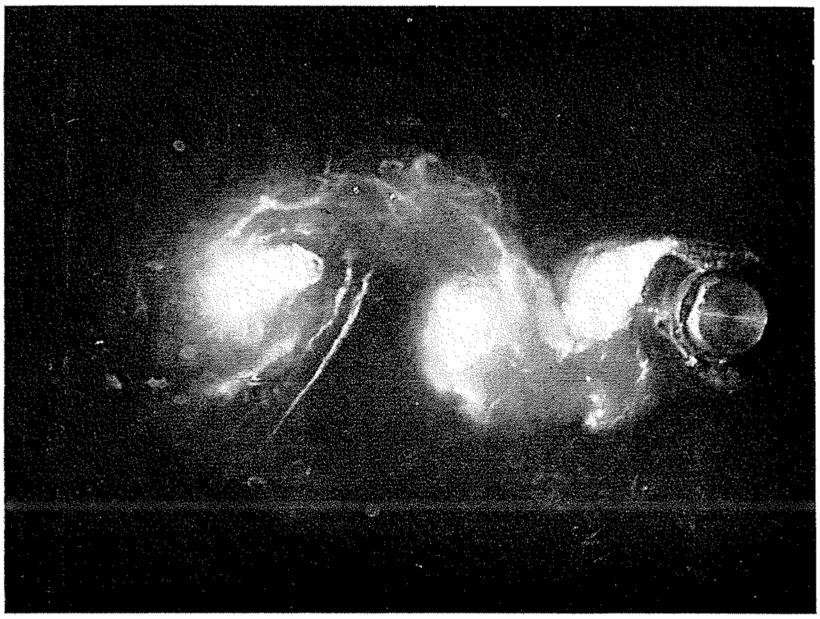
The frequency spectrum of cavitation noise

The automatic level recorder connected to the frequency analyzer registers sound pressure level (n_p) as function of frequency (f). The difference between the cavitation noise level and arbitrary reference sound pressure level may be expressed in the following way:

$$\Delta n_p = 10 \log \left(1 + \frac{1}{10^{\frac{n_{p1} - n_{p2}}{10}}} \right) \text{dB}$$

where Δn_p is the sound pressure level difference expressed in decibels, n_{p1} is a sound pressure level

2/ Photograph of the wakes shedding from the circular cylinder model where $d = 48$ mm, exposure time $t = 2.10^{-6}$ sec., and $\sigma = 2.18$.
Détachement des sillages du modèle cylindrique de section circulaire d = 48 mm; temps de pose t = 2.10⁻⁶ s; σ = 2,18.



3/ Photograph of the wakes shedding from the cylinder model at $\sigma = 1.80$.
Détachement des sillages du modèle cylindrique à σ = 1,80.

by a given frequency, and n_{p2} is the reference sound pressure level at the same frequency.

If the sound levels equal ($n_{p1} = n_{p2}$), the combined total sound pressure level would exceed the sound level of one of the noise sources by 3 dB. If the difference between the two sound pressure levels is 8 dB then, according to unavoidable readings error limit the total sound pressure level is equal to the higher component level.

Investigations of the frequency spectra of various cavitation conditions shows that, within the frequency range of 20, ... 50 cps, the motor and pump noise is intensive enough to mask any cavitation noise. Above this range, however, the machine noise level can be neglected. Thus, for example, the Δn_p value between the sound pressure level selected as cavitation test reference level determined by flow conditions ($\sigma = 2.8$), and the sound pressure level exhibited by the electric motor driven equipment in case of $f > 10^4$, was more than 20 dB and even within the frequency range of 400, ... 10 000 cps was not less than 10 dB.

In order to investigate the development of noise level conditions, sound pressure level-frequency curves for constant flow velocities but variable cavitation conditions have been plotted. Of these cavitation noise spectra Figure 5 presents two $n_p = n_p(f)$ curves referring to different cavitation numbers but to identical flow velocities ($v_\infty = 12$ m/s). The curves plotted by using the values registered by the automatic level recorder show that there is a significant difference existing between the sound pressure level of the cavitating state and the cavitation-free condition selected as reference level. It was found that above the frequency of $f = 10^4$ cps, due to the significant decrease of the sound pressure of external sound sources, sound pressure level comparisons for various cavitation conditions may be safely and reliably performed.

