Flow Pattern and Switching Mechanism in a Wall Attachment Type Fluid Amplifier

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By

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Summary

An experimental investigation has been performed to determine the steady-state pattern and the switching mechanism of the airflow in a wall attachment type fluid amplifier. With the experimental results, it is shown that the jet flow is considerably affected by the splitter distance and the step height of the device, and switching action of the flow caused by a step control jet, i.e. the switching time and the critical velocity range of control jet, is determined. By using some simple assumptions, approximate calculation have been carried out to obtain the relations between the switching time and the step control jet flow, and are compared with the experimental results.

1. Introduction

For a wall attachment type fluid amplifier, it is important to investigate the steady state flow pattern variation due to the geometrical configuration and the switching mechanism of jet flow. The attached flow is essntially caused by the entrainment of turbulent viscous fluid, and accordingly the flow patterns are influenced by the splitter distance and the step height of the present device. Also, the switching mechanism involves two important facters, i.e. the stability of the jet and the switching time.

The experiments were carried out with a large scale model, which is a symmetrical bistable type with a pointed splitter. The geometric configurations of the model are kept constant except for the splitter distance and the step height.

The steady state flow patterns were investigated by measuring the static pressure distribution along the wall, and it is found that the flow patterns

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are roughly separated into two cases, i.e. the case of symmetric flow and the case of wall attached flow.

In addition, the dynamic switching characteristics, or the variation of switching time due to the step control jet were recorded by the hot wire anemometers and the oscilloscope. Those experiments show that there are three modes of switching phenomena, i.e. in the first mode the switching is not recognized, in the second mode the switching is unstable and the time is considerably long and in the third mode the switching is stable and the time decreases rapidly and is inversely propotional to the momentum of step control flow.

2. Nondimensional Representation

Let us consider the steady state flow configuration in which a turbulent air jet emmitted from the model throat attaches to the inclined wall (see Fig. 1). The significant variables of this phenomenon are the throat thickness b,

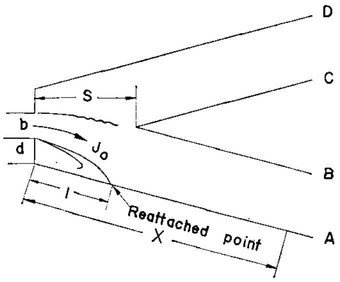

Fig. 1. Notation of attached flow pattern.

the step height d, the splitter distance S, the wall inclined angle α, the main flow velocity U_0, and the kinematic viscosity of the working fluid ν. After the dimensional analysis, when these quantities are specified, the cavity length l and the pressure difference across the jet flow $P-P_\infty$ can be expressed in the following non-dimensional forms,

$$\frac{l}{b}=F_1(\alpha,\ d/b,\ S/b,\ U_0b/\nu) \tag{1}$$

$$\frac{P-P_\infty}{1/2\,\rho U_0^2}=F_2(\alpha,\ d/b,\ S/b,\ U_0b/\nu) \tag{2}$$

where U_0 is related to the jet momentum per unit span $J=\rho U_0^2b$.

In the above expressions, when the splitter distance is sufficiently large compared to the throat thickness, the splitter has no effect on the jet flow, or in other words the parameter S/b is no longer important and may be discarded from Eqs. (1) and (2). For the step height, the same condition will still exist.

In the case of switching phenomena, the step control jet intersects with the main jet flow, and the attached main flow is separated from the wall and reattached to the opposite side wall. Therefore, in this case, as other variables, the step control jet velocity U_c and the control throat thickness b_c should be taken into consideration. By the dimensional consideration, the switching time can be expressed as follows:

$$\tau = G(\alpha,\ d/b,\ S/b,\ b_c/b,\ U_c/U_0,\ U_0 b/\nu) \qquad (3)$$

where τ is a non-dimensional swithing time given by $\tau = U_0 t/b$.

