

# Flapping Characteristics of 2D Submerged Turbulent Jets in Narrow Channels

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**Abstract:** Flapping characteristics of the self-excited flapping motion of submerged vertical turbulent jet in narrow channels are studied theoretically and experimentally. It is found that the water depth is a most important parameter to the critical jet exit velocity and the jet flapping frequency. The results indicate that the critical jet exit velocity increases with water depth and the jet flapping frequency is inversely proportional to the water depth. Meanwhile, experimental result also shows that the surface disturbance wave changes the frequency of flapping motion, i. e. the flapping frequency locks-in the disturbing frequency when the disturbing frequency is near and less than the natural flapping frequency.

**Key words:** turbulent plane jet; flapping motion; critical velocity; flapping frequency

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## 1 Introduction

The flapping motion of a turbulent plane jet, a lateral oscillation of the jet, were investigated theoretically and experimentally by Goldschmidt and Bradshaw<sup>[1]</sup>. Sun et al<sup>[2]</sup> obtained the governing equation of flapping motion through theoretical analyses, and showed an important flow characteristic, i. e. , in the flapping jet there exists a flapping-induced Reynolds stress, which can be utilized to enhance the mixing or dilution of jet flow fields. Therefore, a considerable interest has been held in the design, performance and flow control of diffusers or mixers in chemical engineering, environmental engineering, and so on. Wu et al<sup>[3]</sup> pointed out the relation between the oscillatory frequency and water depth for a jet slot with a constant width, and it is evident from the research of Hsu et al<sup>[4]</sup> and Sun<sup>[5]</sup> that the self-excited jet flapping motion is attributed to the jet instability rather than the coherent turbulent structure. Hsu et al<sup>[4]</sup> studied the flapping motion of plane jets of different water depths, jet-

orifice slot widths and jet exit velocities. Results showed that the critical instability condition of flapping motion is governed by two parameters, that is, the water-depth to jet-slot-width ratio  $(H - z_0)/d$  and the Strouhal number  $St = f_0 d / W_{0c}$  (a dimensionless parameter defined by flapping frequency, critical exit velocity and the jet slot width), where  $z_0$  is the virtual origin of the jet,  $H$  the water depth,  $d$  the jet slot width,  $f_0$  the flapping motion frequency and  $W_{0c}$  the critical jet exit velocity.

In recent years, most of research work have focused on the numerical simulation of flapping motion of turbulent submerged plane jets<sup>[6-12]</sup>. It was clearly presented in Ref. [11] that the flapping phenomenon was verified simultaneously by laser Doppler velocimeter (LDV) measurement and numerical analyses with volume of fluid approach coupled with a large eddy simulation turbulent model. Moreover, the general agreement of mean velocities between numerical and experimental results in self-similar region is good for

the flapping jet, and the decay of the mean velocity along the jet centerline is considerably faster than that of the stable impinging state. Zhao et al.<sup>[10]</sup> presented the detail flow field in numerical simulation, and pointed out that the frequency of longitudinal velocity oscillation at the jet centerline was twice of that of the transverse oscillation, and the mean centerline velocity decay was much faster than that of the stable impinging jet without flapping motion. Moreover, the magnitudes of flapping-induced velocities almost had the same order of that of the turbulent fluctuation, which implied that the flapping-induced components are as important as the turbulent fluctuation for flapping jet.

In addition to numerical simulation, Sun et al.<sup>[13]</sup> addressed the wall effect on Darcy's law by experimental measurement in Hele-Shaw cells. In order to study the effect of wall on the flapping pattern of a submerged turbulent water jet in narrow channels, the flow field was visualized by a laser-induced fluorescence (LIF) system at different Reynolds numbers<sup>[14]</sup>. Those LIF images showed that the flow motion in a narrow channel differs from the motion of a turbulent plane jet without narrow channels. Three flow patterns are detected in narrow channels, namely, stable impinging, stable jet with recirculation vortices and flapping turbulent jet.

In this paper, the flow field of submerged vertical turbulent jets in narrow channels is measured by a wave height gauge and LDV. Two main motives dominate the work of this paper is to verify whether flapping motion still exist for vertical turbulent jet under the effect of narrow channel, and whether the frequency of flapping will be the same as that of plane jet.

