Experimental investigation of side force control on cone-cylinder slender bodies with flexible micro balloon actuators

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Abstract

Side forces on slender bodies of revolution at medium to high angles of attack (AOA > 30°) has been known from a large number of investigations. Asymmetric vortex pairs over a slender body are believed to be the principle cause of the side forces. Under some flight conditions, this side force may be as large as the normal force acting on the slender body. In this paper, experimental results are presented for side force control on a cone-cylinder slender body by using microfabricated balloon actuators. The micro balloon actuators are made of polydimethylsiloxane (PDMS) elastomer by using micro molding techniques. They can be packaged on curve surfaces of a cone-cylinder slender body. As actuator is actuated, the micro balloon actuator inflates about 1.2 mm vertically, which is about 2.4% of the cylinder diameter \( D \) (=50 mm) of the cone-cylinder slender body. Micro balloon actuators are actuated at different roll angles of a cone-cylinder slender body. Aerodynamic force measurement results indicate the effects of micro balloon actuators vary at different actuation locations on the cone-cylinder slender body. The side forces can be significantly reduced if the actuators are actuated in the weak vortex side (the side corresponding to the asymmetric vortex which is far from the surface) and actuation angles are located at about 50–60° (the actuation angle here is measured from stagnation line of the incidence plane toward weak vortex side direction). Significant changes are noticed from the surface pressure, as well as leeside vortex flow field, measurement. Micro balloon actuators change nose shapes of the slender body which decide adverse-pressure-gradient values and directly influence the origin of the separation lines and characteristics of the separated vortices over the leeside surface.

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1. Introduction

As flight envelopes of modern aircrafts and missiles continually increase to a higher angle of attack, an extensive knowledge of the aerodynamics over a large range of angles of attack for a slender body is required. Over the last 30 years, many researchers investigated the flow structures over a slender body at various angles of attack [1–6]. Four principal flow regimes occur over the slender body when angles of attack (AOA) range from 0° to 90°. Vortex-free flow presents at angles of attack up to about 10° (AOA < 10°). With increasing angles of attacks, separated flow structures over slender bodies present symmetric vortices at small angles of attack (10° < AOA < 30°). Steady asymmetric vortex flow appears at medium angles of attack from 30° to 60° and unsteady wake-like vortex flow becomes dominant at high angles of attack above 60° (Keener et al. [9]). In addition to angles of attack, flow structures are also sensitive to nose fineness ratio [7,8]. Reynolds number [9–11], roll angle [4,10], surface roughness [4,12], etc.

At small angles of attack (10° < AOA < 30°), the flow separating off the leeside of a slender body rolls up into a pair of symmetric vortices. Above a critical angle of
attack (AOA > 30°), the vortices become asymmetric, generating significant side force even as large as 1.5 times the maximum normal force that can cause an aircraft or a missile to tumble if these effects have not been considered in the design of control system. The control of a slender body at moderate to high angles of attack is an important issue in flight dynamics of many air vehicles, because of the loss of effectiveness of the empennage surfaces as they become immersed in the wake flow region. In recent years, many techniques of controlling the slender bodies have been developed. The control methods can be divided into passive and active control methods. In passive control methods, a pair of helical strip is used to trip non-uniform cross-flow separation from a slender body to disrupt the formation of concentrated leeside vortices by Rao [13]. Clark et al. [14] install the small winglets on a slender body to alter the wake flow field. In active control methods, spinning nose [15,16], movable strakes [17,18], blowing [19,20], and side jet [21] were used. The main purpose of these methods is to produce counterbalanced aerodynamic forces and moments by influencing the vortex dynamic characteristics over a slender body.

