# OPERATION OF A FLUID JET AMPLIFIER IN THE CAVITATION REGIME

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It is established that a Coanda-effect fluid jet amplifier continues to function in the initial and intermediate stages of cavitation. However, in the separation stage, which extends to the output channels, the effect is disrupted and the amplifier can no longer function normally.

## NOTATION

$a$ — width of nozzle exit section

b — width of output channel

c — ejection coefficient

d — width of working chamber, height of amplifier

e — flow displacement

h — sudden expansion of diffuser

$l$ — distance from nozzle to flow divider

$p_0$ — pressure in diffuser channel

$p_\infty$ — pressure upstream from nozzle

$p_m$ — pressure on eddy axis

$p_1$ — pressure at periphery of eddy in pocket

$p_2$ — pressure at periphery of eddy near tip of flow divider

$p_W$ — pressure at diffuser wall near nozzle exit

$p_V$ — liquid vapor pressure

$p^\circ$ — pressure coefficient

Q — ejected-liquid flow rate

R — Reynolds number

v — flow velocity at nozzle exit

$v_1$ — velocity at periphery of eddy in pocket

$v_2$ — velocity at periphery of eddy near tip of flow divider

$v_0$ — velocity of ejected liquid in output channel

$\alpha$ — diffuser divergence angle

$\varphi$ — nozzle entrance half-angle

$\nu$ — kinematic viscosity

$\rho$ — density of liquid

$\varkappa^*$ — cavitation number corresponding to onset of cavitation

$\varkappa^0$ — cavitation number corresponding to onset of separation stage

Research on fluid jet amplifiers has shown that there is a maximum jet velocity, above which it is impossible to obtain attachment of the jet to the diffuser wall. The limiting value of the cavitation number $\varkappa = 2(p_\infty - p_V)/\rho v^2$, at and below which the amplifier will not function, is equal to $\varkappa^\circ = 1.2$ [1]. According to other sources [2] $\varkappa^\circ = 1.3$. In [3] it was found that the operation of a fluid jet amplifier in the cavitation regime is characterized by several distinct stages of cavitation development, from the initial stage, in which the first cavitation bubbles appear in the flow, to supercavitation, when the jet is no longer attached to the diffuser wall. Further investigation has shown that the geometry of the flow zone has a considerable influence on the critical $\varkappa^*$ and minimum $\varkappa^\circ$ values of the cavitation number ($\varkappa^* = 1.3$-$3.6$, $\varkappa^\circ = 1.05$-$1.4$).

1. Our experiments were performed in the GT2 and GT3 water tunnels of the Institute of Problems of Mechanics, Academy of Sciences of the USSR, whose working chambers measure $12 \times 25$ and $24 \times 100 cm^2$,

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respectively. In the GT 2 tunnel we investigated fluid jet with the following geometry: $\varphi = 45°$, $a = 3$ mm, d = 12 mm, $\alpha = 22°$, $h/a$ = 0.5–2, $l/a$ = 4.7, 6.5, 12.4. The fluid jet amplifiers investigated in the GT3 tunnel had two types of nozzles: conical with $a$ = 8.5 mm, $\varphi = 45°$, d = 24 mm, and ASME type [4] with $a$ = 11.5, d = 24 mm, and a diffuser with $\alpha$ = 22°, $h/a$ = 0–2, $l/a$ = 2–∞.

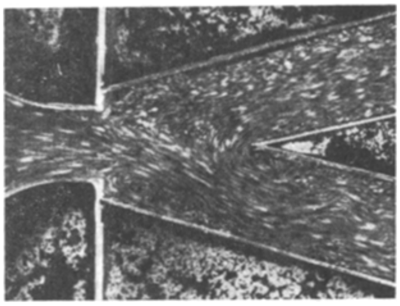

Fig. 1

The flow velocity and pressure in the models were independently regulated. During the experiments the nozzle exit velocity v = 5–25 m/sec, and the pressure in the balance tank was varied from 0 to 3 gage atm. These velocity and pressure ranges enabled us to create various cavitation regimes on the Reynolds number interval $R = va/\nu = (1\text{–}25) \cdot 10^4$.

The onset of cavitation was determined visually from the appearance of cavitation bubbles accompanied by a characteristic sound (crackling).

