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Modification of the Wake behind a Circular Cylinder by Using Synthetic Jets

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***Abstract*:** Experimental tests were conducted to control the flow around a cylinder by means of unsteady blowing (synthetic jet) through a single slot disposed on the wall of the model. The flow Reynolds number (based on the diameter of the model) was $R_D = 10^5$. The efficiency of the synthetic jet is quantified in terms of delaying separation and modifying the drag coefficient. The investigations were of three types: measurements of the mean pressure distribution, wall visualizations of the separation line position and measurements of the mean flow-field in the wake.

***Keywords*:** cylinder, separation, actuator, synthetic jet, flow control.

1. Introduction

Among the many possibilities for controlling the wake behind bluff bodies, various methods have been employed in the past. The following works concern mechanical, acoustical, oscillating and pneumatic investigations around cylinders models (except for some of them, which are relative to generic forebody shapes, flat plate or airfoils) in order to manipulate the flow in a large range of Reynolds numbers.

Zdravkovitch (1989) has classified mechanical means for suppressing vortex shedding surface protrusions (helical strakes, wires, fins, studs or spheres), shrouds (perforated, gauze, axial rods, axial-slats) and near-wake stabilisers (splitter plates, guiding vanes, base-bleed, slots cut across the cylinder).

Blevins (1985) has employed external acoustical procedure by disposing two loudspeakers on the wall of the wind-tunnel section: in such experiments, it was demonstrated that the frequency of vortex shedding could be shifted by sound, either above or below the nominal vortex shedding frequency. Huang (1996) has disturbed acoustically the flow through a slot disposed along the axis of the cylinder, at variable angle positions in azimuth q from the upstream stagnation line. He has proved the ability of suppressing the natural predominant frequency of the wake in the q range [60°, 100°], with only a weak feedback sound (typically 1% of the dynamic pressure). Similar experiments (internal acoustical procedures) conducted by Béra et al. (2000) have lead to the conclusion that the flow around the cylinder can be strongly modified and the separation line delayed by the effects of pulsed jets.

Excitation of separated shear layers by transmitting oscillations to the cylinder is an effective method for controlling the development of Karman vortices in the near wake, both for steady-state and transient perturbations. Unal and Rockwell (1988) have studied the characteristics of the unsteady shear layer within the context of an absolute instability of the near wake. Ongoren and Rockwell (1988) have tested a cylinder subjected to forced oscillations at various angles of incidence with respect to free-stream velocity, leading to both symmetrical and anti-symmetrical modes of vortex formation. Contrary to these authors who excited the cylinder at frequencies f_e slightly above and below the inherent Karman frequency f_0 ($0.5 < f_e/f_0 < 4$), Chyu and Rockwell (1966) have realised with success similar flow control experiments at a frequency corresponding to the inherent instability frequency of the separating shear layer or its sub-harmonics: for example, under adequate conditions concerning the excitation, the formation length of the Karman vortices can be dramatically shortened.

Blowing or suction techniques have been employed for a long time around various other bodies: the wake behind a two-dimensional bluff body (which is not exactly a cylinder but a simple airfoil with truncated trailing edge) has been investigated using base bleed technique by Wood (1964, 1967). The corresponding experiment confirms that small base bleed flows displace the formation region of the vortex street from the body, although the spacing and frequency are virtually unchanged. Over several years, we have personally (Tensi and Paillé, 1998) developed experimental campaigns of steady or unsteady blowing to quantify the effects on the modification of the near-wake behind a cylinder. The technique was a pneumatic one, through a slot or a range of small holes drilled along the axis of the model: the efficiency of both steady and synthetic jets was quantified in terms of reduction of dead zone length (Karman street regime). Steady blowing effect, tangentially to the cylinder model through a slot has been investigated by Waka et al. (1985) and illustrates the modification of the flow for various positions and shapes of the injector. The recent development of synthetic or pulsed jets (Amitay et al., 1997; Williams et al., 1992) on cylinder models has proved that such a new technique is a very efficient way to manipulate the flow. These types of unsteady pneumatic actuators have the characteristics of being possibly miniaturized, they do not produce any average mass addition to the near wake and they require very little energy. Lin et al. (1995) have used simultaneous applications of steady blowing and unsteady blowing-suction (through a helical pattern of small holes about the surface of a cylinder) and prescribed oscillations of the model in the cross stream direction, which produced a dramatic effect on the near-wake structure. The characteristics of unsteady actuators are of great interest and explain that the pulsed jets and synthetic jets have also been tested with success on various types of other models. For example, a pulsed jet has been implanted on a two-element flat plate model by McManus et al. (1995): the wind tunnel experimental results illustrate the efficiency of the actuators in inhibiting separation and delaying stall. Roos et al. (1993, 1996, 1997) have tested microblowing on a fighter aircraft. Very small flush ports, implanted at the nose of a blunted hemisphere-cylinder forebody, delivered a pulsed jet which controlled the flow and could produce a steady change in flow asymmetry. An interesting review of various blowing control experiments on airfoils has been realised by Wygnanski (1997). The influence of the main parameters affecting flow reattachment and delaying separation has been examined. It was concluded that the efficiency of periodic addition of momentum (unsteady blowing) is significant: typically, the momentum coefficients levels were some two orders of magnitude lower than those considered using steady blowing. Seifert et al. (1993) have investigated oscillatory blowing on the trailing edge of an airfoil, the effect of which was an important increase in lift. Smith et al. (1998) have realised experiments on an airfoil with circular cylinder leading edge equipped with synthetic jets and the conclusion was that there are transition effects from separated to reattached flow on the airfoil.

