On Some Influences of the Geometry of a Simplified Flip-Flop Jet Nozzle

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We experimentally investigate a self-exited oscillatory phenomenon of a confined jet entiring a recutangular cylinder as a downstream obstacle using ultrasonic velocity profile UVP, particle-image velocimetry PIV and hot-wire anemometer HWA, focusing on two geometry effects such as its aspect-ratio effect and the effect of a streamwise target size *a*. Furthermore, we conduct two-dimensional numerical analyses. As a result, we reveal a good agreement between experiments and computations, which suggests that the present phenomenon is intrinsically two-dimensional. And, we confirm that the dominant jet's frequency f_D detected by the UVP can be approximately predicted by the proposed empirical formula (Hirata *et al*., 2011), whenever the jet stably oscillates. The effect of a/b upon the occurrence of stable jet's oscillation is not negligible at $a/b \geq 10$, where *b* denotes the breadth of a primary nozzle. Besides, the first and the second POD modes are almost dominant in the present flow.

Keywords: Flip-flop jets, Flowmeter, Fluidic logic, Fluidics, Flow-induced vibration

1. Introduction

A confined jet sometimes becomes unstable and causes self-induced oscillation of flow, due to the existence of a downstream obstacle [1, 2]. The knowledge of this phenomenon is useful for many applications in various aspects, like flip-flop jet nozzles, flowmeters, oscillatory components of fluidics, mixers, chemical reactors and so on.

In the present study, we deal with the self-excited oscillatory phenomenon of a two-dimensional confined jet with a rectangular cylinder as a downstream obstacle, which is similar to the flowmeter reported by Yamasaki *et al*. [3]. More specifically, we experimentally investigate this phenomenon using velocimetries, namely, (1)ultrasonic velocity profile UVP [4, 5], (2)particle-image velocimetry PIV and (3)hot-wire anemometer HWA, focusing on two geometry effects such as the aspect-ratio effect and the effect of the streamwise target size *a*.

The UVP has proposed and developed by Takeda (1986) [4] and Takeda *et al*. (1992) [5]. The UVP gives us a smaller number of instantaneous information, but its accuracy is higher. We may consider alternatives to the UVP, such as a hot-wire velocimetry (HWV), a laser-Doppler velocimetry (LDV), a particle-image velocimetry (PIV) and a tracking velocimetry (PTV). The HWV has high reliability and high accuracy, but it disturbs flow by its probe. The LDV has high responsibility and high accuracy, but it is often sensitive to the condition of tracer particles. As both of the HWV and LDV give us the information at only one point in space, we are required to select the point carefully, especially for unknown complicated flows. Tracer-particle concentration should be kept high and homogenous for the LDV. The PIV and the PTV give us neither the ping-point nor the one-dimesional information, but the two-dimensional information on the basis of flow-visualised photographs [6].

Furthermore, we conduct two-dimensional numerical analyses based on vorticity ζ and stream function ψ using a finite-difference discretization method. Two-dimensional numerical analysis is suitable to examine the two-dimensionality of the phenomenon than three-dimensional one.

2. Experimental Method

Figure 1 shows the present model of a simplified flip-flop jet nozzle, together with the present coordinate system. A jet is emitted from a primary nozzle exit into the flip-flop jet nozzle with an inlet spatially-averaged velocity U_{in} at the nozzle exit. Such a confined jet sometimes oscillates at a dominant frequency f_D in the presence of a downstream target, which has one of the simplest geometries like a rectangular-cross-section cylinder in the present study. Concerning this model, we consider seven geometric parameters as *a*, *B*, *b*, *c*, *D*, *d* and *h*, as shown in Fig. 1.

We should suppose U_{in}, fluid density ρ and viscosity μ in addition to the seven geometric parameters as the dimensional governing parameters for the present model.