3. Experimental Arrangement

The large scale model used in the present experiments is shown in Fig. 2 and 3, where the main throat thickness is 10 mm and the splitter angle α is 15 deg.. The model is covered with two transparent end-plates to satisfy the two-dimensional flow condition and also make the flow pattern observable. Furthermore, the model throat is connected to a reservoir section so as to make the jet flow uniform and smooth. For studying the characteristics of

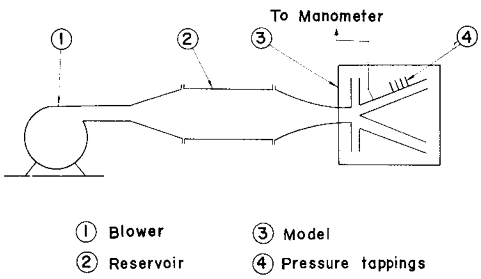

Fig. 2. Experimental arrangement.

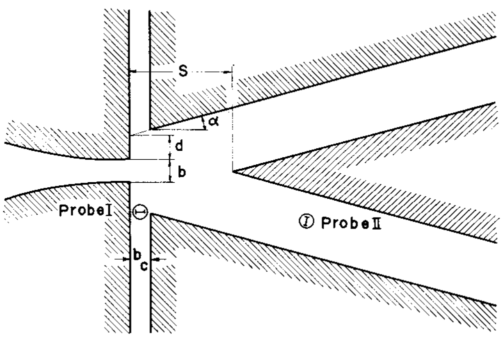

Fig. 3. Schematic representation of the model.

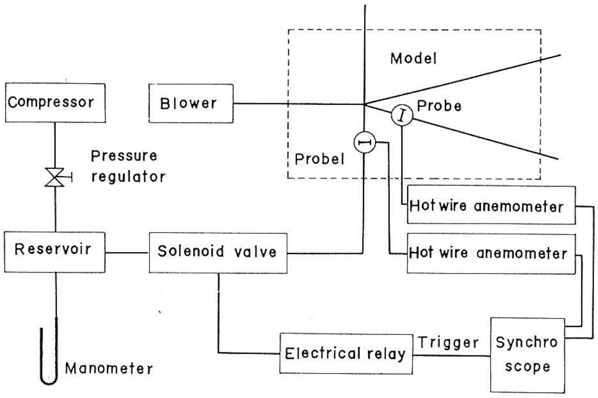

Fig. 4. Block diagram of apparatus for measuring the switching time.

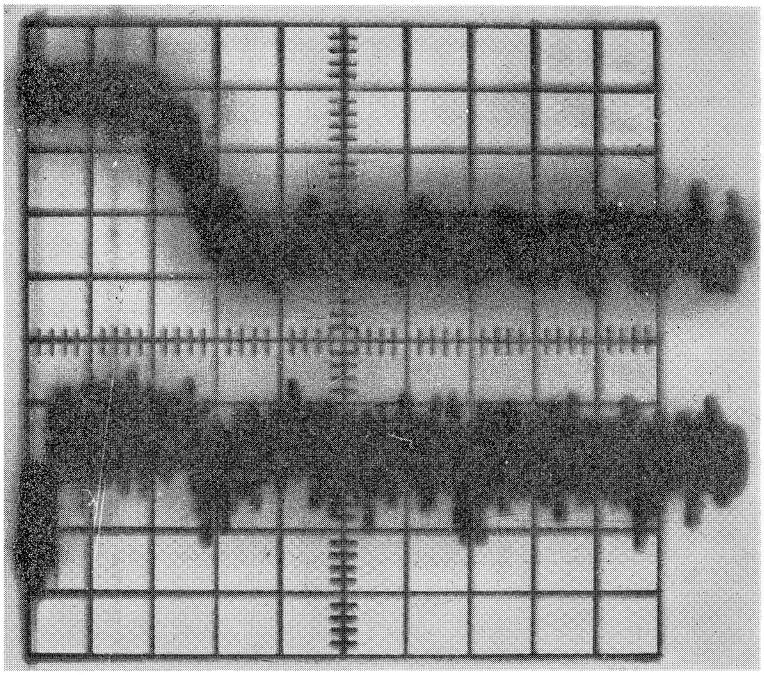

Fig. 5. Observation photograph.

the steady state flow in the model, the static pressure distributions on the walls are measured with the surface pressure hole tappings.