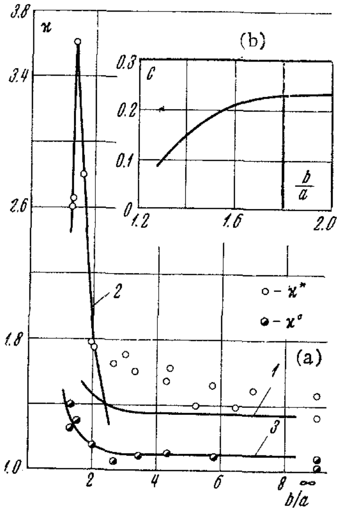


Fig. 2

Other experiments were performed in a water channel with open circulation. Despite the low flow velocity and small Reynolds number (R = 3000), by means of these experiments we were able to obtain a quite detailed picture of free-vortex flow through the models.

2. According to our open-channel experiments (Fig. 1), the flow of liquid through the amplifier is accompanied by two eddy systems. One consists of eddies moving along the inner and outer surfaces of the jet leaving the nozzle. The other is observed at the tip of the flow divider in the ejected stream flowing from one output channel into the other.

Visual observation of cavitation development in these models showed that cavitation first develops in the eddies of both systems, but at different $\varkappa$.

The effect of the Reynolds number $R = (1\text{–}25) \cdot 10^4$ on $\varkappa^*$ and $\varkappa^\circ$ is only slight for an amplifier of the given design and it may be assumed that $\varkappa^*$ and $\varkappa^\circ$ do not depend on R. The occurrence of cavitation is also independent of the type of nozzle. However, it is affected by the relative width of the output channel $b/a$, as follows from Fig. 2a, where we have plotted $\varkappa^* = f(b/a)$ [curves 1 and 2 based on Eqs. (5) and (8), respectively] and $\varkappa^\circ = f(b/a)$ (curve 3 based on water tunnel experiments). At $b/a \geq 2$ cavitation begins in the "pocket," the region bounded by the nozzle exit, the inner concave surface of the jet, and the diffuser wall. On the interval $2 \leq b/a \leq 5$ $\varkappa^* = 1.8\text{–}1.5$, at $b/a \geq 5$ $\varkappa^* = 1.5$.

At $b/a \leq 2$ the critical region for cavitation is the vicinity of the tip of the flow divider. As $b/a$ decreases to $b/a = 1.5$, the number $\varkappa^*$ increases to $\varkappa^* = 3.6$, then falls as $b/a$ continues to decrease.

The progressive development of cavitation in an amplifier with $b/a = 2$ is shown in Fig. 3, where frames $a$, b, and c correspond to $\varkappa$ = 1.5, 1.3, and 1.15. In these experiments v = 21 m/sec, $R = 2.4 \cdot 10^5$. Cavitation develops simultaneously in the pocket, on the concave surface of the jet, and near the tip of the flow divider. As $\varkappa$ falls, the cavitation zone grows and the sound becomes more intense. At $\varkappa$ = 1.41 cavitation develops on the convex surface of the jet. At $\varkappa$ = 1.3 (Fig. 3b) the flow in the discharge channel consists almost completely of a mixture of vapor-air bubbles and liquid, but the amplifier continues to function normally. At $\varkappa$ = 1.15 (Fig. 3c) the separation stage of supercavitation begins, the pressures on either side of the jet are equalized, and the jet separates from the wall and flows symmetrically past the divider. The relation $\varkappa^\circ(b/a)$ is given in Fig. 2a.

3. The determination of $\varkappa^*$ reduces to the determination of the minimum pressure in the amplifier. We will find the minimum pressure from the following conditions:

1) the pressure minimum in the flow separation region is located on the axis of the eddies periodically entrained by the flow;