Through the present study, we simply choose U_{in}, ρ and *b* as characteristic scales. Therefore, it is necessary to induce seven non-dimensional parameters to specify the model's condition. The Strouhal number is a non-dimensional form of f_D, which is defined by $St \equiv f_D b/U_{in}$. When we consider f_D, we get $St = \phi(Re, a/b, B/b, c/b, D/b, d/b, h/b)$. Here, ϕ denotes an arbitrary function.

Among the non-dimensional governing parameters, D/b is to a constant: 47 and 40 in all the water and air experiments, respectively, being approximated to be large enough to ignore D/b effect. As well, *Re* is 500 and 5000 in all the water and air experiments, respectively. We can ignore the *Re* effects upon both *St* and the occurrence condition for *Re* > 200 [2].

Figure 2 shows the details inside the model, in order to show the measuring points for the jet's oscillation frequency by the UVP in water and by the HWA in air. Tracer particles and other main experimental conditions are the same as Funaki *et al*. [7].

3. Results and Discussion

3.1 Velocity fluctuation

Figure 3 shows its corresponding spectrum and a sample raw data of the flow-velocity fluctuation measured on the points indicated in the figure using UVP [1]. Specifically speaking, the inserted figure denotes the *x*-component *u* of a velocity vector at *Re* = 500, *a/b* = 2.5, *B*/*b* = 15, *c*/*b* = 2.5, *d*/*b* = 9 and *h*/*b* = 10 in water. Inserted figure represents a time history, and the main figure represents

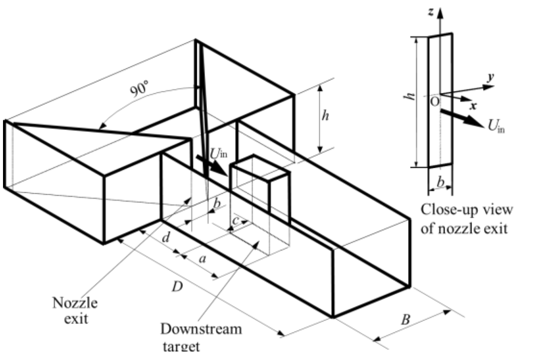


Figure 1: Model (a simplified flip-flop jet nozzle), together with coordinate system.

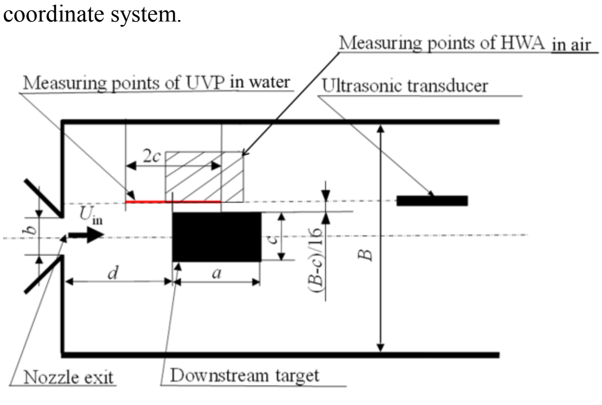


Figure 2: Measuring points for jet's velocity.

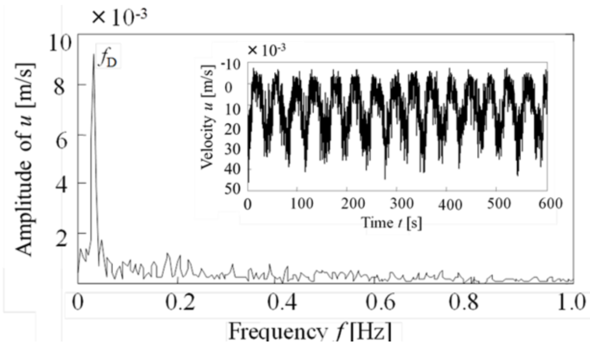


Figure 3: Velocity fluctuation, at *Re* = 500, *a*/*b* = 2.5, *B*/*b* = 15, *c*/*b* = 2.5, *d*/*b* = 9 and *h*/*b* = 10 using UVP in water (Hirata *et al*. 2009) [1].

