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A STUDY ON A FLUIDIC OSCILLATOR AT LOW REYNOLDS NUMBERS

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ABSTRACT

A confined jet sometimes causes self-exited oscillations due to an existence of a downstream obstacle. In this work, the authors study this phenomenon at low Reynolds number (Re~10^2). More specifically, the authors deal with a two-dimensional confined jet into an abruptly expanding channel with a downstream square-cylinder target, experimentally and numerically. Experimentally, the authors conducted the velocity measurements by UVP (Ultrasonic Velocity Profiler). As a result, the authors specified the cylinder-distance effect, the cylinder-size effect, and the channel-beneath effect upon both the Strouhal number and oscillation range. In addition, the authors revealed the Reynolds number effect/limit on the Strouhal number and oscillation range. Moreover, the flow patterns in the fluidic oscillator were measured by PIV (Particle Image Verocimatry). Numerically, analysis was performed using a finite difference method (FDM). As a result, it is confirmed that computed Strouhal number show good agreement with experimental one. Therefore this is intrinsically two-dimensional phenomenon.

Keywords: *Fluidic Oscillator, Flowmeter, Fluid Logic, Flow Induced Vibration, Flip-Flop Jet*

INTRODUCTION

A confined jet sometimes causes self-exited oscillations due to an existence of a downstream obstacle. This phenomenon is useful for fluidic oscillators, heat/material mixers and flowmeters, in order to realize a low-cost high-reliability device without mechanically moving components.

For am application of a flowmeter, Yamasaki, Takahasi and Honda(1988)[(1)] have investigated one of the simplest configurations, that is, a two-dimensional jet inside an abruptly expanded channel with a square cylinder leeward. Flowmeter based on flow-induced-oscillation phenomena, such as Karman-vortex-street-type flowmeters, vortex-precession-type flowmeters and oscillatory-jet-type flowmeters, have common advantages as follows:(1) high reliability due to non-mechanical elements, (2) usability due to a linear frequency response in proportion to flow rate and (3) robustness against fluid density, temperature, pressure and composition. Here, the oscillatory-jet-type flowmeters often called as fluidic-type flowmeters or fluidic-oscillator-type flowmeters. Here, "fluidic" originates from "fluid logic (elements)" or "fluidics", whose researches have massively developed in 1960s. However, most fluidic oscillators have rather complicated geometries with control port, feedback loops and so on. A few exceptions are the above simple one and a three-dimensional one proposed by Shakouchi(1989).[(2)]

Recently, the increasing need for micro machines prompts such oscillators to miniaturize, as well as other device. Then, in this work, the authors study this phenomenon at low Reynolds number (Re~10^2). More specifically, the authors deal with oscillatory phenomenon a two-dimensional confined jet into an abruptly expanding channel with a square-cylinder as a downstream target, experimentally and numerically. This configuration is similar with the flowmeter investigated by Yamasaki *et al.* , but their channel beneath is much narrower than most of the present ones and will be shown not to be best for flowmeters in this paper. From practical points of view, Yamasaki *et al.*'s results show that this jet oscillation is not regarded to be suitable as a flowmeter especially at low Reynolds numbers, because their result showed rather sensitivity of the reduced frequency over flow velocity and over geometrical parameters. In the present study, our experiments and computations about the present confined jet will inform preferable features as a flowmeter or a fluidic oscillator at low Reynolds numbers; namely, (1) linearity of frequency over wide range of flow rate, (2) the existence of less-sensitive region of Reynolds number, and (3) the existence of less-sensitive regions of geometrical parameters.

Experimentally, the authors conduct the velocity measurements by UVP (Ultrasonic Velocity Profiler), where the frequency of the jet oscillation is given by the velocity near the square cylinder. As a result, the authors specify the cylinder-distance effect, the cylinder-size effect, and the channel-beneath effect upon both the Strouhal number and oscillation range. In addition, the authors reveal the Reynolds number effect/limit on the Strouhal number and oscillation range. Moreover, the flow patterns in the fluidic oscillator are measured by PIV (Particle Image Verocimatry) during one cycle of the oscillation. These will explain qualitatively the above geometry effects. Numerically, analysis is performed using a finite difference method (FDM) formulated in terms of vorticity and stream function.