Our own contribution concerns the understanding of blowing effects on the flow around a cylinder. The first investigation phase (Tensi and Paillé, 1998) has consisted in testing the response of the model to steady and unsteady local blowing and blowing-suction, through small holes or slot parallel to the axis, for a very moderate Reynolds number $R_D = 330$. The present work extends the research to a higher Reynolds number: $R_D = 100000$. It contributes to a better understanding of the physics relative to the flow around the cylinder under synthetic jet action through a single slot. The experimental tests associate wall visualization technique (to localize the separation line), measurements of the wall mean pressure distribution at mid-span (to obtain, by integrating the results, the drag and lift local mean coefficients) and velocity measurements in a plane normal to the model (to explore the wake and to quantify the modification of the recirculating zone just downstream the cylinder). The blowing control effects were quantified for various blowing momentum coefficients.

2. Experimental Apparatus

The experiments were conducted in a low-speed closed wind tunnel of a square test section measuring 0.5 m on the side and 0.75 m on the length (Fig. 1). The dimensions of the tested cylinder model are mentioned in Fig. 2 (diameter $D = 50$ mm, span $L = 500$ mm) and the free-stream velocity was fixed at $V_\infty = 30$ m/s (corresponding Reynolds number based on the diameter R_D: 10^5), leading to a laminar wake configuration.

In order to separate blowing and transitional effects, the flow was artificially modified by means of rough strips disposed on the wall of the model, parallel to the axis, at the two positions in azimuth $q_T = \pm 30^\circ$ from the front stagnation line. Such conditions lead to the turbulent separation of the wake at $q_S \approx \pm 95^\circ$ (instead of 80° without rough strips, as characterised by wall visualization).

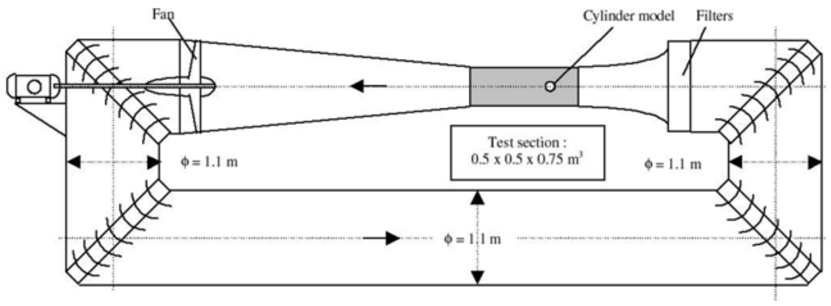

Fig. 1. The low speed wind tunnel: length 10 m, height 3.2 m, V_∞ = 30 m/s.

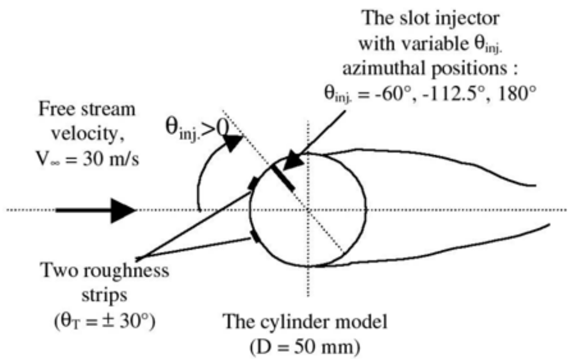

Fig. 2. The basic flow configuration.