## 2 Experimental Set-up

The impingement and flapping motion of vertical 2D turbulent jet were observed with a narrow channel in a rectangular water tank, which is 6 m long, 0.4 m wide and 0.4 m high, as shown in Fig. 1. The slot of narrow channel, which is also considered as a Hele Shaw (H-S)

cell, made up of two glass plates, with the length of 1.8 m, the height of 0.4 m and the thickness of 5 mm. The turbulent jet is governed by a jet generator located in the middle of the tank. The jet generator has a convergent bell-shape orifice of 2 mm wide ( $d=2$  mm) and 10 mm or 6 mm long ( $b=10$  mm or 6 mm). Actually, for a 2D turbulent plane jet, the width of narrow channel is regarded as infinite, i. e.  $b = \infty$ . With the water depth of  $H=100$  mm, 200 mm and 260 mm, it obtains  $H/d=50$ , 100 and 130. The water is recirculated with a pump system, to maintain the water level at constant during measurement. At the ends of the tank, two absorbers are used to eliminate the reflection of surface waves.

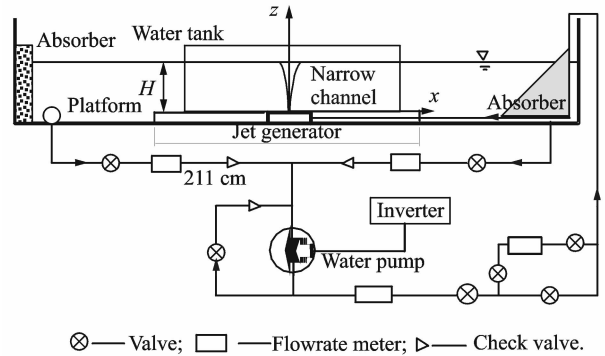


Fig. 1 Schematic diagram of experimental set-up

The velocity of turbulent jet is measured by a LDV system mounted on a 3D traverse. To increase the data rate of the LDV system, the flow field is seeded with titanium oxide ( $\text{TiO}_2$ ) particles of 1–5  $\mu\text{m}$  in diameter. To obtain the phase angle of flapping motion, the oscillation of the water surface deformation is measured by a capacitance wave height gauge and used as a reference. The signal of the capacitance gauge is recorded by a TSI IFA300 system.

## 3 Natural Flapping Frequencies

Fig. 2 shows the signals of surface deformation, which are gathered by the water height gauge, as well as the longitudinal and the lateral velocities obtained by the LDV located at the centerline of turbulent plane jet of  $z/H=0.56$ . The results of power spectrum densities (PSDs), as

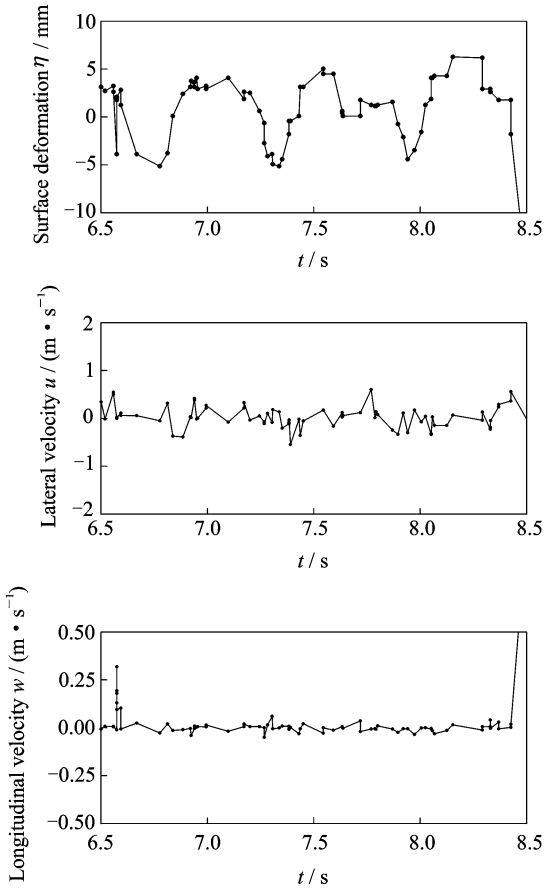


Fig. 2 Time variation of the surface displacement and jet centreline velocities measured by LDV located at  $z/H=0.56$  and  $W_0=5.16$  m/s