The experimental arrangement for investigating the jet switching action is shown in Fig. 3 and 4. In this case, the air is supplied to the control throat through another air reservoir, where a pressure regulator is inserted between the compressor and the reservoir in order to control the reservoir pressure, or the air velocity supplied to the control throat. For injecting the control step flow into the main flow, a solenoid magnetic valve is used.

The experiment is carried out as follows: when the electric relay is switched on, the solenoid valve and the trigger circuit to the recording oscilloscope are simultaneously operated, and the outputs of probe I and II are synchronously recorded with the oscilloscope. The main jet flow emmitted from the throat is measured by the hot wire anemometer probe II and the step control jet flow suddenly issued from the control throat is measured by hot wire probe I. When the control flow impinges perpendicular upon the main flow, the main flow is separated and reattached to the opposite side wall. Therefore, outputs of the hot wire probes represent the switching time t as shown in Fig. 5 and 6.

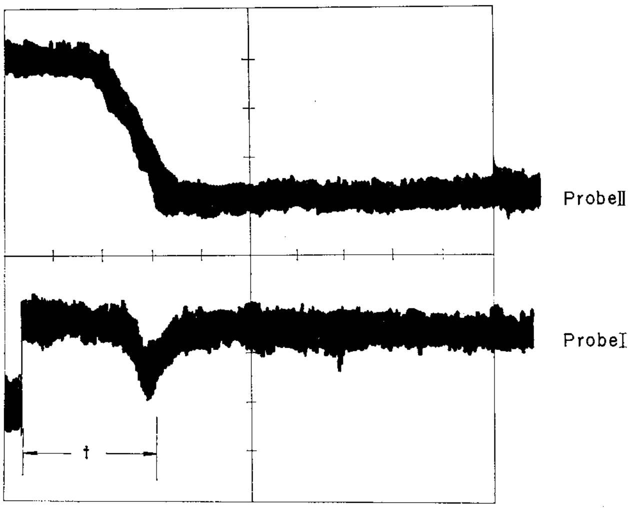

Fig. 6. Difinition of switching time.

4. Experimental Results

4.1 Steady state flow patterns

The steady state flow pattern in the wall attachment type fluid amplifier is considerably affected by the splitter distance and the step height. When the pointed splitter is so close to the throat, the main jet flow is divided into two streams symmetrically (see Fig. 7). On the other hand, when the splitter distance is large, or the splitter is apart from the throat, the flow pattern of the main jet is asymmetric and the main flow is attached to one side wall and pass through one of the output branches only (see Fig. 8 and 9). These phenomena can also be observed by the Schlieren photographs.

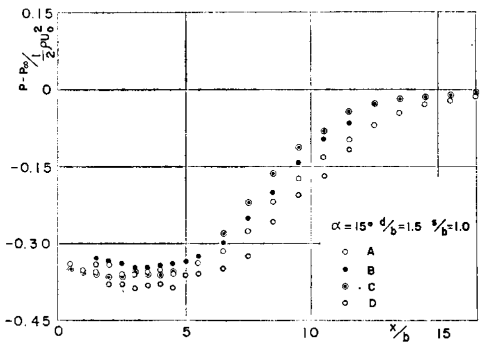

Fig. 7. Static pressure distribution along the walls for a constant step height. ($S/b=1.0$)

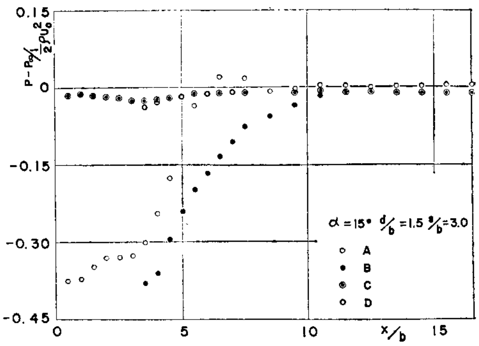

Fig. 8. Static pressure distribution along the walls for a constant step height. ($S/b=3.0$)