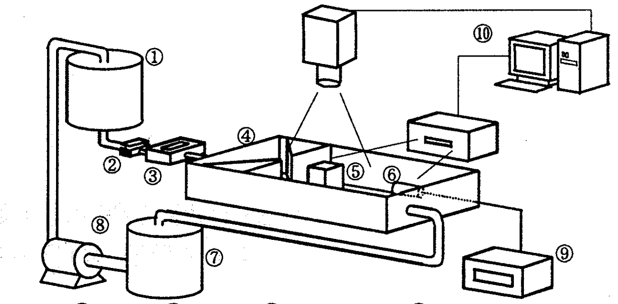
NOMENCLATURE

B	:	Width of fluidic oscillators, m
b	:	Width of a nozzle exit, m
c	:	Length of one side of a square cylinder, m
D	:	Length of fluidic oscillators, m
d	:	Distance from a jet exit to a square cylinder, m
f	:	Oscillation frequency of a jet, s^{-1}
h	:	Height of fluidic oscillators, m
Q_{in}	:	Volumetric flux (flow rate) from a nozzle exit, m^3/s
Re	:	Reynolds number $=U_{in}b/\nu$
St	:	Strouhal number $=fb/U_{in}$
T	:	The oscillation cycle of a jet, s
t	:	Time, s
U_{in}	:	The maximum velocity in a nozzle exit, m/s
u	:	Flow velocity in a parallel direction with mainstream, m/s
v	:	Flow velocity in a perpendicular direction with mainstream, m/s
x,y,z	:	Coordinates, m

EXPERIMENTAL EQUIPMENT AND METHOD

Experimental equipment

Fig. 1 shows the experiment equipment used for this research. Water pumps up into a main tank① by a pump⑧, and flows to an oscillator④. A pressure difference is always kept constant by the overflow attached in the main tank. And the volumetric flux of water can be kept constant by keeping a pressure difference constant. A valve② adjusts volumetric flux. The jet that flows into the oscillator (Length $D=6.0\times10^{-1}$m) from the nozzle exit (Width $b=1.2\times10^{-2}$m, Height $h=1.2\times10^{-1}$m) oscillates in the presence of a square cylinder⑤ placed downstream from the nozzle exit. Fig. 2 shows the detail of the fluidic oscillator used for this research. Water is stored in a sub tank⑦ and returned to a main tank by a pump⑧, again. Thus, water always circulates.



① Tank ; ② Valve ; ③ Flow meter ; ④ Fluidic oscillator ; ⑤ Square cylinder ; ⑥ Ultrasonic transducer ; ⑦ Sub-tank ; ⑧ Pump ; ⑨ Ultrasonic Velocity Profiler ; ⑩ PIV system

Fig.1 Experimental apparatus.

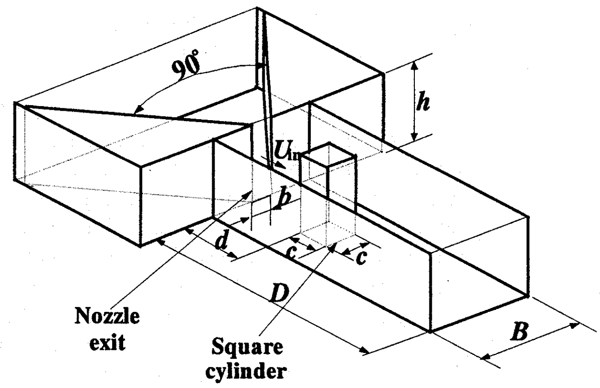


Fig.2 Fluidic oscillator.

Measurement of jet velocity, and oscillation frequency

Fig.3 shows points where the authors measure the representative velocity u of the jet that flows from the nozzle exit. Fig.4 shows a sample data of measured flow velocity fluctuation. The fluctuation is analysed, using FFT, and shows dominant frequency f in a spectrum such as Fig.5.

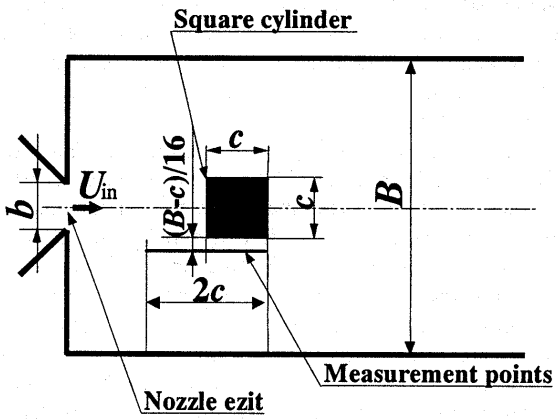


Fig.3 Measuring points of jet's velocity, (z=0.0).