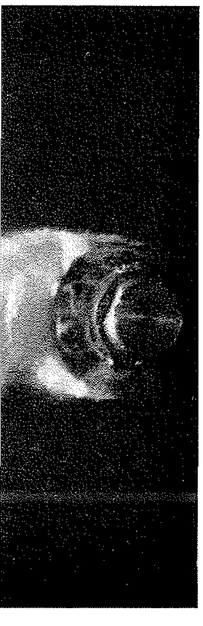
Figure 6 presents curves illustrating sound pressure level values obtained with different flow velocities, in function of the relative length of the cavitation zone. The Figure reveals that the curves have a peak value at $\lambda = 1.5$ with steep variations in either direction. The sound pressure level values decreasing with reduced flow velocities.

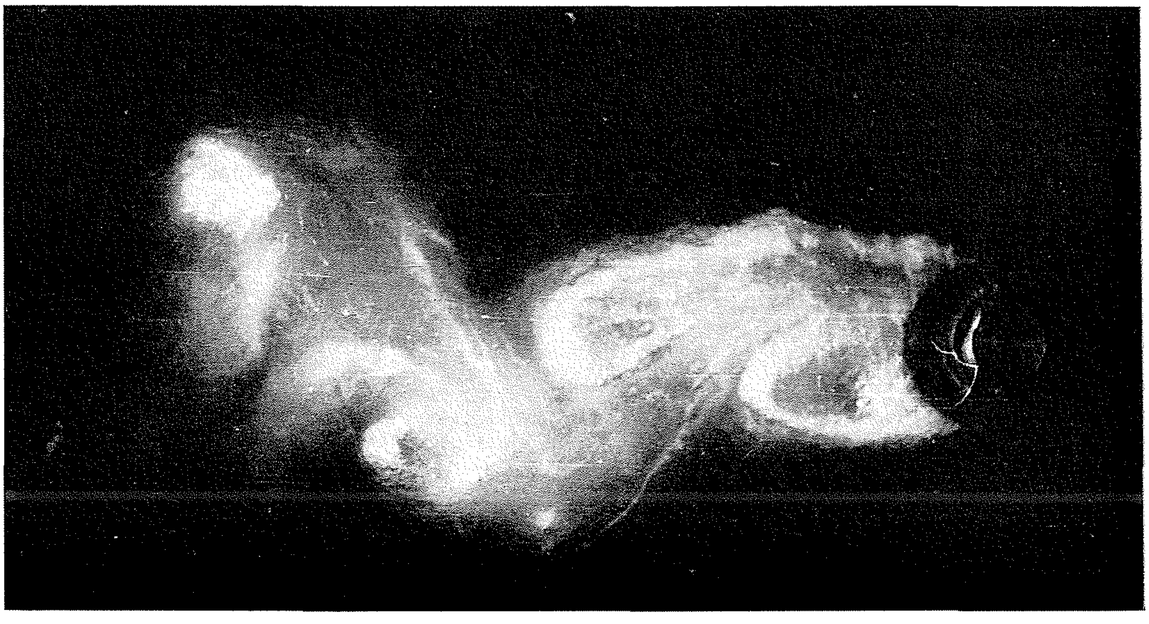
For completeness' sake, the investigations described above have been conducted also by means of vibrometer heads mounted onto the steel and plexiglass wall of the test section where the acceleration level induced by different cavitation conditions was measured. Figure 7 illustrates the acceleration level data obtained at the plexiglass (*a*) and steel (*b*) wall, respectively, of the test chamber, in function of the cavitation number, for constant frequency value, and with two different flow velocities, each. The acceleration level values obtained with identical flow velocities but different frequencies are illustrated by Figure 8. The acceleration level values decrease with increasing frequencies without, however, leading to any changes in curve characteristics. It deserves attention that there may be such a frequency value found (in our case $f = 12\,000$ cps) where the acceleration level curves obtained at the steel and plexiglass walls, respectively, would coincide [6].