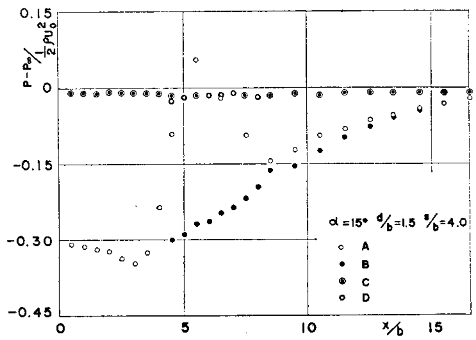

Fig. 9. Static pressure distribution along the walls for a constant step height. ($S/b=4.0$)

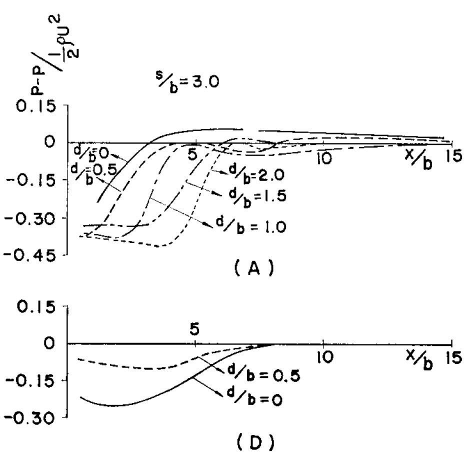

Fig. 10. Static pressure distribution along the walls for a constant splitter distance. ($S/b=3.0$)

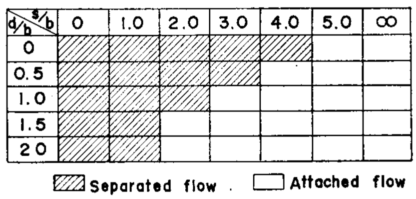

Fig. 11. Relation between the flow pattern and the parameters S/b, d/b.

In the same way, the effects of the step height on the steady state flow patterns are represented in Fig. 10. In these diagrams, (A) represents the pressure distributions on the flow attached wall, and (D) represents those on another side wall. It is seen that the flow patterns are still affected by the step height as well as the splitter distance.

Since the relations between the main flow patterns and those parameters are important practically, those relations are summarized in Fig. 11. In the hatched sections of this diagram, the main flow is divided into two streams symmetrically, and in other blank sections, the flow is steadily attached to one side wall.

4.2 Switching mechanism

From the experimental results, the relations between non-dimensional switching time τ and control jet velocity ratio U_c/U_0 for various splitter distances are shown in Fig. 12, 13 and 14. From those figures, it is obvious that there exists a certain critical value of step control flow, which means switch-

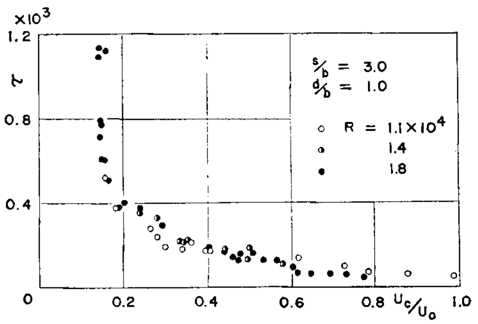

Fig. 12. Variation of switching time with step control flow. (S/b=3.0)

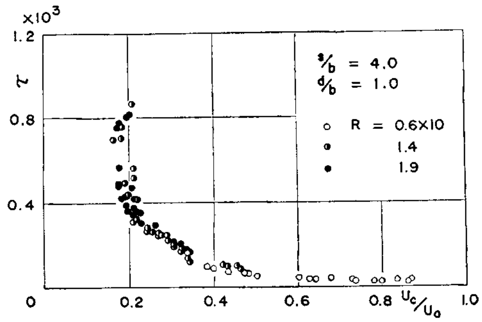

Fig. 13. Variation of switching time with step control flow. (S/b=4.0)

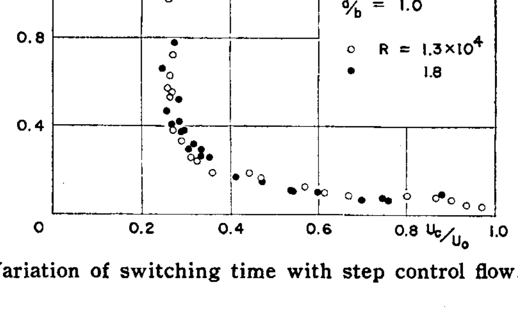

Fig. 14. Variation of switching time with step control flow. (S/b=5.0)

