Active control of the jet in coaxial arrangement

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Abstract. An axisymmetric jet flow, issuing as a fully developed flow from a long straight pipe at $Re = 1600$ and 5500 , was actively controlled by an annular synthetic jet. The Pitot tube, hot-wire anemometry (CTA) and flow visualization were used for an experimental investigation of the flow control. The working fluid was air. The effect of varying Strouhal number ($St = (0.18 \div 1.94)$) on a width and entrainment of the main jet flow was studied. It was found that the main jet is the most sensitive to the actuation at $St = 0.28 \div 0.60$ and $St = 0.18$, for $Re = 1600$ and $Re = 5500$, respectively.

1 Introduction

Active flow control is one of the important and interesting parts of the fluid mechanics. Active control means that the main jet is suitably affected by means of the active excitation. This active excitation can be represented by another jet, so-called control jet. And it turns out that for many applications is very advantageous to use synthetic jet as the control jet.

Synthetic jet (SJ) is a fluid flow generated by an oscillating diaphragm (or piston etc.) in a cavity which is connected with ambient fluid by some orifice. The movement of the diaphragm caused periodical suction/extrusion of the fluid in/out of the cavity. The time-mean mass flux of the oscillatory flow in the orifice is zero but out of the orifice the train of the vortices creates a non-zero flow (see e.g. [1]).

Nature of the SJ, i.e. fluid flow which do not need any fluid supply because it is created (“synthesized”) from ambient fluid, is the reason why SJs have become so popular in an active flow control recently. SJs are usually used in application with heat transfer (e.g. [2, 3, 4, 5]), control of flows, wakes and boundary layer (e.g. [6, 7, 8, 9, 10]).

This work deals with main continual axisymmetric jet flow issuing as a fully developed jet from a long straight pipe which is controlled by an annular synthetic jet. The control flow is arranged concentrically around the main jet.

Similar topic was presented by Koso and Kinoshita [11] and Diep and Sigurdson [12]. The former work studied changes in width and distribution of velocities of the main jet, the latter one used the main jet as a model of a smoke stack which was placed in a cross stream of a wind tunnel.

2 Experimental setup

Figure 1 shows a scheme of the experiment. The main air flow passes through a pressure reducer, a control valve and a rotameter into a long pipe (pos. 1) of inner diameter and length $D = 10.05$ mm and $L = 750$ mm, respectively. The pipe is positioned vertically.

The synthetic jet actuator consists of a loudspeaker Monacor SP-7/4S (pos. 2) and a cylindrical cavity (pos. 3). Synthetic jet issues from annular orifice (pos. 4) of inner and outer diameter $D_i = 11.95$ mm and $D_o = 15.05$ mm, respectively. The loudspeaker was fed with sinusoidal current. The input power was kept constant at 2W.

The velocity was measured by means of hot-wire anemometry (MiniCTA 54T30 DANTEC with single-wire probe 55P16). The hot-wire anemometer operated in the Constant-Temperature mode (CTA). The minimal sampling frequency and number of samples were 7 kHz and $8192 \div 16384$, respectively. The anemometer was calibrated in the range $(0.21 \div 37.0)$ m·s⁻¹. The measurement was performed by DANTEC software, consequent data processing was performed by MATLAB software.

For some measurement the Pitot tube, connected to the electronic pressure gauge, was also used.

The visualization used a water fog. Water fog was produced by an ultrasonic piezoelectric generator (Mini Nebler) and it was fed into the pipe. Three kinds of light were used: continual light, stroboscope and photo flash light. So, three kinds of pictures of flow field were

Fig. 1. Scheme of the experimental apparatus – 1: long pipe, 2: loudspeaker, 3: cavity, 4: annular nozzle.

obtained: path lines, phase-locked streaklines and instantaneous streaklines. Pictures were taken by a digital camera Canon PowerShot G7 on-line operating by PC via USB.

2.1 Parameters of the experiments

Reynolds number Re for continual axisymmetric jet and Reynolds number for annular SJ Re_{SJ} are defined as follows:

$$Re = \frac{U_m D}{\nu}, \quad (1)$$

$$Re_{SJ} = \frac{U_0 D_{SJ}}{\nu}, \quad (2)$$

where ν is kinematic viscosity, U_m is mean velocity of continual jet in the pipe exit, $D_{SJ} = D_H = (D_o - D_i)$ is a hydraulic diameter of the annular nozzle and U_0 is time-mean orifice velocity of SJ, defined from the orifice velocity at the SJ orifice exit [1]:

$$U_0 = \frac{1}{T} \int_0^{T_E} u_0(t) dt, \quad (3)$$

where T_E is the extrusion time, $T = 1/f$ is the duration of one period and u_0 is the velocity at the orifice exit.