In recent years, micro-electro-mechanical system (MEMS) technology has developed rapidly because it has many advantages, such as low cost, fast response, high sensitivity, small volume, light weight, multiple arrays and etc. For aerodynamic control of a flight vehicle by using MEMS technology, Grosjean et al. [22] performed the experiment of fighter F-15 aerodynamic control by using micro shear stress sensors and micro

\[
X, Y, Z \text{ coordinate system fixed with test model, as shown in Fig. 1(a)}
\]

\[v\] dynamic viscosity of air

\[\text{AOA}\] angle of attack, deg

\[\Delta C_s\] side force coefficient change due to actuator’s actuation, \(\Delta S/q_{\infty}A\)

\[\phi_r\] roll angle, \(\phi_r = 0^\circ\) is defined as micro balloon actuator at stagnation line

\[\phi_a\] micro balloon actuator position, \(\phi_a\) is the same as roll angle, \(\phi_r\) in current experimental setup

\[\phi_p\] circumferential location of pressure orifices, \(\phi_p = 0^\circ\) is defined as pressure orifice at stagnation line

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**Nomenclature**

- **A**: cylinder cross-section area
- **C_p**: pressure coefficient, \((p - p_\infty)/q_\infty\)
- **C_s**: side force coefficient, \(S/q_{\infty}A\)
- **D**: cylinder diameter
- **H**: the inflated height of balloon actuator
- **P**: source pressure of the micro balloon actuator
- **p_{\infty}**: free-stream pressure
- **q_{\infty}**: free-stream dynamic pressure, \(1/2\rho U_\infty^2\)
- **Re**: Reynolds number, \(U_\infty D/v\)
- **S**: side force, \(S\) is defined as positive if side force is in \(Y\)-axis positive direction
- **\Delta S**: side force change due to actuator’s actuation, defined as \(\Delta S = S_{\text{after actuation}} - S_{\text{before actuation}}\)
- **U_\infty**: free-stream velocity
- **U, V, W**: velocities in \(X, Y, Z\) directions, respectively
- **\(X, Y, Z\)**: coordinate system fixed with wind tunnel, as shown in Fig. 1(a)

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![Fig. 1. Configuration of (a) coordinate systems and (b) cone-cylinder slender body model.](image-url)
balloon actuators packaged on wing surface. From their flight test results, rolling moment can be effectively influenced once micro balloon actuators were actuated. Lee et al. [23] installed micro magnetic actuators on the leading edge of a delta wing airplane. When the magnetic actuators are actuated, rolling, pitching and yawing moments of a delta wing aircraft can be significantly changed. All these examples show micro actuators can serve as an excellent control device for aerodynamic control despite of their small sizes. As long as micro actuators are actuated at the suitable positions of the flow system, small disturbance of micro actuators can be amplified through the instability mechanism of the flow field. In this study, aerodynamic characteristics of the cone-cylinder slender body are experimentally investigated when a micro balloon actuator is actuated at different locations around the cone-cylinder slender body.

2. Experimental apparatus

The experiments were conducted in an open-type low speed wind channel. The diameter of the test section is 50 cm and 140 cm in length. The speed of the wind tunnel can be operated from 2.0 to 35.0 m/s and the turbulence intensity is less than 0.5% of the time averaged free-stream velocity $U_{\infty}$. Experimental model is a cone-cylinder slender body with cylinder diameter $D = 50$ mm, as shown in Fig. 1(a). Throughout the paper, Reynolds number is based on the free-stream velocity $U_{\infty}$ and the diameter of cylinder $D$. The cone section of the cone-cylinder slender body has a length of $2D$ and a fitness ratio of 2. The length of cylinder section is $3D$. Two coordinate systems are used in this study; they are global coordinate and local coordinate systems, as shown in Fig. 1(a). For global coordinate system, the direction of coordinate system does not change with the angle-of-attack of the model. The notation of global coordinate system is $X, Y, Z$. For local coordinate system, the direction of coordinate system is changed with the angle-of-attack of the model. The notation of local coordinate system is $x, y, z$. There are two micro balloon actuators packaged on the cone-cylinder slender body. The micro balloon actuator packaged on cone section of the slender body is denoted as S1 actuator that stands for section-1 actuator, as shown in Fig. 1(b). The micro balloon actuator packaged on cylinder section of the slender body is denoted as S2 actuator (see Fig. 1(b)) that stands for section-2 actuator. Since only two micro-fabricated flexible micro balloon actuators are packaged at the same roll angle on curve surfaces of the cone-cylinder slender body, they rotate at the same time as roll angle ($\phi_r$). The roll angle ($\phi_r$) of the body is defined as $0^\circ$ when the membrane of the micro balloon actuator is located at the stagnation line of the windward side. Roll angle ($\phi_r$) of the model increases when the cone-cylinder, as well as micro balloon actuator, rotate clockwise as viewed from downstream. Therefore, micro balloon actuator position ($\phi_a$) coincides with roll angle ($\phi_r$), i.e. $\phi_a = \phi_r$. The circumferential location of pressure orifice ($\phi_p$) is defined $0^\circ$ as pressure orifice is located at the stagnation line of the windward side and it increases toward clockwise direction as viewed from downstream. The definitions of $\phi_p$, $\phi_a$, and $\phi_r$ are shown in Fig. 1(a) and (b).