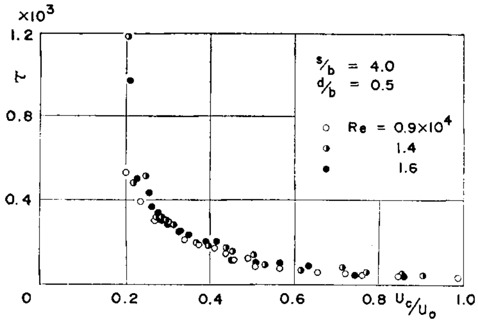

Fig. 15. Variation of switching time with step control flow. (d/b=0.5)

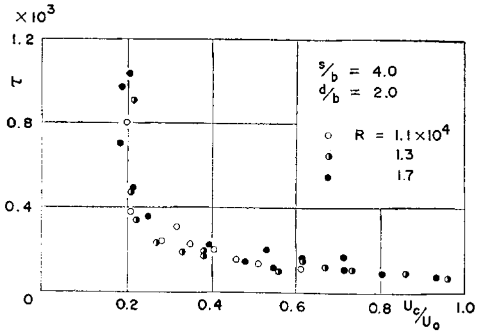

Fig. 16. Variation of switching time with step control flow. (d/b=2.0)

ing occur above this value. This critical value depends slightly on the splitter distance, and it decreases slightly as the splitter distance decreases.

For various step heights similar relations are shown in Fig. 15 and 16. In this case, however, it seems that the step height does not affect the critical value of step control flow. In addition, it is seen that, in the neigh-borhood of critical step control flow, the switching phenomenon is unstable and the switching time is extremely long. However, when the control flow becomes stronger than the critical values, the switching phenomenon becomes quite stable and the main jet flow is switched rapidly.

5. Theoretical Calculation and Discussions

Since the characteristics of the steady state flow pattern in a wall attachment type fluid amplifier already have been studied in many[1~4] papers, the jet swiching mechanism will principally be discussed in this section.

For the calculation of complex turbulent jets, some simplifications and assumptions are given as follows:

1) The jet flow is two-dimensional and incompressible.

2) The jet momentum is constant, or the friction loss is negligible.

3) The cavity pressure is constant within the low pressure region of attached flow.

In the last section, it is found that two different switching phenomena exist, i.e. in the first mode the switching action is unstable and the switching time is so long, and in the second mode the switching becomes quite stable and the switching time is very short.

For the first mode, the process of the switching action is divided into two parts. In the former part, the cavity volume increases by the step control flow and the main jet flow separates from the attached wall gradually. In the latter part, the separated main jet flow reattaches to the opposite side wall, since it can not be stable itself.

With the above-stated assumption (3), the streamline of the attached jet flow is assumed to be circular, and therefore the force balance equation between the centrifugal force and the pressure force is expressed as follows:

$$\frac{dP}{dr}=\frac{\rho U^2}{R}$$

or

$$P=\frac{1}{R}\int \rho U^2 dr=\frac{J_0}{R} \tag{4}$$

where $P=P_V-P_\infty$ is the pressure difference of the cavity, R is the radius of of curvature of the streamline and J_0 is the jet momentum (see Fig. 17).

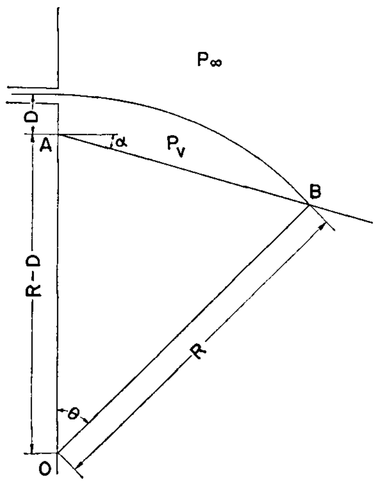

Fig. 17. Notation used in the analysis.

