ON THE RELATION BETWEEN ACOUSTIC NOISES AND EROSION IN HYDRODYNAMIC CAVITATION

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ON THE RELATION BETWEEN ACOUSTIC NOISES AND EROSION IN HYDRODYNAMIC CAVITATION

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Among the numerous manifestations of hydrodynamic cavitation, some of the most important from the practical point of view may be considered erosion and acoustic noises. Obviously, the magnitude of cavitation erosion is ultimately determined by the distribution, in size and in space, of the cavitating bubbles, by their number, and also by the collapse velocity. These same parameters determine the power of the emitted cavitation noise. Thus, one may speak of a single physical cause of noise and erosion in cavitation. Indirect proof of this proposition would be the obtaining of identical dependences of the magnitude of erosion and of the noise intensity on the number or stage of cavitation and on the flow velocity at a given stage of cavitation.

In order to obtain the indicated dependences, the results of works devoted to the study of the characteristics of cavitation destruction were analyzed (^{1}-^{10}), and a study was also carried out of the cavitation noises arising as a result of flow around a cylinder at various stages of cavitation development. It is known (^{3}) that, in cavitation behind a cylinder, on the tested lead specimen, at the stage corresponding to the maximum erosion intensity, several centers of erosion arise. At Reynolds numbers Re $= (1 \div 4) \cdot 10^5$ (^{1}, ^{3}, ^{4}), the maximum of erosion corresponds to the cavitation stage

$$\bar{L}_k = L_k/d = 2 \div 2.5$$

(L_k is the mean length of the cavity, d is the cylinder diameter). In this case the most powerful erosion center is located at a distance $l = (2 \div 3)d$ from the axis of the cylinder. Therefore, in the experiment described below, one of the hydrophones (No. 2) was mounted flush in the wall of the working chamber outside the cavitation zone, directly opposite the mentioned erosion center. The study of cavitation noises was carried out in the cavitation tube of the Institute for Problems in Mechanics of the Academy of Sciences of the USSR, in a slotted section of cross section 100 × 24 mm^2. The test body was a cylinder with

Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

$d = 24$ mm, fastened at its ends into the side walls of the working chamber. In the course of the experiment, by varying the static pressure at constant velocity, the required cavitation stages were set, and the cavitation noises in the range from 40 Hz to 15 kHz corresponding to the given stage were recorded on a tape recorder by means of a hydrophone connected to a special amplifier.

Figure 1 gives the obtained values of the absolute levels of noise intensity in the zone of hydrophone No. 2, corresponding to flow velocities $v_{\infty i} = 15, 16, 23, 25$ m/sec (curves 5, 6, 7, 8). Curve 9 represents the dependence of the noise intensity in the zone of hydrophone No. 1, located opposite the cylinder ($v_{\infty i} = 14.9$ m/sec), and is given for comparison. From consideration of the indicated dependences it may be concluded that, with the appearance of a periodic vortex structure of cavitation ($\bar{L}_k = 0.75 \div 1$), the level of cavitation noises rises sharply, reaching a maximum at $\bar{L}_k = 1.5 \div 3.0$. Thereafter, as the regime approaches jet flow, the level of cavitation noises decreases with increasing $\bar{L}_k$; moreover, at stages $\bar{L}_k \geq 10$ the cavitation noises approach the level of noncavitating flow, i.e., the noises of the tube at the given flow velocity (curves 10, 11). It is also seen that at identical stages of cavitation, in the case

at a higher flow velocity the noise level is higher, and the magnitude of the increase is not the same for different stages. In the same figure, for velocities

Fig. 1. Dependence of the intensity of cavitation noise $I_{\Sigma i}$ and of the erosion volume ΔV_i on the cavitation stage $\bar{L}_{\mathrm{k}}$. 1–4 –ΔV_i at $v_{i\infty} = 14$ m/s (1); 17 m/s (2); 20 m/s (3); 23 m/s (4). 5–11 –$I_{\Sigma i}$, 5–8 –hydrophone No. 2 at $v_{i\infty} = 14.9$ m/s (5); 20.6 m/s (6); 23 m/s (7); 25 m/s (8); 9 –hydrophone No. 1 at $v_{i\infty} = 14.9$ m/s; 10 and 11 –hydrophone No. 2 for $\bar{L}_{\mathrm{k}} = 0$ at $v_{i\infty} = 14.9$ m/s (10) and 23 m/s (11)

$v_{\infty i} = 14,\ 17,\ 20,\ 23$ m/s, the dependences, replotted by us on a logarithmic scale, of the erosion volume on the cavitation stage, taken from work (^{1}) (curves 1, 2, 3, 4), are given.