Surface pressure, aerodynamic forces, and flow field measurements are employed in the current experiments. They are measured by using pressure transducer, load cell, and X-type hot-wire anemometer. The pressure transducer (Validyne company DC23) has resolution about 0.01 mm H$_2$O and the spatial resolution of the X-type hot wire probe is about 2 mm. Fig. 2 shows schematic diagrams of the experimental setup. Aerodynamic forces measurements are used first to study the effects of micro balloon actuators on the aerodynamic forces of the cone-cylinder slender body. The detailed mechanism of micro actuation for side force control can be further demonstrated by using surface pressure and velocity flow field measurements.

3. Micro-fabrication of flexible micro balloon actuator

Micro balloon actuators in the Ref. [22] were fabricated on a silicon substrate. Since the micro balloon actuator base is rigid, geometry of the wing surface re-shapes when the actuators are installed on a curve surface. In this study, flexible micro balloon actuators are made of polydimethylsiloxane (PDMS) elastomer [24] by using micro molding techniques. They can be packaged on curve surfaces of a cone-cylinder slender body. A mother mold is first fabricated by using MEMS technology. PDMS is then injected into the mother
mold. After curing, micro balloon actuators demold from mother mold. The membrane thickness of micro balloon actuators is approximately 50 μm, length and width of the membrane is 50 mm × 2mm. The membrane thickness is controlled by the rotational speed of a spin coater. Flexible PDMS balloon actuators can be packaged and integrated on curve surfaces of the cone-cylinder slender body without surface profile modification. Micro balloon actuators are actuated by using high pressure air. For each actuator membrane region, two holes are drilled on the cone-cylinder slender body and connected, respectively, to a control valve and a compressor tank through tiny stainless steel tubes. The actuator can be independently actuated utilizing control valve. For all wind tunnel experiments in this study, the pressure source is fixed at 12 psig, and the actuator membrane can be inflated about 1.2 mm in height at this pressure setting. Fig. 3 shows the heights of the actuator at different pressure levels.

4. Results and discussions

The experiments are first conducted by measuring side force of the cone-cylinder slender body with or without micro balloon actuator actuation when the free-stream velocity is $U_\infty = 20$ m/s. Reynolds number, defined as $Re = \rho U_\infty D/\mu$, is about $6.7 \times 10^4$ for the current experimental condition. Before studying the effects of micro balloon actuators, experiments investigate side force of the cone-cylinder slender body at various angles of attack (AOA) when the actuators are not actuated. Fig. 4 shows the results of the side force coefficient ($C_s$) as angles of attack of the cone-cylinder slender body increase from $0^\circ$ to $60^\circ$. The side force coefficient ($C_s$) is defined as

$$C_s = \frac{S}{q_\infty A}$$

where $S$ is side force, $q_\infty$ is free-stream dynamic pressure ($q_\infty = \frac{1}{2} \rho U_\infty^2$) and $A$ is the area of cylinder cross-section. Side forces vary with angles of attack (AOA). When angle of attack is small (AOA < $30^\circ$), negligible side force presents vortex-free or symmetric vortex flow over the slender body. When angle of attack is increased beyond a certain value (for example, AOA > $30^\circ$), initial symmetric vortex pairs become asymmetric causing a side force on the slender body. Side force reaches its maximum as angle of attack is increased to about $50^\circ$. If angle of attack is further increased, side force decreases rapidly.