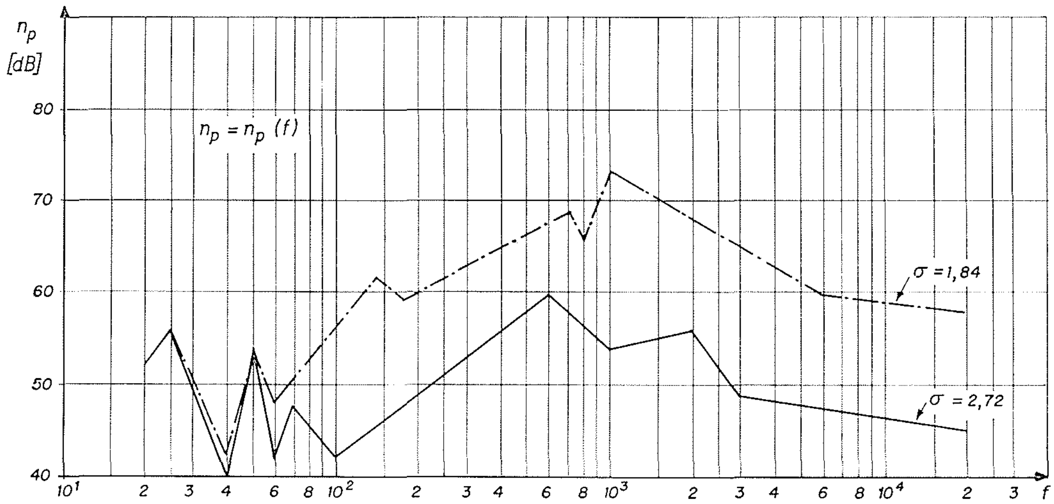
Cavitation damage intensity

Parallel to the frequency analysis, in order to support the result described above, the variations of cavitation damages in function of the cavity length have also been studied. These experiments were conducted in the same flow device outlined previously. As test specimen lead plate of 8 mm thickness was used. Flow velocity was identical to one of those employed for noise level studies ($v_\infty = 12$ m/s). These test results are illustrated

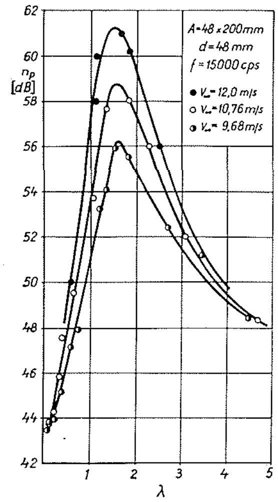
4/ Photograph of the wakes shedding from the cylinder model at $\sigma = 1.45$.
Détachement des sillages du modèle cylindrique à $\sigma = 1{,}45$.



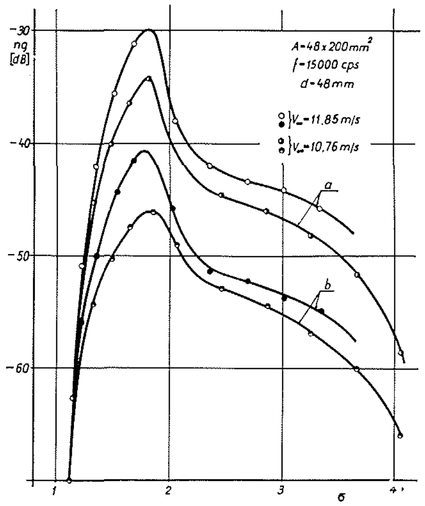




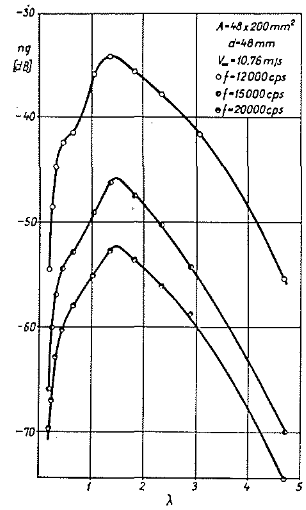
5/ Cavitation noise analysis curves. Sound pressure level (n_p) as function of frequency ($v_\infty = 12$ m/s).
Courbes d'analyse acoustique de la cavitation : pression acoustique (n_p) *en fonction de la fréquence* ($v_\infty = 12$ *m/s*).



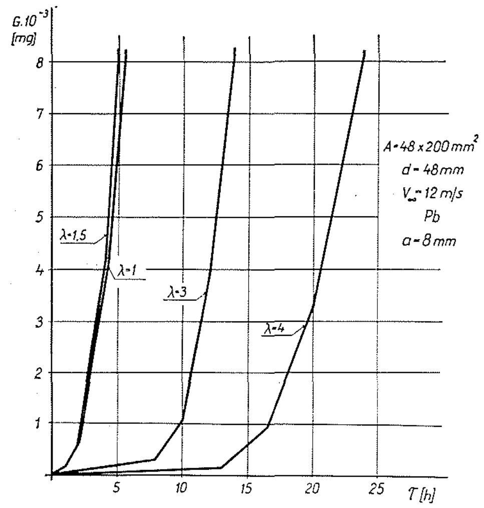
6/ Sound pressure level (n_p) in function of relative cavity length (λ) with different flow velocities.
Pression acoustique (n_p) *en fonction de la longueur de poche relative* (λ) *et de la vitesse de l'écoulement.*



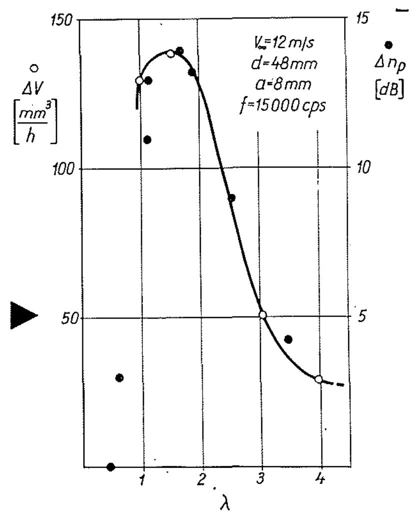
7/ Vibration acceleration level (n_g) as function of the cavitation number (σ).
Accélération des vibrations (n_g) *en fonction du coefficient de cavitation* (σ).