its corresponding spectrum using a fast-Fourier-transform (FFT) algorithm. In the inserted figure, we can see a distinct and stable periodicity, together with higher-frequency random fluctuations due to flow turbulence. In the main figure, we can see a clear dominant frequency f_D of about 1/40 Hz in the spectrum, which corresponds to the oscillation period of about 40 s. As shown by flow visualisation in our previous study [1], f_D is related with a 'stable' jet's oscillation inside the flip-flop jet nozzle. The 'stable' means that where the jet's oscillation is periodic at any time, and the 'less-stable' condition means that where the oscillation is almost non-periodic and sometimes periodic.

3.2 Influence of aspect ratio

Figure 4 shows the present experimental results using the HWA, together with the experimental results using the UVP at *Re* = 500 and the HWA at *Re* = 500 [1, 2]. In the figure, *St* is plotted against *d/b*. We should note that all the data points at *St* = 0 represent such a condition as the jet's oscillation is not 'stable' but 'less-stable.'

Two vertical chained lines in the figure represent the stability boundaries proposed by [1]. That is to say, in order to predict the occurrence condition for the stable jet's oscillation, Hirata *et al*. have proposed a pair of the following empirical criteria:

$$3/2 \le B/d \le 4, \tag{1}$$

and

$$1/10 \le c/d \le 2/5. \tag{2}$$

Concerning the first criterion Eq. (1), it is supposed to be inherent for the stable jet's oscillation that the two recirculating areas should exist on both the sides in the upstream of the square cylinder at any time. Therefore, *B/d* is a primarily-important geometric parameter to secure the spaces for the two re-circulating areas. Concerning the second criterion Eq. (2), it is supposed to be inherent for the stable jet's oscillation that the spacial relationship should be adequate between the jet's shear layers and the downstream-target edges. A chained line at *d*/*b* = 6.3 represents such an equation as *c*/*d* = 2/5, and another chained line at *d*/*b* = 10 represents such an equation as *B*/*d* = 3/2. Of course, in a zone at *d*/*b* = 6.3 – 10 in the figure, both of the criteria Eqs. (1) and (2) are satisfied.

In addition, a dashed line in the figure denotes the empirical formula to predict the stable jet's oscillation frequency by [2]. This formula is given by

$$St = ke^{\alpha(a/b)}(B/b)^{\beta}(c/b)^{\gamma}(d/b)^{\delta}, \tag{3}$$

with such experimental constants as $k = 0.5$, $\alpha = -0.2$, $\beta = -0.7$, $\gamma = 1.0$ and $\delta = -1.5$.

We can see that, for all the experimental results including [1, 2], the empirical criteria for occurrence conditions and the empirical formula for dominant jet's oscillation frequency are valid in spite of wide parameter ranges of *Re* and *h/b*. That is to say, the jet's oscillation is stable at *d/b* = 7 — 10 in agreement with Eqs. (1) and (2). Also, *St* is well predicted by Eq. (3); namely, all the values of *St* are in the order of 10^{-3} tending to decrease with increasing *d/b*. Strictly speaking, *St* is somewhat smaller than Eq. (3) at $h/b \leq 5$. Moreover, we have confirmed the *h/b* effect [1]. The degree of the scattering in experiment suggests that the oscillating phenomenon could be sensitive not only to the supposed governing parameters like *Re*, *a/b*, *B/b*, *c/b*, *D/b*, *d/b* and *h/b*, but also to some other factors such as noise, geometric imperfections, etc.

Moreover, Fig. 4 shows computational results together with experimental ones. As a result, we can observe that the stable jet's oscillation occurs in a closely-wider zone than that between the boundaries with *d/b* = 6.3 — 10. And, whenever the jet stably oscillates ($St \neq 0$), *St* is not close to but qualitatively similar to the empirical formula. Then, regarding these two facts, we can conclude that the two-dimensional computation can simulate the experiments, from a qualitative point of view. This suggests the two-dimensionality of the phenomenon.