At least two possible causes of vortex asymmetry were suggested: (1) Inviscid hydrodynamic instability of the symmetrically separated vortices [9] and (2) asymmetric flow separation and/or asymmetric flow reattachment on each side of slender body [25]. There is no general agreement on the mechanism involved in the creation of the flow asymmetry. However, control of the vortex structure transition from being asymmetric to symmetric is of the major importance for the slender-body-shaped flight vehicles capable of extreme maneuvers. The influence of pressure acting on the surface of cone-cylinder slender body due to these two asymmetric vortices is obviously different. In order to validate aerodynamic force results, surface pressure measurement was also performed. Fig. 5 shows surface pressure measurement at $X/D = 2.6$ when roll angle ($\phi_r$) is fixed at $180^\circ$ and angle of attack is increased from $20^\circ$ to $50^\circ$. The surface pressure distribution is almost symmetric as angle of attack is below $30^\circ$, but the pressure distribution becomes asymmetric as angle of attack reaches
This result is coincident with the results of side force measurement. In Fig. 5(c) and (d), the influence of surface pressure is much stronger in one (right) side of the vortex than the one in the other (left) side. In this paper, the vortex side with much stronger influence of surface pressure is defined as the strong vortex side. The other vortex side is called as the weak vortex side.

Because of asymmetric flow separation on each side of slender body or hydrodynamic instability of symmetric vortex, the strong side vortex happens to appear closer to leeward surface of the slender body. The strong side vortex generates robust negative pressure (suction force) on the slender body. Therefore, the net side force in Fig. 5(c) and (d) is directed rightward, i.e. in positive $Y$-axis direction.

Besides the effects of the angles of attack on side force of a slender body, side force varies with roll angle ($\phi_r$) even the actuators are not actuated. In this paper, roll angle ($\phi_r$) of the slender body is defined as $0^\circ$ when the micro balloon actuator is located at stagnation line of the incident plane. Roll angle ($\phi_r$) of the slender body increases when the test model, as well as micro balloon actuator, rotates counterclockwise around $X$-axis. Since only one micro balloon actuator is packaged on a fixed circumferential location of the slender body model, it rotates at the same time as roll angle ($\phi_r$). Micro balloon actuator position ($\phi_a$) coincides with roll angle ($\phi_r$), i.e. $\phi_a = \phi_r$, in the current experimental setup. The side force coefficient $C_s$ (or $\Delta C_s$) is positive if the side force (or side force change) is in $Y$-axis direction. Fig. 6 shows the results of the side force coefficient $C_s$ as roll angles of the cone-cylinder slender body rotate from $0^\circ$ to $360^\circ$. The side forces vary with the roll angle ($\phi_r$), as well as the angle of attack (AOA). When the angle of attack is small (AOA $< 30^\circ$), original side force of the cone-cylinder slender body is very small and insensitive to roll angle of the slender body (Fig. 6(a) and (b)). At moderate angles of attack (AOA $= 40^\circ$), the distribution of the side force along roll angles is presented as a sinusoidal curve. At large angles of attack (AOA $= 55^\circ$), the bistable state for the side force exhibits a square-wave-like behavior and periodically changes its direction between positive and negative as roll angle ($\phi_r$) varies. For examples in Fig. 6(g), side force is positive when roll angles are within $0^\circ < \phi_r < 50^\circ$ or $170^\circ < \phi_r < 240^\circ$. Then, side force changes to negative when roll angles are within $60^\circ < \phi_r < 160^\circ$ or $260^\circ < \phi_r < 330^\circ$.