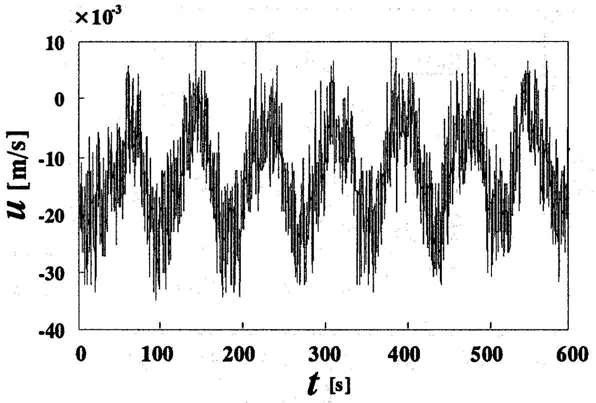


Fig.4 Velocity Fluctuation of jet, at c/b=2.5, B/b=15, d/b=9, and Re=500.

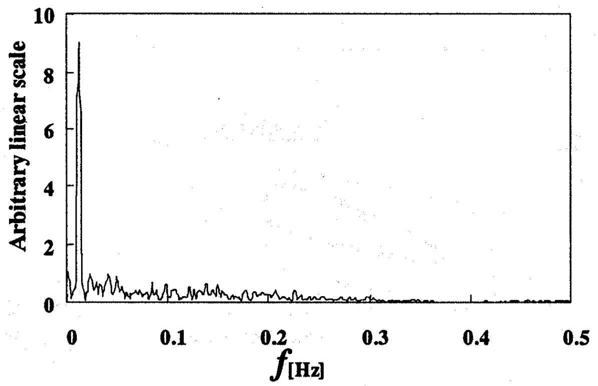


Fig.5 frequency of confined jet, , at c/b=2.5, B/b=15, d/b=9, and Re=500.

Visualization by PIV

The flow patterns in the fluidic oscillator are observed, and are analysed by cross-correlation PIV (Particle Image Verocimatry). Laser is irradiated from the side of the fluidic oscillator, and the x-y plane was photoed with the CCD camera installed above the fluidic oscillator.

THE CALCULATION METHOD

Numerically analysis is performed using a finite difference method (FDM) formulated in terms of vorticity and stream function. The governing equations consist of a vorticity-transport equation and a Poisson equation for stream function. To specify the value of stream function on the cylinder surface, the condition of single valuedness of pressure is applied. As an inflow boundary condition, velocity distribution measured experimentally at the nozzle exit is used. The mesh is set to 1/8 of the nozzle width b, and the regular mesh system is used with same spacing. Model geometry is the same with the experiment, i.e., the length of the fluidic oscillator is set to 50b and width of the fluidic oscillator is set to 15b.

RESULT

Influence of Reynolds Number *Re*

Length c of a square cylinder and width B of fluidic oscillator are fixed, and the authors investigate the effect of distance d from a jet exit to a square cylinder for some Reynolds numbers less than 1000. Experimental result is shown in Fig.6 and Fig.7. Fig. 6 shows the oscillatory range of d/b is almost fixed at $Re \geqq 200$, and decreases rapidly at $Re \leqq 200$. In the present study, we can see that the lower limit of Re on oscillation is just below 100, while the limit depends on geometry.

Fig.7 shows that St is almost independent of Re. Then, we can see, if geometry is properly chosen, this phenomenon is suitable for a flowmeter.