In summary, we have revealed a good agreement in experiment and computation with various *Re* and *h/b*. This suggests that the present phenomenon is intrinsically two-dimensional, and that the influences of *Re* and *h/b* are negligible from a qualitative point of view at $Re > 500$ and $h/b > 3$. Then, we discuss the phenomenon only by the two-dimensional computation at *Re* = 500 and *h/b* = ∞ or the water experiment at *Re* = 500 and *h/b* = 10.

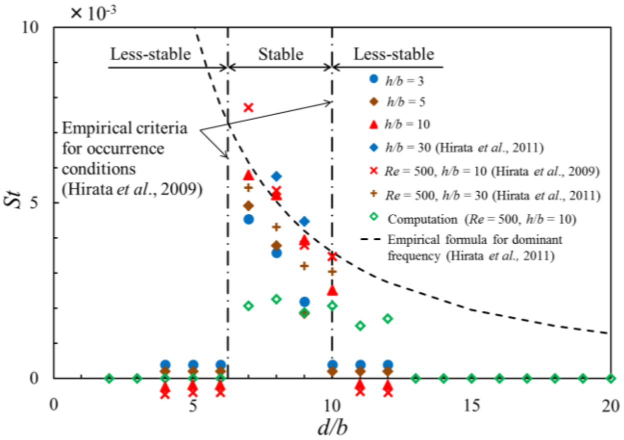
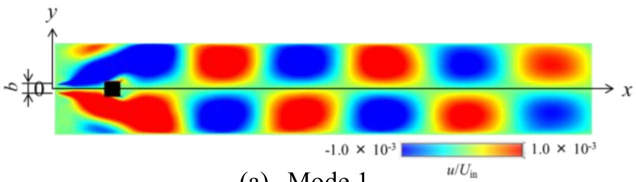
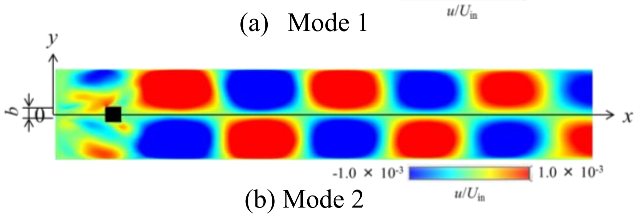


Figure 4: Strouhal number *St* against the distance *d* from a nozzle to a target, at *Re* = 5000, *a/b* = 2.5, *B/b* = 15 and *c/b* = 2.5 using HWA in air.



(a) Mode 1



(b) Mode 2

Figure 5: The first two POD modes (at *n* = 100): eigenfunctions of the *x*-component velocity *u* at *Re* = 500, *B/b* = 15, *c/b* = 2.5, *d/b* = 8 and $h/b \equiv \infty$ by computation.

3.3 Flow visualisation

In order to explain the physics of problems, flow visualisations often give us useful information. The proper orthogonal decomposition (hereinafter, referred to as POD) is another alternative. Figure 5 is an example analysed by the POD technique. More specifically, the figure shows the first two POD modes (at a snapshot number *n* = 100); namely, eigenfunctions of the *x*-component velocity *u* at *Re* = 500, *B/b* = *15, c/b* = 2.5, *d/b* = 8 and *h/b* = ∞ by computation. Because the first and the second POD modes are almost dominant in the present flow, we can clearly see the downstream travelling of a spatially-staggered periodic pattern.

3.4 Influence of streamwise-target dimension

In this section, we discuss the influence of the target's shape upon the flow. More specifically, we consider the effect of one geometric parameter a non-dimensional streamwise target size *a/b* upon both the dominant frequency and the occurrence of stable jet's oscillation.