The topic of active control is closely connected with the existence of the large vortex structures in the turbulent flows. Natural frequency f_0 of coherent structures shedding is usual to use in dimensionless form per Strouhal number as:

$$St_0 = \frac{f_0 D}{U_m}. \quad (4)$$

Strouhal number for the present task of the periodic flow control is defined as:

$$St = \frac{fD}{U_m}. \quad (5)$$

According to Crow and Champagne [13] the turbulent jet is the most sensitive to the actuation at $St = 0.3$, i.e. at the “preferred mode”. The knowledge about the sensitivity of the turbulent jets to actuation were summarized e.g. by Thomas [14], according to him the preferred mode can be in wider range of the Strouhal numbers, $St = (0.25 \div 0.85)$.

The strength of the control SJs can be quantified by relating to the main annular jet in terms of the ratios of velocities, flow rates, and momentum rates as:

$$c_u = \frac{U_0}{U_m}, \quad (6)$$

$$c_q = \frac{U_0 (D_o^2 - D_i^2)}{U_m D^2}, \quad (7)$$

$$c_m = \frac{\rho \left(\frac{\pi^2}{4} \right) \left(\frac{\pi D_{SJ}^2}{4} \right) U_0^2}{M_0}, \quad (8)$$

where ρ is the density and M_0 is the momentum flux at the pipe exit (for laminar flow is obtained by integration of the ideal parabolic profile $u/u_{\max} = 1 - (2r/D)^2$, for turbulent flow is obtained by integration of an ideal profile $u/u_{\max} = (1 - 2r/D)^{1/7}$).

The summary of the present experiments is shown in Table 1 and Table 2. The main jet was operated in two regimes with corresponding nominal Reynolds numbers 1600 and 5500. More details about used SJ can be found in [15, 16].

Table 1. Parameters of experiments, $Re = 1600$.

no.	U_m [m·s ⁻¹]	f [Hz]	U_0 [m·s ⁻¹]	Re_{SJ}	St	c_u	c_q	c_m
1	2.5	70	3.66	725	0.28	1.5	1.2	3.3
2	2.5	150	6.98	1407	0.60	2.8	2.3	11.9
3	2.5	185	5.65	1143	0.74	2.2	1.9	7.7
4	2.5	230	3.92	767	0.93	1.6	1.3	3.8
5	2.6	500	5.84	1175	1.94	2.3	1.9	7.8

Table 2. Parameters of experiments, $Re = 5500$.

no.	U_m	f	U_0	Re_{SJ}	St	c_u	c_q	c_m
	[m·s ⁻¹]	[Hz]	[m·s ⁻¹]					
6	8.5	150	6.98	1407	0.18	0.8	0.7	1.4
7	8.5	230	3.92	767	0.27	0.5	0.4	0.4
8	8.6	475	4.91	984	0.55	0.6	0.5	0.7
9	8.6	550	5.41	1084	0.64	0.6	0.5	0.8

3 Results

Figure 2 shows visualization of the jet, $Re = 1600$, without control. In Figure 2a photograph was taken with continual light, in Figure 2b with flash light. It can be seen that the jet is initially laminar, in some distance from the pipe exit the jet column become sinuous (namely, this shape is 3D helical curve) and after that the turbulent transition is done (similar to [13]). The natural frequency of the jet was identified by means of the stroboscope light, $f_0 = 100.7$ Hz ($St_0 = 0.4$).

Fig. 2. Visualization of the jet with $Re = 1600$ without control,
(a) continual light, (b) flash light.

Figure 3 shows visualization of the jet, $Re = 1600$, with control. The frequency of the control jet is $f = 70$ Hz (i.e. $St = 0.28$, number 1 from Table 1). A continual light, a flash light and a stroboscope light were used. The visualization shows that the control flow causes the (nearly) immediate transition to turbulence and consequently the widening of the main jet. The widening is the most appreciable from the distance $y/D = 2$, this distance corresponds to the position of the point of reattachment of the solo-standing annular SJ (see [16] for more details). It means that the control jet fully joins the main jet in this distance. Moreover the phase-locked visualization shows that the jet has not ideal symmetry, and it indicates that the jet probably tends towards the nonsymmetrical mode.

Fig. 3. Visualization of the jet with $Re = 1600$ with control,
 $f = 70$ Hz (no. 1 from Table 1),
(a) continual light, (b) flash light, (c) stroboscope light.

Fig. 4. Visualization of the jet with $Re = 5500$ without control,
(a) continual light, (b) flash light.

Figure 4 shows the visualization of the jet, $Re = 5500$, without control and Figure 5 shows the same jet with control. The frequency of the control jet is $f = 150$ Hz (i.e. $St = 0.18$, number 6 from Table 2). The main jet is turbulent from the beginning here. In spite of this, the control jet also causes the growth of the width of the main jet. And again, the considerable widening can be seen approximately from the distance $y/D = 2$, as was described above.