The side force coefficient change $\Delta C_s$, defined as $\Delta C_s = (C_s)_{\text{after actuation}} - (C_s)_{\text{before actuation}}$, presents the side force change due to micro balloon actuation. The side force coefficient changes $\Delta C_s$ due to micro balloon actuation are shown in Figs. 7 and 8.
open diamond, open square, and solid triangle symbols represent micro balloon actuators were actuated at S1 (section-1 or cone section), S2 (section-2 or cylinder section), and both S1&S2 (section-1 and section-2), respectively. At angles of attack $\alpha \geq 30^\circ$, the side force is negligible because the symmetric vortex pairs rolled up on the leeward side. The side force change due to micro balloon actuator actuation is small and exhibits symmetric at starboard and larboard, as shown in Fig. 7. When angle of attack $\alpha \leq 40^\circ$, side forces increase since the initial symmetric vortex pair becomes asymmetric. It is found that the largest changes happen when micro balloon actuators are actuated in the locations around $\phi_a = 50^\circ$ and $300^\circ$ if angle of attack is between $40^\circ \leq \alpha \leq 55^\circ$. Fig. 8 shows the typical effects of micro balloon actuators on side forces at angle of attack $\alpha = 55^\circ$. Since the micro balloon actuator rotates at the same time as roll angle $\phi_r$, micro balloon actuator position $\phi_a$ coincides with roll angle $\phi_r$, i.e. $\phi_a = \phi_r$, in the current experimental setup. When roll angle is at $\phi_a = 50^\circ$ and angle of attack $\alpha = 55^\circ$, Fig. 6(g) shows the side force before actuation is positive ($C_s > 0$). Once the actuators are actuated at angles at about $\phi_a = 50^\circ$, Fig. 8 shows side force change is negative ($\Delta C_s < 0$). The side force after actuation is reduced to a small value when micro balloon actuators are actuated at $\phi_a = 50^\circ$. It is found that the side force can be profoundly reduced once the actuators were actuated. Fig. 9 also represents the best actuation combination (S1, S2, or both S1 & S2) that the smallest side force can be achieved. The best actuation combination can significantly decrease the side force at $\alpha = 55^\circ$ from $C_s = 1.7$ to 0.7, as well as increase the AOA without significant side force from $\alpha = 40^\circ$ to a higher angle $\alpha = 50^\circ$. In addition, the experimental results also show the effect for the side force reduction due to S1 actuator actuation is more profound than S2 actuator actuation at $\alpha = 55^\circ$.

On the other hand, negative side force ($C_s < 0$) is found before actuation in Fig. 6(g) when roll angle at

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**Fig. 6.** Variations of the side force coefficient ($C_s$) with roll angles ($\phi_r$) when $\alpha = (a) 20^\circ$, (b) 30$^\circ$, (c) 35$^\circ$, (d) 40$^\circ$, (e) 45$^\circ$, (f) 50$^\circ$, (g) 55$^\circ$, (h) 60$^\circ$.

**Fig. 7.** The side force change at different actuation angles ($\phi_a$) for $\alpha = 20^\circ$.

**Fig. 8.** The side force change at different actuation angles ($\phi_a$) for $\alpha = 55^\circ$.

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$C_s$ represents the side force coefficient, $\phi_a$ is the actuation angle, and $\phi_r$ is the roll angle.
degree of asymmetric vortex flow. The experimental results have pointed to that side force on the cone-cylinder slender body at high angles of attack can be effectively reduced if the actuators are located in the weak vortex side and actuated in the region of 50–60° from the windward stagnation line. To investigate the detailed mechanisms of reduction for side forces on the slender body, pressure transducer and X-type hot wire are used to measure surface pressure and flow field of the slender body when the actuators are actuated within 50–60° from the windward stagnation line toward the weak vortex side direction. For examples, micro balloon actuators are located at so-called weak vortex side when angle of attack AOA = 50° and roll angle is at \( \phi_r = 300° \). The surface pressure distributions \( C_p \) at \( X/D = 2.6 \) before and after actuation were shown in Fig. 11. Where the hollow diamond mark represents the actuators be not actuated, the triangle solid mark is the S1 actuator be actuated at \( \phi_a = 300° \) (60° from the windward stagnation line toward the weak vortex side direction) in Fig. 11. It can be found that side force is toward left side in Fig. 11, but when the section 1 actuator was actuated, the right side vortex strength is enhanced and the side force is alleviated. This result is coincident with force measurement result. Beside surface pressure measurements, velocity vector \( (V, W) \) distributions at section \( X/D = 3.2 \) are given in Fig. 12. Fig. 12 shows the left side vortex (so-called strong side vortex) is close to the model surface and the right side vortex (so-called weak side vortex) is far away from the model leeward. These two asymmetric vortices induce a strong side force toward the negative \( Y \) direction. Control of vortex structures from being asymmetric to symmetric is of the most obvious mechanism for the slender-body-shaped flight vehicles to reduce side force. However, vortex structures become even more asymmetric

\[ \phi_r = 300° \]
and side force change is positive (\( \Delta C_s > 0 \)) in Fig. 8 once the actuators are actuated at angle \( \phi_a = 300° \). Therefore, side force is also decreased to a small value when micro balloon actuators are actuated at angle \( \phi_a = 300° \). Fig. 10 plots the side force variation before and after actuation at \( \phi_a = 300° \). Similar results of side force reduction are achieved at both actuation angles \( \phi_a = 50° \) and \( \phi_a = 300° \). The effective actuator and roll angles at 50° or 300° are all related since the actuators are all actuated in the so-called weak vortex side (the side corresponding to the vortex far from the surface). If actuation angle is measured from stagnation line of the incidence plane toward weak vortex side direction, the side forces can be significantly reduced if the actuators are actuated in the weak vortex side and actuation angles are located in the region around 50–60°.