shown in Fig. 3, indicate that there indeed is a low frequency oscillation at the flapping frequency imbedded in the turbulent fluctuations. Figs. 3(a) and 3(b) show that the frequency of water surface deformation (SD) is the same as the frequency of lateral velocity measured by LDV at  $f=1.66$  Hz. Since it is the consequence of double passes of jet maximum velocity through the LDV measurement volume for each jet flapping cycle, the frequency of longitudinal velocity oscillation at the jet centreline is twice of the lateral oscillation<sup>[5,10]</sup>. Unfortunately, the power spectrum densities of longitudinal velocity in Fig. 3(c) cannot verify the above results clearly due to the poor random data in Fig. 2(c). However, it is evident that the double frequency phenomenon persists along the jet centreline by theoretical analyses and experimental measurement in turbulent flapping jets.

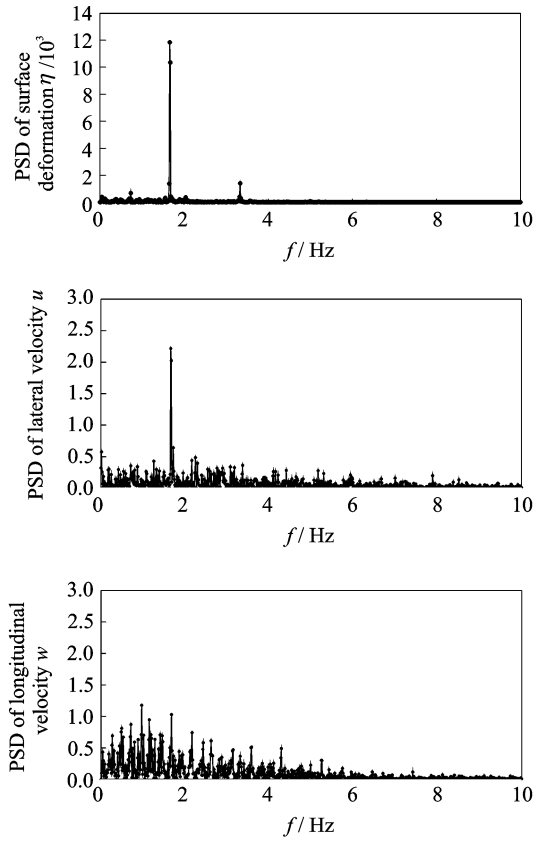


Fig. 3 PSDs of surface deformation, lateral velocity and longitudinal velocity when  $H=100$  mm,  $z/H=0.56$  and  $W_0=5.16$  m/s

#### 4 Analyses of Flapping Characteristics in Narrow Channels

Since the water surface cannot keep still with jet impingement and the height of water hump will be increasing with the increase of jet exit velocities, the water hump must be measured firstly in order to analyse the accrual natural flapping frequency in narrow channel. The profile of water hump is shown in Fig. 4, when the initial water depth (without jets) is  $H=100$  mm. Obviously, the height of hump will raise with the increase of jet exit velocities  $W_0$  when  $W_0 < W_{0c}$ . However, the height will decrease when  $W_{0c} > W_0$ , since the width of hump becomes large. In this section, the average height of hump when  $W_0$  approaches to  $W_{0c}$  will be regarded as  $\bar{\eta}_0$ , so do for the other cases of water depth from 50 mm to 220 mm. Here,  $\bar{\eta}_0$  is about 20 mm for  $H=100$  mm.