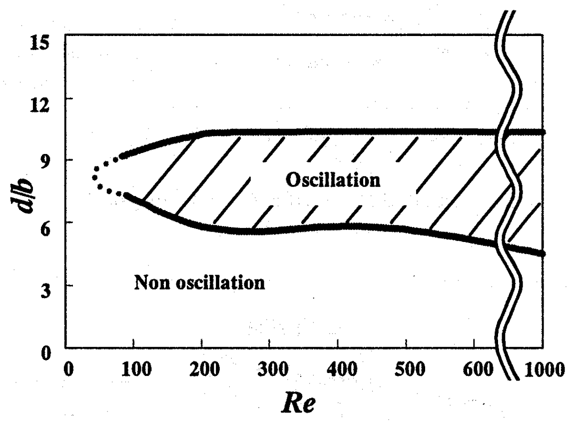


Fig.6 Oscillatory region changing Re and d/b, B/b=15 and c/b=2.5.

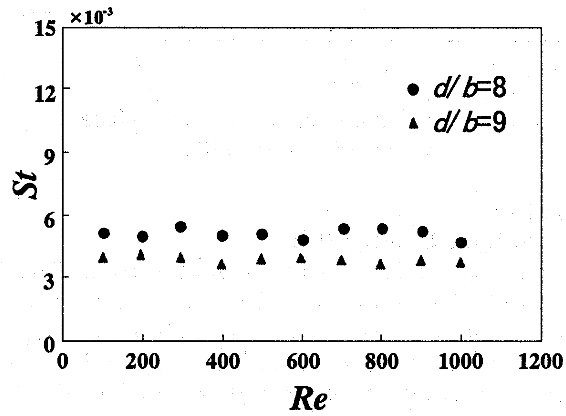


Fig.7 Strouhal number against Reynolds number, at c/b=2.5, and B/b=15.

At *Re*=500

Influence of oscillator width B.

Fig.8 shows the oscillatory regime of jet at c/b=2.5 and Re=500. It turns out that the oscillatory regime becomes large, as B/b or d/b becomes large. But there are upper limits of B/b and d/b. When the contour line about the value of St is drawn, a contour line is sparce at higher d/b, and it is dense at lower d/b. Moreover, d/b effect has the quite larger influence on St than B/b effect.

<u>Influence of Square cylinder width *c*</u>

Fig.9 shows the oscillatory regime of jet at *B*/*b*=15 and *Re*=500. It turns out that the oscillation regime becomes large, as *c*/*b* becomes small. But, it stops oscillating rapidly at *c*/*b*=0.5. When the contour line about the value of *St* is drawn, the value of *St* increases with decreasing *d*/*b*. But, *c*/*b* has almost no influence on *St*. These results show that *d*/*b* effect on *St* is much larger than *B*/*b* effect and *c*/*b* effect.

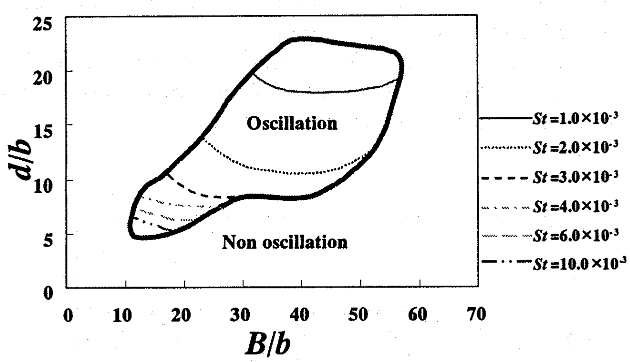


Fig.8 Oscillatory regime on the *B*-*d* plane, at *c*/*b*=2.5, and *Re* =500.

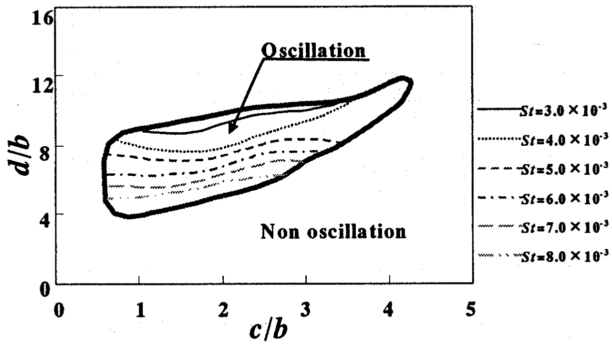


Fig.9 Oscillatory regime on the *c*-*d* plane, at *B*/*b*=15, and *Re* =500.