Several studies have indicated that side forces of slender bodies at high angle of attack are due to a high
when the S1 actuator was actuated at $\varphi_a = 300^\circ$. The right (weak) side vortex core changes to a higher position. Though velocity vector plot after actuation did not see symmetric vortex structures, previous experiments in Fig. 11 have clearly found that the surface pressure in the weak vortex side is enhanced. It is suspected that unseen vortex structures are not clearly shown in the near-wall of slender body. Fig. 13 shows the constant contours of non-dimensional streamwise vorticity $\omega_x$ calculated from velocity vectors in Fig. 12. The maximum vorticity $\omega_x$ in the flow field is also indicated at each vortex core in Fig. 13. Besides two vorticity-concentrated areas near the cores of two asymmetric vortex structures, a third vorticity-concentrated area is clearly found in the weak vortex side even before the actuation. The strength of the third vortex originally is small when it compared with the strong vortex before micro balloon actuators' actuation. Once micro balloon actuators are actuated at $\varphi_a = 300^\circ$, this third vortex is evidently strengthened and changed to a near-wall location. The vorticity at the third vortex core is increased that is comparable with the strong vortex core strength. Therefore, it is reasonable to conclude that the influence of pressure acting on the surface of cone-cylinder slender body due to this third vortex becomes more symmetric, as shown in Fig. 11. The side is therefore decreased if the actuators are actuated in the weak vortex side (the side corresponding to the asymmetric vortex which is far from the surface) and actuation angles are located at about 50–60$^\circ$ (the actuation angle here is measured from the windward stagnation line toward weak vortex side direction).
In the present study, the experiments also investigate the side-force variation of the cone-cylinder at different inflated heights of the micro balloon actuator. Fig. 14 shows the side-force variation with different inflated heights of the actuator. The results show that the side force reduces dramatically when the inflated height of the actuator changing from 0 to 0.4 mm. Once the inflated height of the actuator is above 0.4 mm, the side force decreases slowly. It shows that the side-force of the cone-cylinder is extremely sensitive to the any geometry change of the forebody. The minimum effective height is expected to relate with the boundary layer thickness near the micro balloon actuator.

5. Conclusion

In this study, micro balloon actuator is dramatically effective in reducing the side force of a cone-cylinder slender body. If the actuators are actuated in the weak vortex side (the side corresponding to the asymmetric vortex which is far from the surface) and the actuation angles are located at about 50–60°, the side force can be significantly reduced after actuation.

It is commonly believed that control of vortex structures from being asymmetric to symmetric is of the most obvious mechanism to reduce side force. However, instead of controlling vortex structures from being asymmetric to symmetric, micro balloon actuators change nose shapes of the slender body that decide adverse-pressure-gradient values and directly influence the origin of the separation lines and characteristics of the separated vortices over the leeside surface to reduce side force of a slender body. The leeside vortex structures above a cone-cylinder slender body have been further verified to be a three-vortex system, instead of a two-vortex system, in the flow structure. The reduction mechanism of side force can be characterized by the occurrence of the early weak-side vortex lift-off since micro balloon actuation changes the vortical structures substantially. It allows a new (third) vortex to form close to surface prematurely. The vortex seems to have farther re-attach point after actuation, as shown in Fig. 12, and form a concentrated high-vorticity region in the near-wall region, which may be the possible explanation for $C_s$ reduction. Moreover, the induced new (third) vortex is strengthened due to micro balloon actuation. Therefore, the resultant three-vortex structure after actuation has caused the pressure distribution on the cone-cylinder’s surface becomes more symmetric once micro balloon actuators are actuated at the angle toward weak vortex side about 50–60°.

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References