From the geometrical configuration, since the volume of the cavity is given by

$$V=\frac{1}{2}R[R\theta-(R-D)\sin\theta] \tag{5}$$

and the relation between R and θ is as follows:

$$\cos(\theta-\alpha)=\left(1-\frac{D}{R}\right)\cos\alpha \tag{6}$$

In general, θ and α/θ are smal, accordingly the following relation is obtained

$$V=\frac{1}{2}D\theta R,\quad \frac{1}{2}\theta^2=\frac{D}{R} \tag{7}$$

Therefor, from Eq. (7),

$$dV=\frac{1}{4}D\theta dR \tag{8}$$

On the other hand, from Eq. (4),

$$PR=J_0=\text{const.} \tag{9}$$

and then from Eqs. (7) and (8), the relation between P and V is expressed by

$$PV^2=\text{const.}=P_0V_0^2 \tag{10}$$

where P_0 and V_0 denote inital values of the steady state pressure difference and volume of the cavity respectively. The volume flow inserted to the cavity is represented by

$$dV/dt=Q_c-(Q_{ent}-Q_{rev})=Q_1 \tag{11}$$

where Q_c, Q_{ent} and Q_{rev} denote the control flow, the entrained flow and the reversed flow respectively.

Using Eqs. (10) and (11),

$$P(Q_1t+V_0)^2=P_0V_0^2 \tag{12}$$

If the former part, or the separation of the main jet flow from a side wall, is caused at $P=\gamma^2P_0$ $(0<\gamma<1)$, the time t_1 required is given as follows:

$$t_1=\frac{1}{Q_1}\frac{1-\gamma}{\gamma}V_0 \tag{13}$$

In the same way, the latter part or the reattachment of main jet flow can be calculated. The relation between the volume flow and the volume of cavity is given by

$$dV/dt=-(Q_{ent}-Q_{rev})=-Q_2 \tag{14}$$

or

$$P\left(-Q_2t+\frac{V_0}{\gamma}\right)^2=P_0V_0^2 \tag{15}$$

If it is assumed that the switching action is finished at $P=P_0$, the switching time is

$$t_2=\frac{1}{Q_2}\frac{1-\gamma}{\gamma}V_0 \tag{16}$$

Thus, the total switching time is given by

$$t=t_1+t_2=\left(\frac{1}{Q_1}+\frac{1}{Q_2}\right)\frac{1-\gamma}{\gamma}V_0 \tag{17}$$

or

$$\tau=\left(\frac{1}{Q_1^*}+\frac{1}{Q_2^*}\right)\frac{1-\gamma}{\gamma}V_0^* \tag{18}$$

where

$$\tau = U_0 t/b, \quad V_0^* = V_0/b^2$$
$$Q_1^* = (Q_c - Q_1)/U_0 b, \quad Q_2^* = Q_2/U_0 b$$

In this calculation, the value of γ is important for the switching time, and it is principally related to the splitter distance. From the experimental results, $\gamma = 0.4 \sim 0.5$ is considered as reasonable. Accordingly, using $\gamma = 0.45$, $Q_2^* = 0.11$ and $V_0^* = 15.0$, the dimensionless switching time τ is calculated and shown in Fig. 18 with a solid line. The agreement with the experimental values is comparatively good except the region of large step control flow.

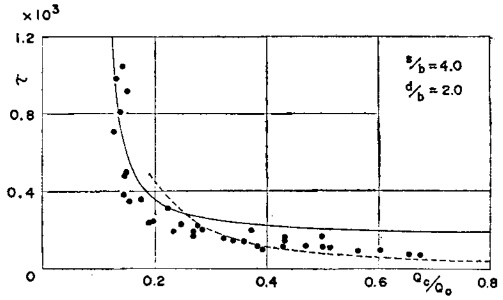

Fig. 18. Variation of switching time compared with the analysis.