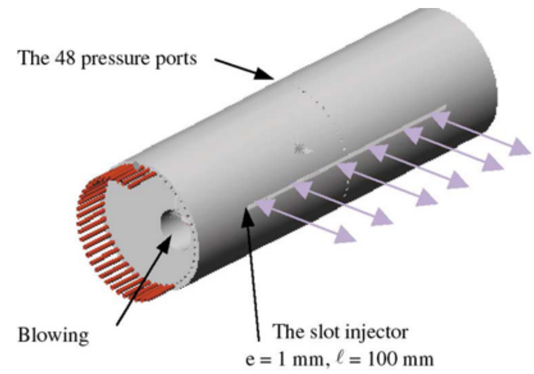

Fig. 3. The cylinder model: *D* = 50 mm, *L* = 500 mm.

The model was equipped with a thin slot injector (Fig. 2 and Fig. 3) positioned at the successive positions $q_{inj.} = -60^\circ, -112.5^\circ$ and 180°. This injector (width e = 1 mm, length l = 100 mm) was disposed at the mid span of the model parallel to the axis. In order to measure the wall pressure distribution, 48 pressure ports were equally spaced around the cylinder at mid span, every $dq = 7.5^\circ$.

An original actuator type (Fig. 4) was used to produce a synthetic jet, by exciting a cavity with an alternative piston system. The frequency could vary up to 120 Hz, corresponding to a Strouhal number maximum value of 0.2. Preliminary measurements were realised using a hot wire probe to quantify the blowing velocity signal at the edge of the slot (slightly into the injector). The two alternative phases (A) blowing phase and (B) suction phase of the actuator signal are represented in Fig. 5, for the frequency f_e = 60 Hz. Due to the insensitivity of the hot wire to the flow direction, the sign of the velocity must be reversed in the case of suction phase. The corresponding maximum value of the velocity is about 30 m/s, and its RMS value is 16 m/s. It can be noted that the maximum signal is slightly smaller in the case of suction phase.

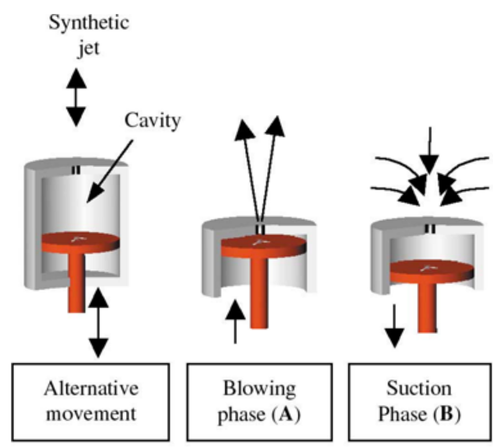

Fig. 4. Principle of the actuator.

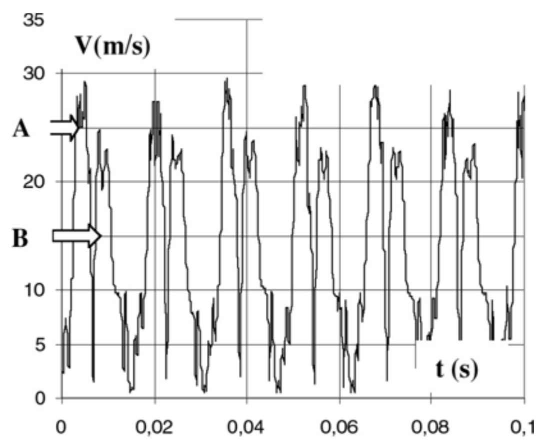

Fig. 5. Typical synthetic blowing signal.