Figure 6 shows *St* plotted against *a/b* for several values of *d/b*, at *Re* = 500, *B/b* = 15, *c/b* = 2.5 and *h/b* = 10 using the UVP. Dashed lines in the figure denote the empirical formula proposed by [2], for reference. The results for *St* = 0 represent the flow with less-stable jet's oscillation as well as Fig. 4. Whenever the jet stably oscillates, *St* can be approximated by the formula (3). On the other hand, the oscillation tends to suppress at $a/b \gtrsim 10$, in addition to such an empirical criterion with $d/b < 7$ or $d/b > 9$.

In order to examine the above *a/b* effect concerning the occurrence/suppression of stable jet's oscillation, Figs. 7 to 9 show the stable-oscillation domain on the *a/b*-*d/b* plane, at *Re* = 500, *B/b* = 30, *c/b* = 2.5 and *h/b* = 10 using the UVP. In the figures, dots represent the 'stable' condition where the jet's oscillation is periodic at any time as shown in Fig. 3, and crosses represent the 'less-stable' condition where the oscillation is almost non-periodic and sometimes periodic. Then, a red solid line denotes the boundary of the stable-jet-oscillation domain.

Two chained lines in each figure denote the stability boundaries proposed by [1]; namely, the upper and lower ones represent such equations as *B/b* = 3/2 and *c/b* = 2/5, respectively. We can observe using PIV that the stable jet's oscillation occurs in a zone between the two boundaries with *d/b* = 6.25 – 10 in Fig. 7, with *d/b* = 6.25 – 13.3 in Fig. 8 and with *d/b* = 7.5 – 20 in Fig. 9, whenever the jet stably oscillates.

However, even inside the zone between the two chained lines, the stable jet's oscillation does not always occur. That is to say, we cannot observe any stable jet's oscillation at $a/B > 4/5$ (a blue solid line in each figure). Then, we now get an additional criterion for the occurrence condition of the stable jet's oscillation, as follows.

$$0 < a/B \leq 4/5. \tag{4}$$

We can confirm the effectivity of this criterion in a range of *B/b* = 15 – 30, as shown in Figs. 7 — 9.

This new criterion is not enough, as shown in the figures.

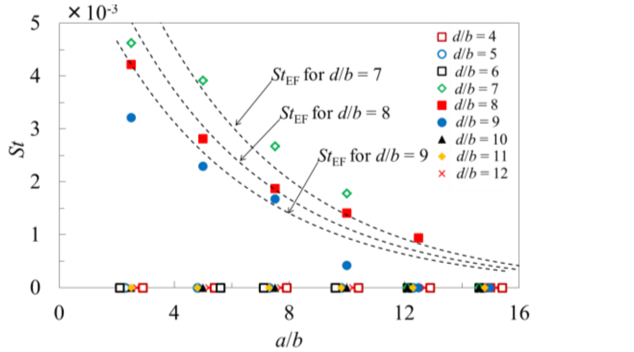


Figure 6: Strouhal number *St* against streamwise length *a* of a target for several values of *d*/*b*, at *Re* = 500, *B*/*b* = 15, *c*/*b* = 2.5 and *h*/*b* = 10 using UVP in water. Dashed lines denote the empirical formula proposed by Hirata *et al.* (2011) [2].

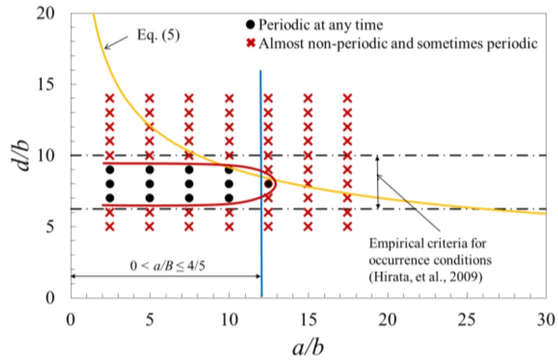


Figure 7: Stable-oscillation domain on the *a*/*b*-*d*/*b* plane, at *Re* = 500, *B*/*b* = 15, *c*/*b* = 2.5 and *h*/*b* = 10 using UVP in water.

