Control of flow separation over a circular cylinder using synthetic jet

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Abstract. The development of methods of active separation flow control is of great applied importance for many technical and engineering applications. Understanding the conditions for the flow separation from the surface of a bluff body is essential for the design of aircrafts, cars, hydro and gas turbines, bridges and buildings. Drag, acoustic noise, vibrations and active flow mixing depend drastically on the parameters of the vortex separation process. We investigated the possibility of reducing the longitudinal length of a reverse-flow region using the method of «synthetic jet» active separation flow control. The experiment was carried out on a compact straight-through wind channel with a 1-m long test section of a cross-section of 125x125 mm. The jet was placed at the rear stagnation point of a circular cylinder. The Reynolds number, based on the cylinder diameter and the free-stream velocity, was 5000 and the von Kármán street shedding frequency without the synthetic jet was equal to 64.8 Hz. For the first time, for such a set of parameters, we applied high speed PIV to demonstrate that the injection of the synthetic jet into the cylinder wake region leads to a significant reduction in the longitudinal length of the reverse-flow region.

1. Introduction

The subject of separation flow control is of great importance in various engineering applications. For many decades, due to its importance, the ability to control the flow to achieve the desired effect, actively or passively, has been most actively studied by scientists and engineers in comparison with any other direction in fluid and gas mechanics. The potential benefits of implementing efficient flow control systems range from billions of dollars in annual fuel costs savings for land, air and marine vehicles to more economically and environmentally effective devices and processes associated with fluid flows in one way or another.

In the literature, methods of control are divided into three groups: passive, active closed-loop and active open-loop methods [1]. Active flow control techniques include application of steady or unsteady energy input with or without regard to the particular state of the external flow [2]: namely a closed-loop and an open-loop device, respectively. The main idea behind the unsteady active flow control concept is that the flow can be sensitive to some specific, well-chosen perturbations. Such unsteady perturbations may be more effective way of flow control than steady continuous actuations.

Active flow control is more flexible and can be easily adapted for any operating condition than passive. The «synthetic jet» is an example of an active flow control method. In this case, the material of the main-stream flow forms a jet that introduces perturbations that allow the flow control. This method is usually preferred over steady or pulsated actuations because it leads to the same performance improvement but requires a much lower momentum coefficient, which can be up to two
orders of magnitude smaller [3]. This improvement is based on the actuation frequency of synthetic jets that can be chosen based on the fundamental frequencies of the system.

2. Experimental setup
The experiment was conducted on the straight-through wind tunnel. The working part of the experimental setup circuit consists of a honeycomb, a confuser and horizontal transparent working section made of plexiglass.

A PIV system consisting of a BNC 575 synchronization unit and a high-speed Photron Nova S12 camera (1024×1024 pixels) with a long-distance microscope lens Infinity K2 was used to study the characteristics of the near wake. The laser sheet was created using a Photonics solid-state pulse Nd: YAG laser (wavelength of 532 nm, pulse energy of 8 mJ, pulse duration of 150 ns, and pulse repetition rate of 8 kHz).

The working part of the experimental setup is a transparent pipe with a rectangular cross-section of 125×125 mm² and a length of 1000 mm (figure 1). In the central part of the working area, a mount is provided for installing the cylinder with synthetic jet actuator (figure 1). The synthetic jet actuator is obtained by coupling a hollow cylinder with a helmholtz resonator. The helmholtz resonator consists of adjustable volume and a loudspeaker (Pioneer TS-G1330F). The hollow cylinder is centered on the 125 mm side of the wind tunnel test section. The cylinder is placed on a rotation mount, which allows adjusting the angle of the synthetic jet relative to external flow. The hollow cylinder inner and outer diameters are 12 and 15 mm, respectively. In the present experiments, the Reynolds number Re and the shedding frequency f₁ (based on a Strouhal number, for St = 0.21) are 5000 and 64.8 Hz, respectively. In the framework of this work, 32, 64, 128 Hz actuation frequencies are chosen, based on shedding frequency. A slot for synthetic jet actuations is placed on the cylinder surface with width h = 1 mm and length l = 100 mm. A sinusoidal oscillation of the loudspeaker is produced by an electrical sinusoidal signal, generated using GW-Instek SFG-2004 signal generator coupled with a power amplifier.

![Figure 1](image.png)

**Figure 1.** Left – image of the cylinder with helmholtz resonator. Right - scheme of experimental setup: 1 – incoming flow; 2 – mirror; 3 – measuring area; 4 – camera; 5 – mirror; 6 – laser. White dots are tracers.

The cylinder is streamlined by an air flow with a constant flow rate. To implement the PIV method, monodisperse suspended liquid glycerin particles – tracers with a diameter of 5 microns – are used (figure 2).
3. Results

First, the uncontrolled baseline case was analyzed. Then, controlled cases with different actuation frequencies were analyzed to understand the effect of selected parameters of synthetic jet on the vortex separation process. Finally, the effectiveness of the flow control method was substantiated.

Baseline case is reported in figure (3, a). One can see a view of the reverse-flow region behind a circular cylinder without implementation of a synthetic jet. The end of the reverse-flow region is placed far behind the edge of the measuring area. Figure (3, b, c, d) represents cases with 32, 64 and 128 Hz actuation frequencies, respectively. The smallest length of the reverse-flow region is recorded for the case with a synthetic jet generation frequency equal to the natural frequency of vortex stripping $f_s$ and amounts to 0.52D. For the cases of actuation frequencies of 0.49 and 1.97, the longitudinal size of the separation region is 0.61D and $>1.3$D, respectively. The length of the reverse-flow region for each case is shown in table 1.

Table 1. The length of the recirculation zone for the studied cylinders in relative coordinates $x/D$.

| $f_a/f_s$ | length of reverse flow region l/D |
|----------|----------------------------------|
| 0        | $>1.3$                           |
| 0.49     | 0.61                             |
| 0.99     | 0.52                             |
| 1.97     | $>1.3$                           |

Figure 2. Left – image of the flow with glycerin particles. Right - instantaneous flowfield.
Figure 3. The average field of the longitudinal velocity component $V_x$ relative to the velocity of the incoming flow $U$ for the baseline case (a) and actuation frequency $f_a = 32$ (b), 64 (c), 128 (d) Hz.

According to [4], the size of the separation zone can be used to estimate the drag of the bluff bodies relative to each other. A synthetic jet with an actuation frequency close to the natural frequency of vortex stripping from a cylinder of a given diameter has the greatest influence on the size of the reverse-flow region.

4. Conclusion
For the first time, for such a set of parameters, we applied high speed PIV to demonstrate that the injection of the synthetic jet into the cylinder wake region leads to a significant reduction in the longitudinal length of the reverse-flow region. This study demonstrates the effect of the synthetic jet on the von Kármán street vortex shedding, being injected in the cylinder wake region, for a Reynolds number of 5000. In this configuration, the most significant effect was registered for actuation frequency close to the shedding frequency $f_s$ (for a $St = 0.21$) 64.8 Hz. We could achieve a reduction in the length of the reverse-flow region up to 0.52D.

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