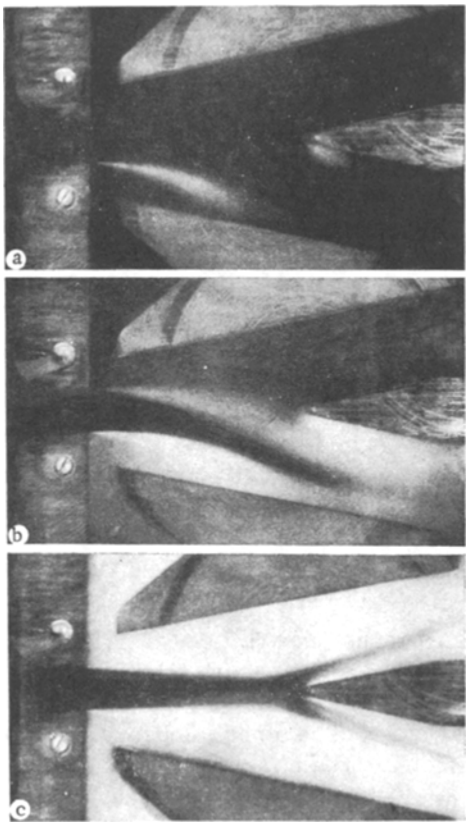

Fig. 3

2) within each eddy the liquid rotates at a constant angular velocity [5];

3) the pressure at the boundary of the eddy and the jet and at the diffuser wall near the nozzle exit are equal [6].

With these assumptions, on the eddy axis

$$p_m = p_{1,2} - {}^1/_2 \rho v_{1,2}^2 \tag{1}$$

In order to find the minimum pressure in the pocket, we write Bernouilli's equation for the jet from the section 0-0 at the nozzle exit to a section 1-1 through the eddy axis normal to the channel axis (Fig. 4)

$$p_0 - p_1 = {}^1/_2 \rho (v_1^2 - v_2) \tag{2}$$

Using Eqs. (1) and (2), we find

$$\varkappa^* = 2(v_1^2/v^2 - 0.5) \tag{3}$$

The pressure coefficient at the periphery of the eddy $P_1^\circ = 2(p_1 - p_0)/\rho v^2$ is transformed, using expression (2), to

$$p_1^\circ = 1 - v_1^2/v^2 \tag{4}$$

Comparing (3) and (4), we find that

$$\varkappa^* = 1 - 2p_W^\circ \tag{5}$$

since from our third condition we have $p_1^\circ = p_W^\circ$. Thus, we can replace the relation $\varkappa^*(b/a)$ with the relation $\varkappa^*(\overset{+}{P}{}_W^{\overset{+}{\circ}})$

The experimental $\varkappa^*$ (Fig. 2a) are approximately 7% greater than those calculated from Eq. (5), where $p_W^\circ$ was taken from [3].

In order to find the minimum pressure near the tip of the divider, we write Bernouilli's equation for the part of the flow from a section passing through the output channel, from which the ejected liquid flows, to a section 2-2 passing through the axis of the eddy at the tip of the divider and normal to the axis of the channel, through which the main and ejected flows are discharged (Fig. 4). Here we assume that the velocity $v_0$ is small and may be neglected. Then

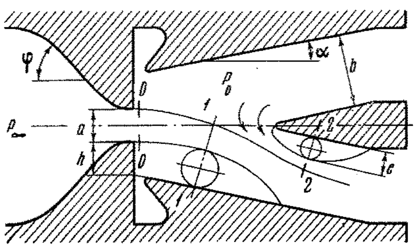

Fig. 4

$$p_2 = p_0 - {}^1/_2 \rho v_2^2 \tag{6}$$

We find the velocity $v_2$ from the condition [5]

$$e = 0.63\,(b - a)$$

where e is the displacement of the flow from the divider wall associated with the bending of the stress of ejected liquid.

Then

$$v_2 = \frac{Q}{0.37\,(b - a)} \quad (Q = cav) \tag{7}$$

Starting from Eqs. (1), (6), and (7), we obtain an expression for determining the critical cavitation number in the neighborhood of the divider tip

$$\varkappa^* = 1 + 14.6\left(\frac{c}{b/a - 1}\right)^2 \tag{8}$$

An investigation of Eq. (8) with the relation $c(b/a)$ (Fig. 2b) represented in the exponential form

$$c = 0.25\left[1 - \exp\left(-\frac{b/a - 1.2}{0.2}\right)\right]$$

indicates the existence of a maximal $b/a = 1.5$, $\varkappa^* = 3.6$. As the area of the output channel increases ($b/a > 1.5$), the velocity in the output channel $v_2$ decreases. As the area of the output channel decreases ($b/a < 1.5$), the velocity $v_2$ likewise decreases owing to the reduced ejected flow. A decrease in $v_2$ leads to an increase in pressure in the neighborhood of the divider tip and to a fall in the value of the critical cavitation number $\varkappa^*$.

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