At *Re*=100

<u>Influence of oscillator width *B*</u>

Fig.10 shows the oscillatory regime of jet at *c*/*b*=2.5 and *Re*=100. This shows that the oscillatory regime at *Re*=500 is much larger than that at *Re*=100. At longer *B*/*b*, we cannot observe oscillation at *Re*=100. The authors consider that the reason is closely related with the decrease of effective local Reynolds number.

<u>Influence of square cylinder width *c*</u>

Fig.11 shows the oscillatory regime at *B*/*b*=15 and *Re*=500. It turns out that the oscillation regime becomes large, as *c*/*b* becomes large. Moreover, as compared with that at *Re*=500, the oscillation regime becomes small, which is at *c*/*b*=1.5-2.5 and at *d*/*b*=7-9. This is nearly the center of the oscillatory regime at *Re*=500.

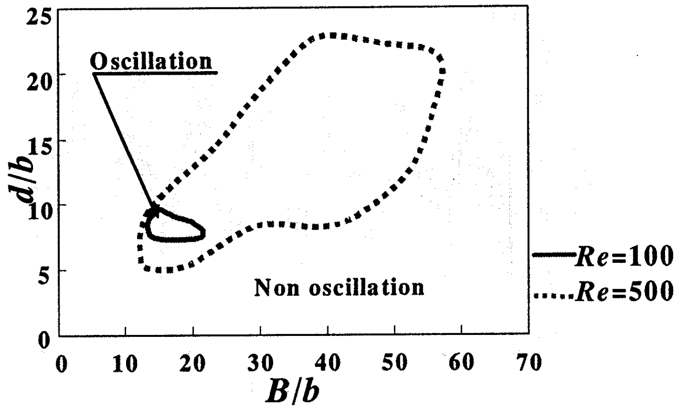


Fig.10 Oscillatory regime on the *B*-*d* plane, at *c*/*b*=2.5, and *Re* =500.

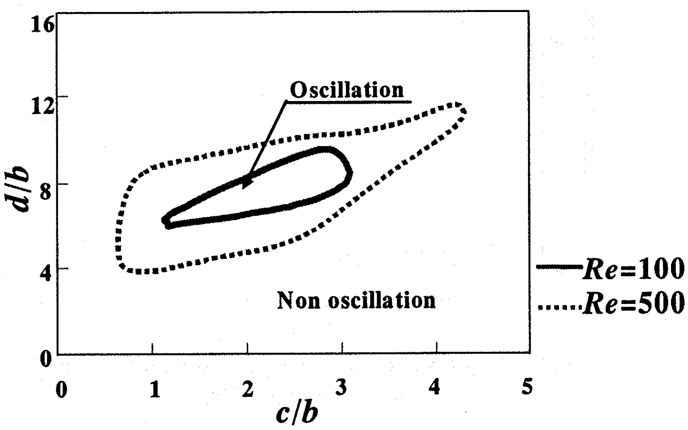


Fig.11 Oscillatory region on the *c*-*d* plane, at *B*/*b*=15, and *Re* =100.

Influence of oscillator height *h* (aspect ratio).

Using the present MEMS technology, it is not so easy to make 3D structures. So, it becomes practical to check the aspect ratio effect of this device. Fig.12 shows the influence of the oscillator aspect ratio *h*/*b* on the oscillatory range of *d*/*b*. The oscillatory range of *d*/*b* decreases gradually at $h/b \geqq 4$, and decreases rapidly at $h/b \leqq 4$. While there are no experimental results at $h/b \leqq 2$, it seems difficult to get oscillatory flow at very low *h*/*b*. This agrees with computational results shown later, which reveal that this oscillatory phenomenon is essentially 2D.

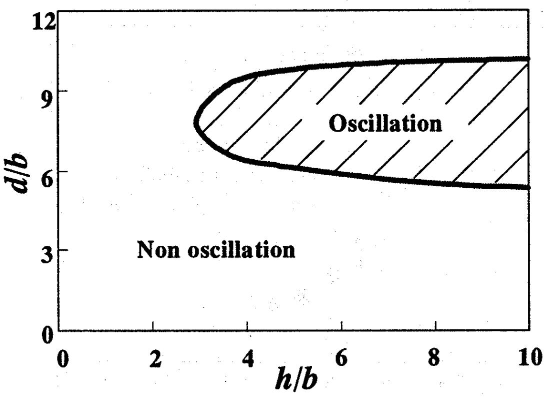


Fig.12 Oscillatory region changing h/b and d/b, B/b=15, c/b=2.5 and Re=500.