The self-excited flapping motion still exists in

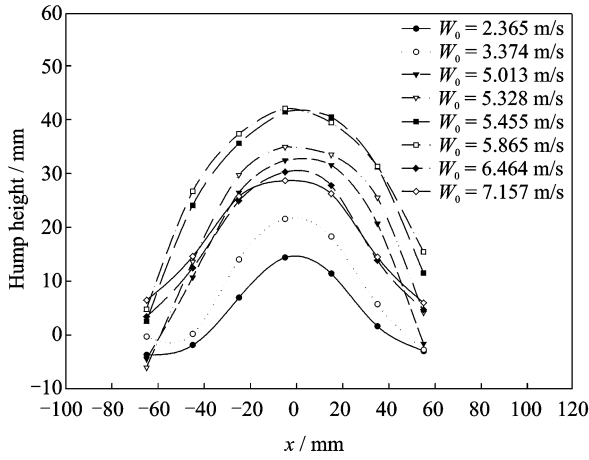


Fig. 4 Water surface humps in different jet exit velocities when  $H=100$  mm

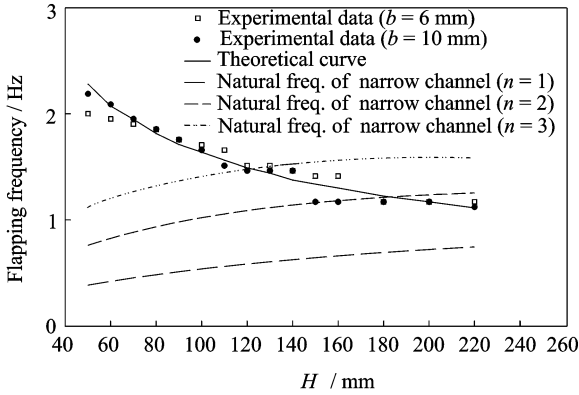


Fig. 5 Self-excited flapping frequencies with different effective water depths in narrow channels ( $b=6, 10$  mm)

narrow channels. Measurement results indicate that the natural flapping frequency is constant for a defined water depth, which does not change with the increase of  $W_0$ . It is the same as that of turbulent plane jets. Fig. 5 reflects the relation between flapping frequency  $f_0$  and effective water depth  $H_e$ . One can tell that the experimental data agree well with the theoretical curve<sup>[5]</sup>, as rewritten in Eq. (1).

$$f_0 = \frac{1.14}{2\pi} \sqrt{\frac{g}{H_e}} \quad (1)$$

where  $g$  is the gravitational acceleration,  $H_e = H - z_0 + \overline{\eta_0}$  the effective water depth.

Meanwhile, the frequencies of two different order steady waves are also illustrated in Fig. 6, which gives a clear explanation for those data departed from the theoretical curve. According to

the wave theory in shallow water, the disturbance or a wave with small amplitude in H-S cells or narrow channels will be reflected in the two ends of cells, with the behaviour of a series of standing waves. Considering that the jet is mounted on the centre of narrow channels, the wavelength and frequency can be indicated as

$$\lambda = \frac{2L_{1/2}}{n} = \frac{2(L/2)}{n} = \frac{L}{n} \quad n = 1, 2, 3, \dots \quad (2)$$

$$f = \sqrt{\frac{ng \tanh\left(\frac{2n\pi H}{L}\right)}{2\pi L}} \quad n = 1, 2, 3, \dots \quad (3)$$

where  $L$  is the length of a narrow channel. The disturbance with defined frequencies will excite the flapping motion as soon as possible when the disturbing frequency is approaching to the natural flapping frequency. From Fig. 6, it has no effect on the flapping frequency  $f_0$  when the disturbance frequency is much less than  $f_0$ . On the contrary, the effect is also very small when the disturbance frequency is so large that will decay very fast in narrow channels. Therefore, in present experiment, the effect of  $n=2$  is apparent, and the flapping frequency will lock-in the disturbing frequency when the disturbing frequency is near and less than the natural flapping frequency. That is similar to the effect of surface wave on the 2D turbulent plane jet<sup>[15]</sup>.