2.1 Steady and Unsteady Blowing Momentum Coefficients

The adequate momentum coefficient used to quantify the blowing rate was defined as follows

$$C_\mu = \frac{Q_m \times V_{\text{inj.}}}{\frac{1}{2} \times \rho \times V_\infty^2 \times S_R}$$

where Q_m is the blowing mass flow-rate, $V_{\text{inj.}}$ the blowing velocity, ρ the air density, V_∞ the flow velocity and S_R a surface of reference (here, the frontal surface of the cylinder, i. e. $\lambda \times D$). Because the mass blowing flow-rate can be expressed as

$$Q_m = \rho \times S_{\text{inj.}} \times V_{\text{inj.}}$$

where $S_{\text{inj.}}$ is the surface of the slot (i. e. $\lambda \times e$), then, the expression of C_μ becomes

$$C_\mu = 2 \times \frac{e}{D} \times \left(\frac{V_{\text{inj.}}}{V_\infty} \right)^2$$

In the case of unsteady blowing (C_μ is then noted C_μ^*), the steady blowing velocity $V_{\text{inj.}}$ is replaced by its root mean square value $V_{\text{inj.}}^*$.

2.2 Mean Wall Pressures and Local Drag and Lift Coefficients

The 48 ports, disposed on the wall of the model at mid-span, deliver simultaneously the mean wall pressures $P_{\theta i}$. At every position θ_i, the corresponding non-dimensional mean pressure coefficient K_{Pi} is defined as

$$K_{Pi} = \frac{P_{\theta i} - P_\infty}{\frac{1}{2} \times \rho \times V_\infty^2}$$

where P_∞ is the mean static pressure upstream the cylinder.

The local drag and lift mean coefficients at mid-span (C_X and C_Z respectively) were obtained by integrating the mean pressure K_p distribution around the cylinder:

$$C_X = \frac{1}{2} \times \sum_{i=1}^{48} K_{pi} \times d\theta_i \times \cos\theta_i, \quad C_Z = \frac{1}{2} \times \sum_{i=1}^{48} K_{pi} \times d\theta_i \times \sin\theta_i$$

2.3 Velocity Field Measurements

The average velocity field was obtained by using PIV (Particle Image Velocimetry) technique in a plane normal to the cylinder, at mid-span. The flow was seeded with smoke produced by an aerosol generator. The size of the particles was 0.3 μm in diameter. The technique was based on two coupled YAG laser sources, the power of which was 2 × 160 mj. The light scattered by the particle was recorded with a 768 × 576 pixel CCD camera. The window size was limited to 150 × 100 mm^2, and the corresponding spatial resolution was about 3 × 3 mm^2. The settled time delay between two pulses was 50 μs, and the repetition frequency of the laser pulse was 10 Hz. The cross correlation image analysis method was employed and the results were obtained by averaging 150 instantaneous flow-field.

2.4 Wall Visualization

Some additional wall velocity visualizations were carried out to characterize the displacement of the separation line. The mixture employed was composed of linseed oil and yellow painting pigments. The photographs were recorded with a line of sight normal to the flow.

2.5 Tests Procedure

Successively, steady and unsteady blowing were injected to carry out many measurements. The present study only deals with the results on the modification of the flow under synthetic jets action. The experiments were conducted for various blowing parameter values:

- position in azimuth of the injector $\theta_{\text{inj.}}$,
- frequency of the synthetic jet f_e,
- blowing momentum coefficient C_μ^*.

Due to the technology of the actuator employed for the tests, the excitation frequency f_e and the blowing velocity $V_{\text{inj.}}$ are dependent: for progressive blowing rates, f_e and $V_{\text{inj.}}$ increase together.

The investigations were carried out by comparing the wall pressure distributions $K_P(q)$, the results of flow-field measurements and the identification (by visualization) of the position q_S of the boundary layer separation line on the cylinder.

3. Results and Analysis

As a first preliminary result, Figure 6 shows the modification of the mean pressure distribution when provoking the boundary layer transition with strips. During this test, the slot injector was positioned at $q_S = 180^\circ$, and there was no blowing. The position of the separation line is delayed (displacement measured from previous wall visualizations: q_S is increased from $q_S = 80^\circ$ to $q_S \approx 95^\circ$ when forcing the transition) and the K_P value in the separated region was slightly increased. The corresponding drag coefficient was also reduced by 28% (from $C_X = 1.28$ to $C_X = 0.92$). It should be noted that the C_X value reached by forcing transition with strips differs from the one obtained when provoking transition by increasing the flow Reynolds number above the critical number (in such a case, C_X reaches a minimum value of 0.3).