Figure 6 shows the velocity along the axis of the main jet without and with control. The jet without control behaves typically – the velocity is initially approximately constant, i.e. U_m (potential core), and after that the progressive decrease begins (for comparison, the slope typical for turbulent jets, $u \sim y^{-1}$, is also drawn, see Blevins [17]). On the other hand, the curve of the velocity of the main jet with control is different – the velocity after pipe

exit drops and after that increases again. The maximum in the curve can be seen approximately at $y/D = 4$. The reason of this nonmonotonic and unusual behaviour can be following: In the initial region the control jet causes the shortening of the potential core and consequently the control jet fully joins the main jet and causes the growth of the velocity (as was seen and described in Figure 3 and 5). This behaviour is obvious for the jet with $Re = 1600$, less for $Re = 5500$. Note the jet with $Re = 5500$ controlled with frequency $f = 150$ Hz (number 6, Table 2) whose behaviour is slightly different, nearly without the mentioned nonmonotonic behaviour – see Figure 6(b).

Fig. 5. Visualization of the jet with $Re = 5500$ with control, $f = 150$ Hz (no. 6 from Table 2), (a) continual light, (b) flash light, (c) stroboscope light.

Fig. 6. Velocity along the axis of the main jet without and with control, (a) $Re = 1600$, (b) $Re = 5500$.

Figure 7 shows a comparison of velocities along the axis and visualizations of the solo-standing control jet, solo-standing main jet and the main jet actively controlled ($Re = 1600$, $f = 70$ Hz). It can be seen that the distance of the widening of the main jet agrees with the maximum of velocity on the axis of the SJ and also on the axis of the main jet which is actively controlled.

Fig. 7. Comparison of velocities along axis and visualizations, $Re = 1600$, $f = 70$ Hz, (a) control jet, (b) main jet without control, (c) main jet with control.

Figure 8 shows the half-width of the jet without and with control. For comparison the curve according to Blevins [17] for turbulent flows is also shown. It is obvious that for $Re = 1600$ the every used control jet caused the growth of the half-width (laminar flow becomes turbulent). The most extensive growth can be identified for SJ with $f = 70$ Hz (i.e. $St = 0.28$, number 1

from Table 1). On the other hand, for $Re = 5500$ the growth of the half-width is not very significant, except the control with SJ with $f = 150$ Hz (i.e. $St = 0.18$, number 6 from Table 2).

Fig. 8. Half-width of the main jet without and with control, (a) $Re = 1600$, (b) $Re = 5500$.

Fig. 9. Volume flow rate of the main jet without and with control, (a) $Re = 1600$, (b) $Re = 5500$.

Figure 9 shows the volume flow rate of the main jet without and with control. Q_0 is the volume flow rate at the pipe exit. Again for comparison the curve according to Blevins [17] for turbulent flows is also shown. For the jet with $Re = 1600$ the control jets cause always the increase of the volume flow rate. The most extensive growth can be seen for control jet with $f = 150$ Hz (i.e. $St = 0.60$, number 2 from Table 1). For the jet with $Re = 5500$ the growth of the volume flow rate is appreciable mainly closer to pipe exit. The main jet controlled with frequency $f = 150$ Hz (i.e. $St = 0.18$, number 6 from Table 2) is again exceptional.

Fig. 10. Power spectrum density, $Re = 1600$, $y/D = 6.2$, $r = 0$, (a) without control, (b) with control, $f = 70$ Hz..

Figure 10 shows the power spectral density (PSD) of the main jet, $Re = 1600$, without and with control. PSD was obtained on the basis of CTA measurement on the jet axis at the distance $y/D = 6.2$. It can be seen that the jet without control has dominant frequency in spectrum, it is approximately 100 Hz, it agrees very well with the frequency obtained by means of stroboscope light ($f_0 = 100.7$ Hz, $St_0 = 0.4$) - see Figure 10(a). For the jet with control (Figure 10(b), the control frequency is $f = 70$ Hz, i.e. $St = 0.28$, number 1 from Table 1), the values of PSD increase and the spectrum has the slope typical for turbulent jets (see e.g. [18]). Obviously, the dominant frequency in the spectrum is the frequency of the control flow, 70 Hz.

4 Conclusions

The active control of the main continual axisymmetric jet by means of the concentrically placed annular synthetic jet were performed experimentally and presented.

Experiments shown that the main jet with $Re = 1600$ (i.e. jet initially laminar) was the most sensitive to the actuation at $St = 0.28 \pm 0.60$ and the actuation at all used Strouhal numbers caused the nearly immediate transition to turbulence and consequently the growth of the half-width and the entrainment of the main jet.

For the jet with $Re = 5500$ all actuations caused the growth of the half-width and the entrainment of the main jet but the jet was initially turbulent and the changes were not as extensive as for the jet with $Re = 1600$. It was shown that the main jet was very sensitive to the actuation at $St = 0.18$, this actuation caused also the change towards nonsymmetrical mode of the jet.

The results agree quite well with expected preferred modes known from literature. Moreover the lower limit ($St = 0.18$) has been found to be lower than commonly referred values.

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