An experience equation is also used to indicate the flapping frequency in narrow channels, as shown in Fig. 6. It is obvious that, for these ca-

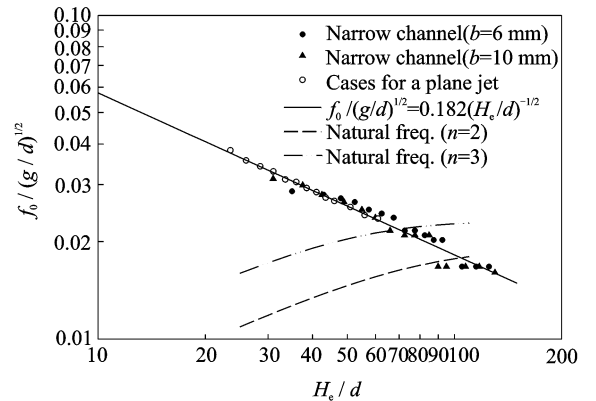


Fig. 6 Variation of flapping frequency with different effective water depths and jet orifice widths in H-S cells ( $b=6, 10$  mm)

ses with a small effect of reflected surface disturbance wave, the measured frequency at the inception of jet flapping motion for different effective water depths and jet orifice width is presented in terms of  $f_0/\sqrt{gd}$  and  $H_e/d$  for a turbulent plane jet, which can be rewritten as

$$f_0/\sqrt{gd} = 0.182(H_e/d)^{-1/2} \quad (4)$$

Actually, Eq. (4) takes a form of  $-1/2$  power, which is coincident with Eq. (1). However, it does not agree with Eq. (2) under the surface disturbing reflected wave, for instance,  $H_e/d > 70$  and  $H_e/d > 90$ . That indicates the frequency of flapping in narrow channels is the same as that of 2D turbulent plane jets.

Fig. 7 presents a curve of critical jet exit velocities in different effective water depths, where the width of narrow channel remains 10 mm. The critical velocities in narrow channels will shift more than that of a turbulent plane jet. Although the effect of surface disturbing water waves will make it out of good linearity when  $H_e/d > 70$ , the linearity is good when  $H_e/d < 70$ , which can be expressed by a fitting result

$$W_{oc}/\sqrt{gd} = 0.309(H_e/d) + 11.96 \quad (5)$$

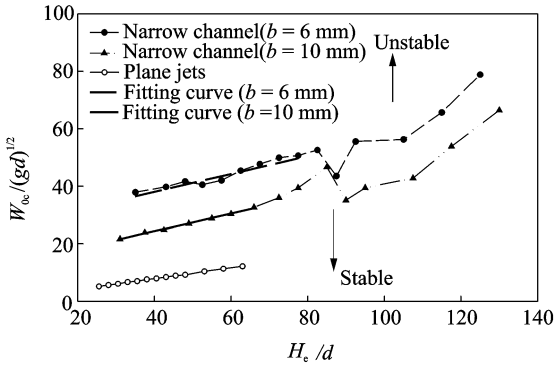


Fig. 7 Critical jet exit velocity which onsets jet flapping motion in narrow channels ( $b=6, 10$  mm)

Comparing with plane jet, the slope is larger in narrow channels. Therefore, the wall effect can keep the water hump more steady, and increase the critical jet exit velocity. However, under the effect of surface disturbance waves, the instability of water hump increases with the frequency of disturbing wave approaching to the natural flapping frequency.

## 5 Conclusions

The experimental study is carried out on the self-excited flapping motion of submerged vertical turbulent jet in narrow channels. At a fixed water depth, the turbulent jet in narrow channels is also observed to flap at a nearly constant frequency when the jet exit velocity is greater than a critical velocity, which proves that the flapping motion is a flow pattern of 2D turbulent jet either for submerged vertical plane jet or in narrow channels, even though the detail of flow field is not exactly same. It is found that the water depth  $H$  is a most important parameter to the critical jet exit velocity  $W_{oc}$  and jet flapping frequency  $f_0$ . The results indicate that  $W_{oc}$  increases with  $H$  and the jet flapping frequency  $f_0$  is then found to be inversely proportional to the water depth  $H$ . Meanwhile, theoretical analyses on experimental result show that the surface disturbance wave changes the frequency of flapping motion, i. e. the flapping frequency will lock-in the disturbing frequency when the disturbing frequency is near and less than the natural flapping frequency.

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