Flow visualization

Flow pattern during in one cycle

The flow patterns in the fluidic oscillator are measured by PIV during one cycle of the oscillation. Fig. 13 shows the flow patterns drawn every 1/8 cycles. From these figures, two re-circulating areas A and B are made at the upstream of a square cylinder. Two vortical structures C and D are made in square cylinder leeward. At $t=T/8$, the jet is deflected upwards. The vortical structure C is stronger than D, and the flow is downward in the down stream of a square cylinder. At $t=2T/8$, vortical structure C flows downstream. The jet becomes deflected downwards at $t=3T/8$. Vortical structures C and D flow downstream, and at $t=5T/8$ the new vortex C is made at downstream of the square cylinder. At $t=6T/8$, vortical structure D flow downstream.

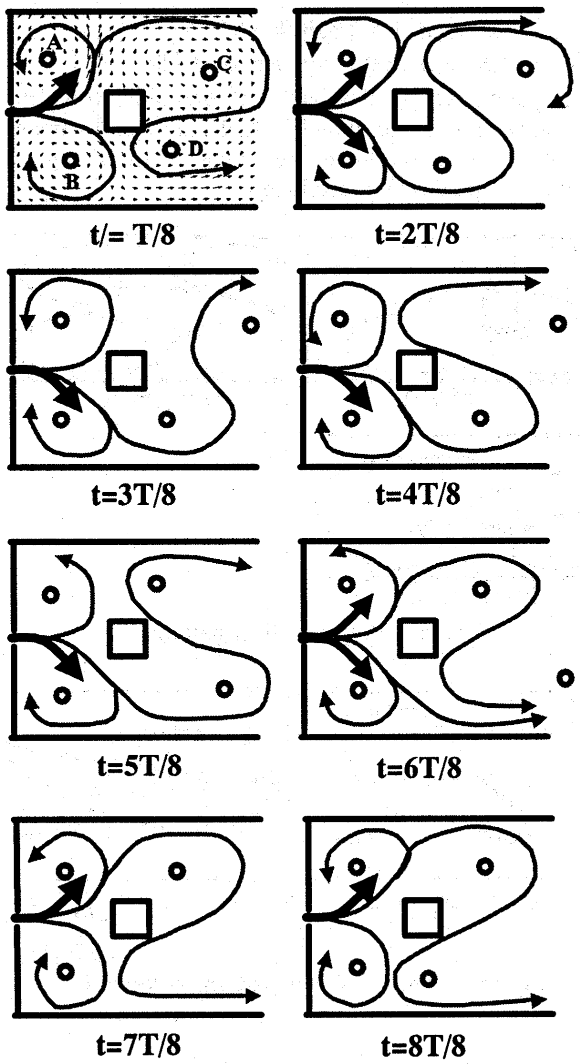


Fig.13 Flow pattern in one cycle, at B/b=15, c/b=2.5 d/b=7, and Re=500.

Flow patterns

As a result of flow pattern observation, flow patterns are divided into three types. These flow patterns are shown in Fig.14. And the regimes of flow patterns are shown in Fig.15. Pattern A is oscillating one. As shown in the above, in the downstream of square cylinder, two vortical structures are generated and flow downstream, altenatively. With increasing B/b, increasing c/b, or decreasing d/b, the flow pattern becomes pattern B from pattern A. The boundary between pattern A and B is approximated by the following equation.

$$d/b = 0.18B/b + 1.50c/b + 0.60.$$

(valid for $0.5 \le c/b \le 5.0, 10 \le B/b \le 62,$ and $Re = 500$)

As for pattern B, flow is in vertical symmetry, and it does not oscillate. Two symmetric vortical structures exist in the downstream of square cylinder and they don't flow downstream. Moreover, with decreasing B/b, or increasing d/b, flow pattern becomes pattern C from pattern A. The boundary between A and C is expressed by the following approximated equation.

$$d/b = 0.33B/b + 4.10.$$
(valid for $0.5 \le c/b \le 5.0, 10 \le B/b \le 62,$ and $Re = 500$)

As for pattern C, a jet is biased to one side, with less collision with a square cylinder. And only one dominant vortical structure exists in the downstream of square cylinder. A jet does not oscillate.