The following results concern unsteady blowing effects at a fixed slot position $q_S = -112.5^\circ$ (247.5° in the figures) of the injector. The effects of synthetic jets on the pressure distribution, at various frequencies and blowing intensities is reported in Fig. 7. It is noteworthy to observe that the position of the injector has a significant influence on the initial curve $K_P(q)$ without blowing, and consequently on the drag coefficient C_X. For this slot position, the value of C_X was 0.70 (which can be compared to the value of 0.92 when $q_S = 180^\circ$). The evolution of $K_P(q)$ as a function of C_m^* (the frequency f_e and the blowing RMS velocity $V_{inj.}^*$ being progressively increased) is remarkable and affects a q range from -45° (315°) to -210° (150°). The corresponding values of C_X increase with C_m^*. The most important modification of K_P was obtained for the highest blowing coefficient $C_m^* = 0.032$ ($f_e = 120$ Hz) and denotes an important delaying of the boundary layer separation line. It will be noted that the excitation frequency f_e of the test is approximately the natural flow frequency f_0, based on the Strouhal number $S_0 = f_0 D / V_\infty = 0.2$.

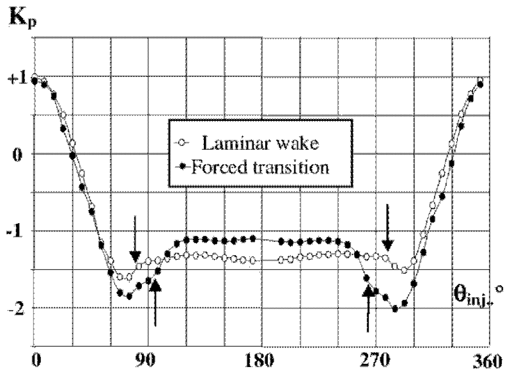

Fig. 6. Modification of wall pressures by forcing transition.

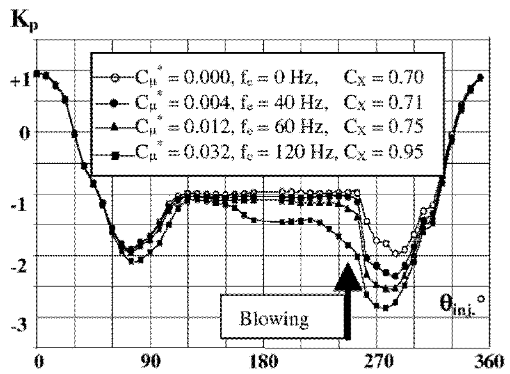

Fig. 7. Modification of wall pressure distribution under blowing action.

For the lower blowing rates, neither the level of mean pressure in the separated region nor the position of the separation are greatly affected by blowing. Nevertheless, the curves relatively change in the upstream of slot position ($q_S < -112.5^\circ$): the K_P optimum value reaches -2.0 without blowing, and -2.4 and -2.6 for $C_m^* = 0.004$ and 0.012 respectively. On the contrary, the variation is noteworthy for the highest value of C_m^* (0.032), as well upstream and downstream from the slot, likely because of the proximity of the excitation frequency to the natural typical frequency of the wake ($f_0 = 120$ Hz).

This effect is more visible on the photographs of Fig. 8, issued from wall visualization experiments : it is clearly observed, for the higher blowing momentum coefficients (and $f_e \approx f_0$), that the separation line was displaced from $q_S = -95^\circ$ to -135° at mid span (mid-slot).

The results of average flow-field velocities, obtained from PIV technique, confirm, at high C_m^*, the great modification of the flow and particularly of the near-wake. Figure 9 illustrates, for the extreme case of blowing rate ($C_m^* = 0.032$, $f_e = 120$ Hz), both the displacement of the separation line and the reduction of the dead zone behind the cylinder, which was reduced from one diameter length to approximately half a diameter.