Fig. 2. Dependence of the erosion volume on the flow velocity $v_{\infty i}$ for different model sizes and cavitation stages. 1–4 –scale ΔV_1 at values $\bar{L}_{\mathrm{k}} = 3,\ d = 6,\ a \times b = 7.5 \times 25$ (1); $\bar{L}_{\mathrm{k}} = 2,\ d = 6,\ a \times b = 7.5 \times 25$ (2); $\bar{L}_{\mathrm{k}} = 3,\ d = 6,\ a \times b = 15 \times 25$ (3); $\bar{L}_{\mathrm{k}} = 2,\ d = 6,\ a \times b = 15 \times 25$ (4). 5–8 –scale ΔV_2 at values $\bar{L}_{\mathrm{k}} = 3,\ d = 12,\ a \times b = 15 \times 50$ (5); $\bar{L}_{\mathrm{k}} = 2,\ d = 12,\ a \times b = 15 \times 50$ (6); $\bar{L}_{\mathrm{k}} = 1,\ d = 12,\ a \times b = 15 \times 50$ (7); averaged according to the data of work (^{1})

Fig. 3. Dependence of the root-mean-square value of the exponent $\sqrt{\overline{n^2}}$ on the stage of cavitation development

Figure 3: Fig. 3. Dependence of the root-mean-square value of the exponent $\sqrt{\overline{n^2}}$ on the stage of cavitation development

(8)

In Fig. 2, for different Reynolds numbers, dependences are given of the magnitude of the erosion volume on the flow velocity at specified cavitation stages, obtained in various cavitation tubes and published in works (^{1}-^{5}). From consideration of Figs. 1 and 2 it is seen that the erosion volume also depends substantially on the Reynolds number and on the cavitation stage; moreover, as for noise, the maximum erosion volume for large Reynolds numbers is observed at smaller cavitation stages, and the erosion volume decreases substantially upon reaching stages $\bar{L}_\text{k} \geq 4$.

However, the decrease in noise and erosion upon reaching jet regimes cannot be explained by the influence of Froude numbers (^{2}), since at $\bar{L}_\text{k} = 4 \div 6$ the cavern still consists of individual bubbles suspended in the flow, and only at $\bar{L}_\text{k} \geq 8$ does a small region of continuous vapor cavity arise in the zone immediately behind the cylinder. Therefore the influence of buoyancy should be taken into account for individual bubbles, and not for the cavity as a whole. Estimates show-

show that the rate of rise of bubbles with diameter $d_0 \leqslant 0.5$ cm is approximately two orders of magnitude smaller than the flow velocity; i.e., the influence of the Fr number on the characteristics of noise and erosion at these stages of cavitation may be neglected.

The decrease in noise and erosion upon the attainment of jet regimes can apparently be explained by a substantial increase in the gas content in the cavity, which is more stationary in time, and in the bubbles formed as a result of the breakup of its tail part; and also by the fact that these bubbles are formed at a static pressure that is, in order of magnitude, close to the static pressure at infinity, i.e., in the absence of substantial pressure gradients capable of causing loss of stability and abrupt collapse of the bubbles.

Fig. 3. Dependence of the root-mean-square value of the exponent $\sqrt{\overline{n^2}}$ on the stage of cavitation development

On the basis of the dependences presented and assuming that the erosion volume ΔV_i and the noise intensity in the audio frequency range $I_{\Sigma i}$, at a constant stage of cavitation, exhibit a dependence on the flow velocity of the form

$$\Delta V_i = k_1 v_{\infty i}^{n_1}, \qquad I_{\Sigma i} = k_2 v_{\infty i}^{n_2}, \tag{1}$$