Next, when the control pulse flow is strong enough, the switching phenomena can not be treated as the quasi-steady process stated previously. In this case the step control jet flow breaks instantaneously the low pressure cavity and impinges directly on the main jet flow. Therefore, in this case the switching

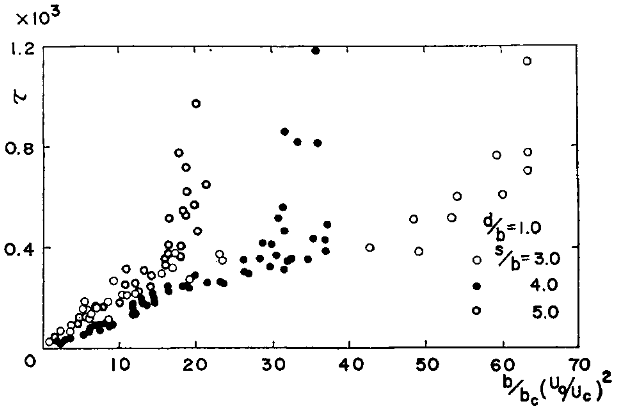

Fig. 19. Variation of switching time with control pulse flow momentum. $(d/b = 1.0)$

action of main jet flow is caused by the momentum effect of the step control flow, and accordingly the switching time is inversely proportional to the momentum of control jet flow. The geometrical configuration, i.e. the splitter distance, the step height etc., does not affect it so much.

Then, referring to Eq. (3), the switching time τ can be expressed as follows:

$$\tau = G(b_c/b,\ U_c/U_0) \tag{19}$$

In order to show that the switching time is inversely proportional to the control jet momentum, the experimental results are summarized in Fig. 19 and 20. Obviously those results show that the switching time is inversely proportional to the control flow momentum when it is strong.

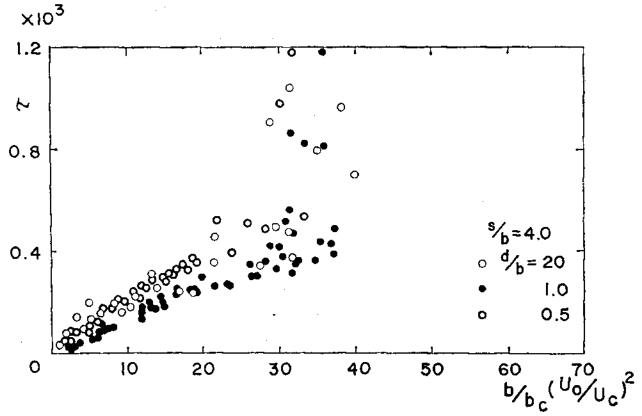

Fig. 20. Variation of switching time with control pulse flow momentum. (S/b=4.0)

Accordingly, in this case, τ is expressed by

$$\tau = A\left(\frac{b_c}{b}\right)\left(\frac{Q_0}{Q_c}\right)^2 \tag{20}$$

The switching time calculated by Eq. (20) is shown in Fig. 18 by the dotted line, where the constant value A is chosen 25.7 from the experimental results.

6. Conclusion

As the important characteristics of a wall attachment type fluid amplifier, the steady state flow pattern and the mechanism of jet switching action have been investigated experimentally.

The steady state flow pattern is considerably changed due to the splitter distance and the step height, and both affect the wall attachment characteristics of main jet flow.

Concerning the switching phenomena, it is found that three distinct modes exist, depending upon the step control flow. First, when the step control jet flow is below a certain critical value, the switching of main jet flow can not be realized, secondly, when the control jet is in the neighborhood of the critical value, the switching is unstable and the switching time is so long, and thirdly when the control jet is strong enough, the switching becomes quite stable and the switching time is very short.

Using the simplified flow model, the switching actions are investigated analytically. In those analyses, the second mode of switching is treated as a quasi-steady flow, and the third mode is treated by the jet momentum consideration. From the experimental results, those treatments are considered to be reasonable.

Notation

b : main throat thickness
b_c : control throat thickness
α : inclined angle
d : step height
S : splitter distance
P : static pressure
P_∞ : ambient pressure
U_0 : main jet velocity
U_c : control jet velocity
l : cavity length or distance of attached point from the step
J_0 : main jet momentum per unit span $J_0=\rho U_0^2 b$
J_c : control jet momentum per unit span $J_c=\rho U_c^2 b_c$
Q_c : volume flow of control jet per unit span
t : switching time
τ : non-dimensional switching time $\tau=U_0 t/b$
R : radius of main jet centerline
R_e : Reynolds number
ρ : density of the fluid
ν : kinematic viscosity of the fluid

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