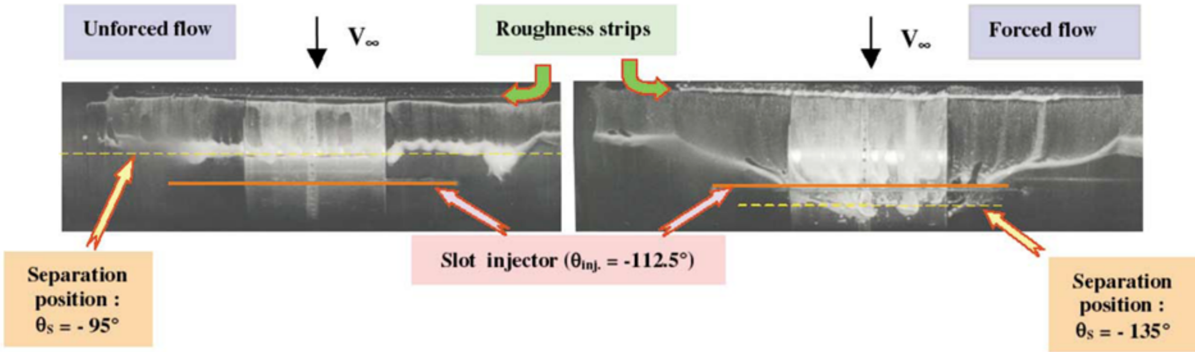

Fig. 8. Observation of delayed separation line under synthetic jet action V_∞ = 30 m/s, (q_{inj} = –112.5°), f_e = 120 Hz, C_m^* = 0.032, $V_{inj\ RMS}$ = 27 m/s.

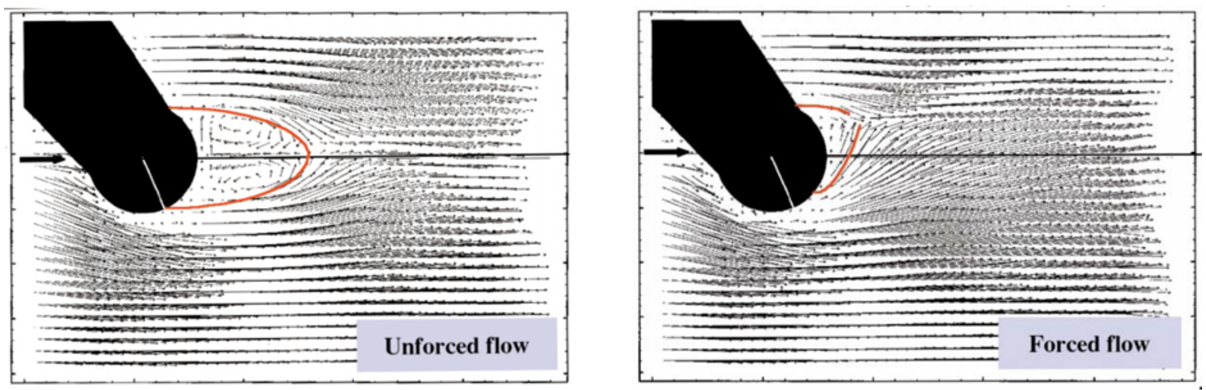

Fig. 9. Effect of synthetic jet on the near wake: V_∞ = 30 m/s, q_{inj} = –112.5°, C_m^* = 0.032.

4. Conclusions

The experiments conducted with a simple unsteady blowing slot injector prove the efficiency of such a flow control technique around a cylinder. Previous results using a similar slot for flow of small Reynolds number had shown that steady blowing was also an adequate means for controlling the flow, provided it is applied on the rear part of the cylinder in the separated region. The peculiarity of this steady manipulation is to require a great blowing momentum coefficient (typically C_m of the order of 1 or more) which needs high blowing velocities and consequently high additional mass flux introduced in the flow. On the contrary, unsteady blowing effects, using synthetic jets (which do not produce any additional average mass-flux), are significant for very low blowing momentum coefficients, as shown in the principal result, where C_m^* reached the small value of 0.032, and $f_e \approx f_0$. Moreover, the efficiency of the synthetic jet was noted to be more important when positioning the slot in the vicinity of separation or just upstream, like in the experiments presented here (q = –112.5°): as a matter of fact, other tests have been realised with success at the slot position $q = -60°$.

As an extrapolation of the results presented here, which concerned a single slot, recent experiments have been conducted with two slots symmetrically placed just after the upper and the lower positions of the separation lines of the flow. The model which was equipped with two injectors (dimensions: width e = 0.5 mm, l = 100 mm) disposed at $q = \pm 112.5°$, is presented in Fig. 10. These injectors deliver two blowing signals which have the same phase and the same intensity. The test which is presented here concerns the highest frequency f_e = 120 Hz, the unsteady blowing rate of each injector being C_m^* = 0.017. The modification of the wall pressure distribution $K_P(q)$ under synthetic jet action is reported in Fig. 11. Compared with the effect observed by using a single slot (Fig. 7), the evolution under blowing action is relatively small, which reveals that the blowing rate is insufficient to significantly modify the flow. The corresponding PIV measurement results are illustrated in Fig. 12, where the average flow field streamlines (issue from 150 samples statistically independent) are represented for both the unforced flow and for the forced flow. It will be observed that the dead zone is slightly reduced in the case of forced flow and that blowing leads to a more symmetric near-wake. These preliminary results using a double slot