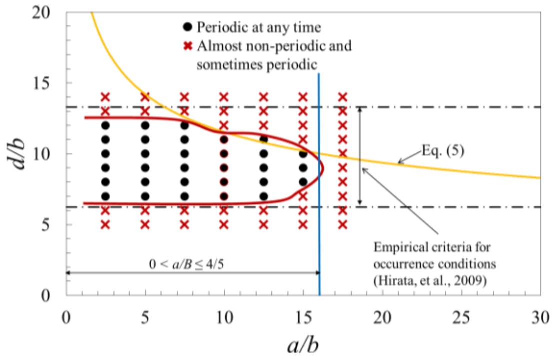


Figure 8: Stable-oscillation domain on the *a*/*b*-*d*/*b* plane, at *Re*= 500, *B*/*b* = 20, *c*/*b* = 2.5 and *h*/*b* = 10 using UVP in water.

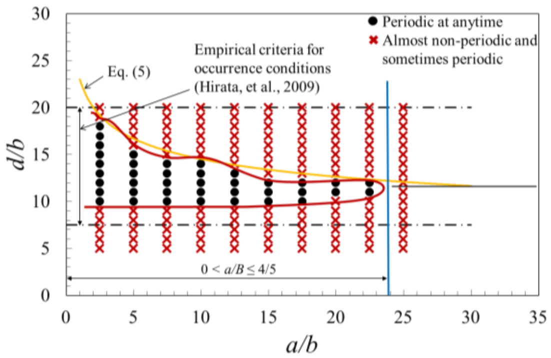


Figure 9: Stable-oscillation domain on the *a*/*b*-*d*/*b* plane, at *Re*= 500, *B*/*b* = 30, *c*/*b* = 2.5 and *h*/*b* = 10 using UVP in water.

So, we propose another additional criterion. This criterion is given by the following equation.

$$d/b \le 23\ (a/b)^{-6/(B/b)}. \qquad (5)$$

A yellow solid line in the each figure denotes this criterion. We can see a good agreement between the criterion and the boundary of the stable-jet-oscillation domain. Of course, we can confirm the effectivity of this criterion in a range of *B*/*b* = 15 – 30, as well. On the present stage, the mechanism of this *a*/*b* effect upon the occurrence/suppression of stable jet's oscillation is not obvious yet, being expected to be solved in future.

4. Summary

We have experimentally investigated a self-exited oscillatory phenomenon of a two-dimensional confined jet with a cylinder as a downstream target using velocimetries, namely, (1)ultrasonic velocity profile UVP, (2)particle-image velocimetry PIV and (3)hot-wire anemometer HWA, focusing on two effects of the geometry such as an aspect-ratio effect and a streamwise-target-size effect. Furthermore, we have conducted two-dimensional numerical analyses based on vorticity ζ and stream function ψ using a finite-difference discretisation method.

As a result, we have revealed (1) a good agreement between experiments and computations, which suggests that the present phenomenon is intrinsically two-dimensional, and (2) the importance and the complexity between the upstream and the downstream target. Concerning (2), we have confirmed on the basis of UVP's measurements that the dominant jet's frequency f_D can be approximately predicted by the proposed empirical formula [2], whenever the jet stably oscillates at various values of the non-dimensional streamwise target size *a*/*b* where *b* denotes the length scale of the jet's breath. The effect of *a*/*b* upon the occurrence of the stable jet's oscillation is negligible at *a*/*b* < 10. Then, the occurrence can be predicted by the proposed empirical formula [1]. On the other hand, at *a*/*b* ≥ 10, the effect of *a*/*b* is not negligible. Besides, we conduct the proper orthogonal decomposition POD, where the first and the second POD modes are almost dominant in the present flow.

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