Figure 4

Figure 4: Figure 4

the exponents of the power-law dependence of these quantities on the flow velocity were obtained (Fig. 3). It turned out that the values of the root-mean-square exponent $\sqrt{\overline{n^2}}$ for noise (curve 1) and erosion (curve 2) practically coincide; moreover, in both cases they show a strong dependence on the cavitation stage and may vary within the limits from 5 to 8. Accordingly, the reason for the large scatter in the magnitude of the exponent according to the data of various authors ($^{1-10}$) becomes clear: Rata (^{8}), in experiments with two-sided porous projections, obtains $n = 4$–8; Govinda-Rao (^{9}), with cylinders, $n = 5$–8, and with rectangular blocks, $n = 4$–8; according to the investigations of Knapp (^{6}) with models of axisymmetric bodies and with a turbine in full scale (^{10}), $n = 4$–6; Kerr and Rosenberg (^{5,7}), in experiments with a full-scale turbine, obtained $n = 5$ for turbine operating regimes with maximum erosion. According to the data of K. K. Shalnev [$^{1-4}$], for the stage corresponding to maximum erosion, the value of n is also close to 5. However, as shown by our processing of the data (^{1,3,4}), for other stages the exponent also varies within the limits from 5 to 8. All the listed values of n agree well with the values of $\sqrt{\overline{n^2}}$ for the intensity of cavitation noise and may be explained not by the method of conducting the experiment, but by the fact that in the above-mentioned experiments insufficient attention was paid to the form and stage of cavitation and, consequently, erosion caused by the collapse of bubbles with different properties was studied.

At the beginning of the work the task was formulated: to determine the mutual correspondence between the volume of erosion and the noise intensity in hydrodynamic cavitation. In connection with the foregoing it may be concluded that both of these characteristics of cavitation exhibit the same dependence both on the stage of cavitation and on the flow velocity at a constant stage. The position of the maximum of noise and erosion is also governed by an identical dependence on the Re number. Since acoustic tests and erosion studies were carried out in different cavitation tunnels and at different Re numbers, the mutual correspondence between erosion and noise can be established only with accuracy up to coefficients that do not depend on velocity. Accordingly, let us introduce the functions:

$$Z_i = \lg I_{\Sigma i} - \frac{1}{2} \lg \overline{k_2^2}, \qquad Y_i = 2 + \lg \Delta V_i - \frac{1}{2} \lg \overline{k_1^2}, \tag{2}$$

where k_2^2 is the variance of the proportionality coefficient of the power-law dependence of noise on velocity; k_1^2 is the variance of the proportionality coefficient of the power-law dependence of the erosion volume on velocity.

Fig. 4. Relation between the intensity of acoustic noise and the volume of

erosion in hydrodynamic cavitation.
a—$Z_i,\ \overline{L}_k = 2.5;\quad b$—$Y_i,\ \overline{L}_k = 3$

In Fig. 4 a mutual correspondence is established between erosion and noise in hydrodynamic cavitation. Owing to the differences in the Reynolds numbers, the quantities Z_i are plotted on the graph at $\overline{L}_k = 2.5$, and Y_i at $\overline{L}_k = 3$. It is interesting to note that earlier a similar dependence—the proportionality of noise intensity to weight loss as a result of erosion—was established in acoustic cavitation (^{11}), which is further evidence of the commonality of many mechanisms of hydrodynamic and acoustic cavitation.

On the other hand, it is known (^{4,12}) that the value of the weight loss per unit time, even at a constant stage of cavitation, changes with time; i.e., with an increase in the roughness of the surface of the specimen subjected to erosion and with an increase on this surface in the number of weak zones, the effect of cumulative erosion appears at certain sites, and the value of the weight loss per unit time increases with time. According to the data of work (^{12}), the dependence of the weight loss as a result of erosion on time can be approximated by two straight-line segments with angles of inclination to the abscissa axis equal to $\gamma_1 = \operatorname{arc\,tg} \alpha$ and $\gamma_2 = \gamma_1 + \operatorname{arc\,tg} \beta$. In this case one can write the relation between the intensity of cavitation noise and the weight loss as a result of erosion over time t in the form

$$\alpha t I_{\Sigma i} = k_3 G_i, \qquad t \leqslant t^*$$

$$\left[\alpha t + \frac{(t - t^*) \cdot \sin(\gamma_2 - \gamma_1)}{\cos\gamma_1 \cdot \cos\gamma_2}\right] \cdot I_{\Sigma i} = k_3 G_i, \qquad t \geqslant t^*, \tag{3}$$

where G_i is the weight lost by the specimen as a result of erosion over time t; k_3, α, β are certain constants characterizing the dependence of the specimen' s weight loss on time; t^* is the characteristic time after the expiration of which the cumulative effect begins to appear, depending, at the given stage of cavitation, on the characteristics of the flow and on the properties of the material being destroyed. Thus, on the basis of the last expression, one may conclude that the relation between noise intensity and weight loss is in fact nonlinear, but the weight loss per unit time will be proportional to the intensity of cavitation noise. However, the value of the proportionality coefficient between them will depend on the time during which the specimen is subjected to erosion.

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