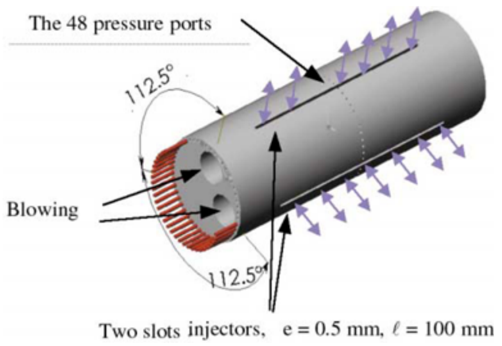

Fig. 10. The second cylinder model: *D* = 50mm, *L* = 500mm

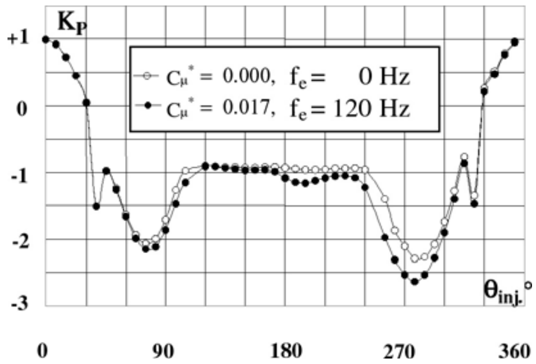

Fig. 11. Modification of wall pressure distribution under blowing action (2 slots).

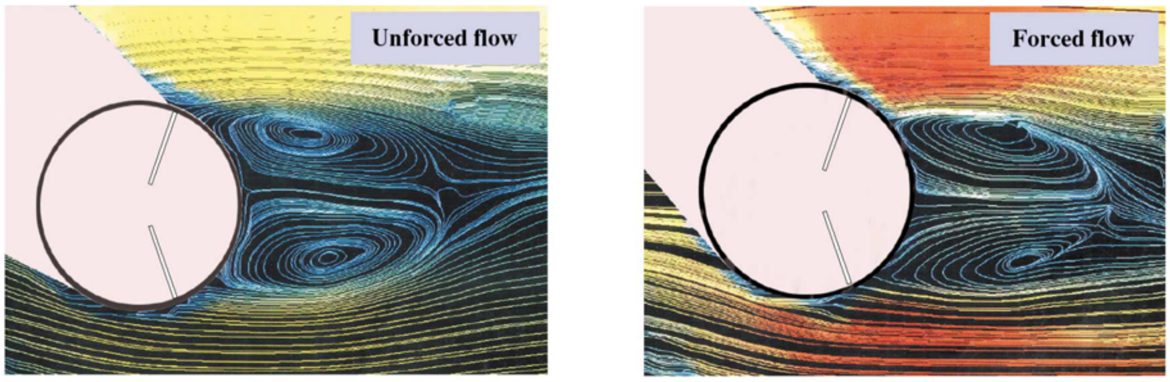

Fig. 12. Effect of synthetic jet on the near wake (2 slots): V_∞ = 30 m/s, q_{inj} = ±112.5°, C_m^* = 0.017.

system are moderately satisfying because the actual generating synthetic jet system is inadequate for producing high blowing rates. Further works will consist in modifying the actuator system in order to reach higher values of C_m^*. Moreover, the conception of a new actuator is projected, which would dissociate the two blowing main parameters: the frequency (f_e) and the intensity ($V_{inj.\ RMS}$). With this aim in view, to obtain a variation of one parameter, the other being constant, the cavity of the new actuator (see again Fig. 2) has to be variable in size.

Probably due to the alternative effects of blowing and suction obtained with synthetic jets, unsteady blowing is of good efficiency in delaying separation and reducing drag coefficient. Using zero-mass-flux actuator types, which require little energy, is a very promising way for further flow control around various bodies including airfoils.

In the future, various actuators like piezoelectric systems and, more generally, MEMS (Micro-electronic-mechanical systems), directly installed into the cylinder model, will be tested in comparison with synthetic jets actuators.

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