8/ Vibration acceleration (n_g) as function of the relative cavity length (λ).
Accélération des vibrations (n_g) *en fonction de la longueur de poche relative* (λ).



9/ Eroded material quantity (G) as function of the test period (τ), at flow velocity $v_\infty = 12$ m/s.
Volume de matériau érodé (G) en fonction du temps d'essai (τ). *Vitesse d'écoulement* $v_\infty = 12$ *m/s.*



10/ Eroded material volume per unit time (ΔV) and sound pressure level differences (Δn_p) as function of relative cavity length (λ).
Volume de matériau érodé par unité de temps (ΔV), *et différences de pression acoustique* (Δn_p), *en fonction de la longueur de poche relative* (λ).

by Figure 9 where the erosion weight losses (G) versus time (τ) for different relative cavity length values (λ) are presented.

When, according to Figure 9 the eroded volume loss per unit time $\Delta V = G/\gamma\tau$ (where γ represents the specific weight of the test specimen) is plotted as function of the relative cavity length (λ), for constant eroded material quantity (for example $G = 8\,000$ mg), then the curve illustrated by Figure 10 could be obtained. The diagram includes, in a suitably selected scale, also the sound pressure level values for identical flow velocity. Taking the measurement scatter into consideration, the points of the curve of eroded volume loss per unit time, and those of the sound pressure level differences show good agreement. The maximum intensity of the cavitation damages is at $\lambda = 1.5$ whereto also the maximum sound pressure level pertains.

In our previous papers [7], [8], [9] reference had been made to the fact that the extent of cavitation erosion damage would be jointly governed by the frequencies of wakes shedding from the model, and the pressures prevailing in the flow. The bubble, starting to move away from its place of origin may grow to the size determined by the flow conditions as its growth capacity is in correlation with the cavity length. The energetical maximum of the conditions determined by the double functionality, as interpreted from erosion aspects, is arrived at in the vicinity of $\lambda = 1.5$ or so. It seems, however, that the mathematical description of this problem requires further experiments to be conducted.

A proportional part of the collapse energy of the bubbles emitted as vibration and sound energy based on the experimental results referred to above, will characterize of erosion intensity in reliable manner.

Shalnev [10], [11] conducted similar experiments on the determination of erosion intensity, and found that the intensity of erosion varies as function of the cavity length, arriving at its maximum value at around $\lambda = 3$. The comparison of Shalnev's and the authors results, respectively, reflects the fact that, among others, the Reynolds number also affects the position of peak intensity values. Shalnev has conducted his experiments within the critical Reynolds number range ($\mathcal{R} = 10^5 - 2.3 \cdot 10^5$) whereas our investigations took place in the range above the critical Reynolds number ($\mathcal{R} > 2.3 \cdot 10^5$).

Conclusions

In case of model tests, according to the aforementioned findings, cavitation conditions can be readily followed and surveyed by means of noise test methods. On grounds of visual observations and cavitation erosion measurements, a close correlation may be demonstrated between the cavitation condition, erosion intensity, and the character of the noise associated with cavitation, respectively. According to the results of the above experimental investigations, noise pattern of different cavitation conditions gives an unequivocal correlation on cavitation damage intensity as well, which appears sufficiently verified by the resemblance of the curves characterizing sound pressure level and erosion intensity, respectively, as well as by the position of the peak values in function of λ.

On grounds of the results thus obtained, the cavitation noise test of hydraulic machinery seems suitable to give information on the cavitation phenomena taking place in the equipment permitting, at the same time, the elimination of cavitation, or, at least, to reduce their intensity.

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Résumé

Etude expérimentale du bruit de cavitation

par J. Varga * et G. Sebestyén **

Les auteurs — en partant de l'hypothèse que les coups de bélier provoqués par les bulles s'écrasant après l'apparition du phénomène de cavitation, rendent possible l'examen des phénomènes de cavitation au moyen de méthodes acoustiques — ont effectué des expériences dans le cas d'un obstacle cylindrique placé dans la veine d'essais d'un tunnel hydrodynamique fermé, pour établir les rapports entre le niveau de bruit de la cavitation d'une part et l'érosion de cavitation d'autre part. Les mesures de fréquence et de niveau de pression acoustique ont été effectuées dans la gamme de fréquences de 20-20 000 Hz avec un microphone électrostatique, puis avec l'accéléromètre relié à un analyseur de fréquence.