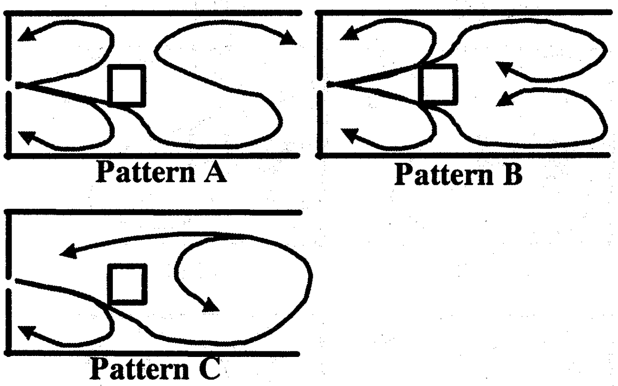
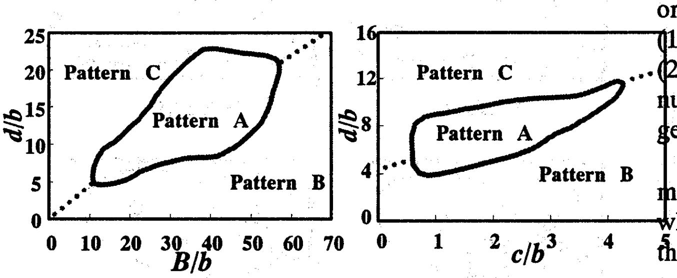


Fig.14 3 types of flow pattern.



(a) c/b=2.5 (b) B/b=15

Fig.15 Regime of flow patterns at Re=500.

Comparison between experimental and numerical results

At B/b=15, c/b=2.5 and Re=500, d/b effect on St is shown in Fig.16. The numerical results that are substituted the poiseuille flow as inflow conditions are not good agreement with the experiments. But the numerical result that substituted the flow velocity distribution measured by the experiment is in good agreement with the experiment result. This shows that oscillation is properly two-dimensional phenomenon, and that St is sensitive to the velocity profile of inflow.

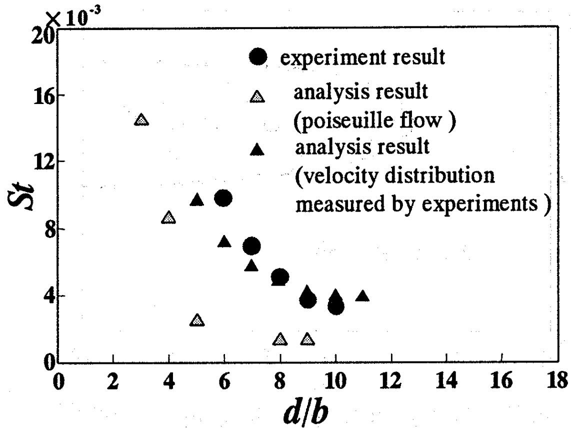


Fig.16 Strouhal number St against target distance d, at c/b=2.5, B/b=15, and Re=500.

CONCLUSION

Experiments and computations about the present confined jet informed preferable features as a flowmeter or a fluidic oscillator at low Reynolds numbers; namely, (1) linearity of frequency over wide range of flow rate, (2) the existence of less-sensitive region of Reynolds number, and (3) the existence of less-sensitive regions of geometrical parameters.

Experimentally, the authors conducted the velocity measurements by UVP (Ultrasonic Velocity Profile), where the frequency of the jet oscillation was given by the velocity near the square cylinder. As a result, the authors specified the cylinder-distance effect, the cylinder-size effect, and the channel-beneath effect upon both the Strouhal number and oscillation range. In addition, the authors revealed the Reynolds number effect/limit on the Strouhal number and oscillation range. Moreover, the flow patterns in the fluidic oscillator were measured by PIV (Particle Image Verocimatry) during one cycle of the oscillation.

Numerically, analysis was performed using a finite difference method (FDM) formulated in terms of vorticity and stream function. As a result, the numerical result that substituted the flow velocity distribution measured by the experiment was in good agreement with the experiment result. And the authors revealed jet oscillation in this fluidic oscillator was properly two-dimensional phenomenon. (But, even at h/b=3.0, flow can oscillate.)

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