En premier lieu, on a établi le rapport existant entre la longueur l_z observable de la zone de cavitation naissant derrière l'obstacle cylindrique, comptée à partir de l'obstacle cylindrique et le coefficient de cavitation (σ). La figure 1 montre la variation de la longueur sans dimension $\lambda = l_z/d$, où d est le diamètre de l'obstacle cylindrique. On a constaté ensuite que n'importe quelle fréquence supérieure à 10 000 Hz permet de comparer des niveaux de bruit entre différents états de cavitation. La figure 5 représente deux courbes de niveau de bruit correspondant à deux coefficients de cavitation différents en fonction de la fréquence, à vitesse constante. De ces courbes, on peut déduire qu'il y a une différence importante du niveau de bruit selon l'état de cavitation et le niveau de bruit choisi comme valeur de base pour l'état exempt de cavitation. Après avoir établi les valeurs du niveau de bruit pour des longueurs relatives différentes de la zone de cavitation, on a obtenu les résultats présentés sur la figure 6 qui montrent que le bruit atteint un maximum prononcé pour la valeur de $\lambda = 1{,}5$. Ce résultat a été également confirmé par des mesures de niveau d'accélération (fig. 7 et 8).

Les auteurs ont établi pour une vitesse constante de courant, en mesurant le niveau de bruit avec des éprouvettes en plomb, les courbes de perte de poids des éprouvettes en fonction du temps, pour différentes longueurs relatives de zone de cavitation (fig. 9). Les résultats de mesure obtenus de cette façon ont permis de calculer les volumes érodés par unité de temps pour différentes longueurs de la zone de cavitation. Les résultats sont portés sur la figure 10, avec les résultats des mesures de niveau de bruit. L'évolution identique de la perte en poids par unité de temps et des différences du niveau de bruit ainsi que la valeur maximale qui se manifeste au même endroit donnent une signification satisfaisante aux mesures de bruit.

Les résultats présentés permettent de constater qu'il y a une relation étroite entre l'état de cavitation, l'intensité de l'érosion et le bruit accompagnant la cavitation, et que le niveau de bruit pour divers états de cavitation fournit une information sur l'intensité de l'érosion de cavitation. Les résultats présentés permettent d'espérer que cette méthode soit appliquée fructueusement à l'examen de la cavitation dans les machines hydrauliques.

Résumé

Etudes expérimentales de l'érosion de cavitation pendant la période d'incubation

par J. Varga * et G. Sebestyén **

Les auteurs exposent les résultats d'essais effectués dans un tunnel hydrodynamique avec un obstacle cylindrique. Ces essais avaient pour but d'étudier la « période d'incubation » de l'érosion de cavitation. Les courbes représentant la perte en poids par érosion en fonction du temps peuvent être divisées en deux branches bien distinctes (fig. 1). La première branche représente la période d'incubation suivie d'une période de destruction totale. Le point d'intersection de ces deux branches est un point critique caractérisé par un temps critique et une perte en poids critique. Les auteurs montrent que seule la première branche correspond à une véritable érosion de cavitation, car au-delà du point critique apparaissent déjà divers effets cumulatifs. La limite de rupture du matériau est déjà atteinte au point critique.

Les auteurs exposent une méthode permettant de déterminer le point critique. Le temps critique se détermine avec une précision satisfaisante en calculant l'accélération de l'érosion de cavitation (fig. 5). Les auteurs montrent que, dans le cas d'un coefficient de cavitation constant, la perte en poids critique est indépendante de la vitesse d'écoulement et ne dépend que des dimensions de l'obstacle et de la veine d'essai. On constate également que la relation déjà proposée par les auteurs, $\tau v^5 =$ Cte entre la durée de l'essai et la vitesse, à perte en poids constante, reste valable au point critique (fig. 7).

Les résultats des essais montrent que la durée critique diminue avec la dureté superficielle (fig. 8, 9, 16), alors que cette dernière n'influence pas considérablement la perte en poids dans la deuxième période de destruction.

Les auteurs démontrent enfin que l'effet d'échelle dû aux dimensions géométriques peut se déterminer à partir des pertes en poids critiques pour des veines d'essais géométriquement semblables, le liquide, le matériau et les vitesses restant constants par ailleurs.

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