CONTROL OF THE WAKE BEHIND A DISK USING ELECTRO-MAGNETIC ACTUATORS

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ABSTRACT

Open-loop response of the wake behind an actuator-equipped disk was experimentally investigated. The disk edge had flush-mounted tabs that moved radially in specified frequency and relative phase using electro-magnetic actuators. In spite of small amplitude of tab motion, significant modification of the helical mode of wake oscillation was observed.

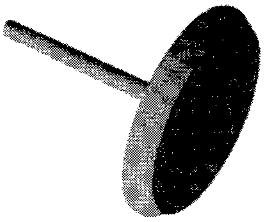
INTRODUCTION

Wake control behind some axisymmetric bluff-bodies such as a sphere may be achieved by controlling the boundary-layer transition and separation. Practical examples of passive controls of the wake include roughness and seams on sports balls (Mehta 1985.) Kiura and Higuchi (2000) examined in detail the effect of the baseball seam on the boundary layer separation as related to the knuckle-ball side-force variations. The boundary layer on the sphere may be actively controlled; Choi et al (1998) have achieved reduction of reverse flow region with actuators. An alternative to controlling the separating shear layer is a base bleed. Also for a sharp-edged disk, passive control of the disk wake has been established by adding porosity (Cannon, 1991, Higuchi et al, 1996). However, the solid disk has a fixed separation line, which is not directly affected by the boundary layer manipulation, and thus the flow configuration poses a different challenge. Higuchi and Balligand (2001) demonstrated the establishment of the 3D wake behind a disk started from rest. The onset of the 3D wake structure was enhanced behind polygonal plates such as hexagon (Higuchi, et al., 1996). As for the active control of the disk wake, Berger et al (1990) oscillated the disk itself in a nutation mode resulting in an enhanced helical mode. In the present experiment, the disk model is equipped with moveable edge (i.e., tabs) that is oscillated by the electro-magnetic actuators. The aim of the present study was to ascertain whether the already separating shear layer itself may be manipulated in this manner. The multiple actuators can be moved simultaneously or in various sequences at different frequencies.

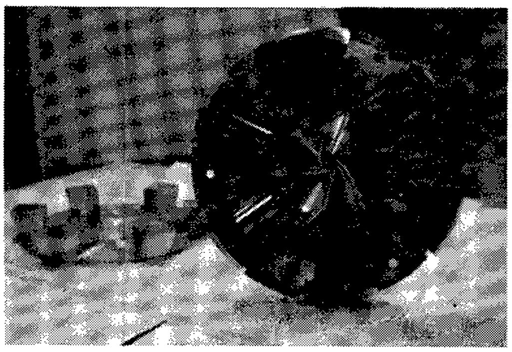
EXPERIMENT

The experiment was conducted in the open test section of the Low Turbulence Wind Tunnel with 0.81m cross section at Tohoku University and in the low speed closed-return wind tunnel with a 0.61mx0.61m test section at Syracuse University. An additional experiment with a stationary disk was conducted in the Syracuse 0.61mx0.61m water channel. The disk was 10cm in diameter and 1.5cm in thickness with a beveled edge with downstream face of 9.2cm diameter. Six TDK P1002A electro-magnetic actuators translated 6 equally spaced segments of the disk edge in radial directions at specified frequency and phase. A sketch of the overall model and a photograph showing the actuators within the model are shown in Figs. 1.

The stroke of the actuator was limited to 2 mm, and in the retracted position the moveable segments were flush with the remainder of the disk edge. Analog outputs from a D/A signal processor or a waveform generator were input to the 1-6 power amplifiers. In most of the experiment, a 0.1mm latex film covered the edge of the disk and tabs. The actuated tab displacement was measured with the laser displacement meter and the overall operation and phase were checked with a strobe light.



(a) Model geometry (Front diameter 100mm and rear diameter 92mm)



(b) Interior of the disk showing 6 electro-magnetic actuators.
Fig. 1 Disk Model

The results in air presented below corresponded to a Reynolds number ranging between 34,000 and 68,000 based on the disk diameter. The disk had to be aligned carefully with respect to the free stream direction to assure reasonable wake axisymmetry. Originally the model was supported by piano wires with electrical leads extending from the settling chamber of the wind tunnel. The support was modified to a streamlined cantilever support upstream of the model for ease of alignment and electrical connection.

Constant-temperature anemometers were used in the hot-wire measurement at Tohoku University, and the subsequent experiment at Syracuse University was conducted using a DANTEC Time-Resolved Particle Image Velocimetry system (TR-PIV). The latter PIV system is powered by a Q-switched high-repetition rate Nd:YAG laser coupled with a high frame rate CMOS camera. It can capture full frame 1280x1024 movies up to 500 frame/sec, and at much higher frame rate at reduced resolution. Olive-oil based seeding was introduced near the downstream diffuser from a Luskin nozzle seeder.

RESULTS AND DISCUSSIONS

Natural Wake

The wake of the stationary disk was surveyed in the Syracuse water channel using the time-resolved PIV system. A water-proof replica of the model was used. The Reynolds number was 7500. Seeding was provided upstream using the electrolysis technique. A typical instantaneous velocity field is shown in Fig. 2 depicting instability waves within the separating shear layer. The time averaged mean velocity field is shown in Fig. 3. The rear stagnation point is located at 2.0 diameter downstream of the front surface, which is less than what has been nominally observed behind a thin disk (see also e.g. Berger et al. 1990.)

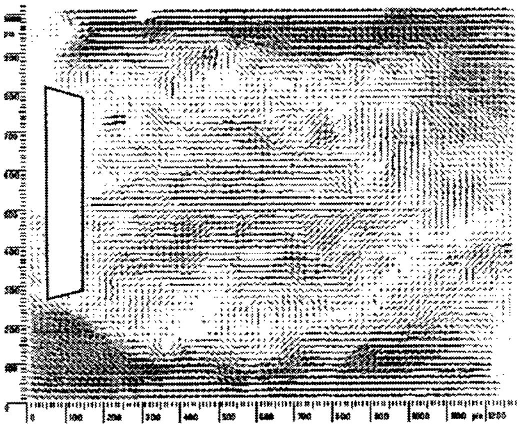


Fig. 2 Instantaneous velocity vector field behind stationary disk measured in water at Re=7500

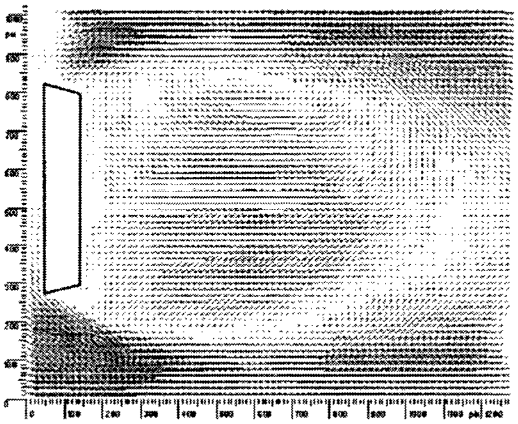


Fig.3 Time-averaged velocity vector field behind stationary disk measured in water at Re=7500

Wake behind Actuated Disk

The experiment with the actuator-equipped disk was conducted in air. Behind the non-actuated stationary disk, the wake exhibited a spectral peak at Strouhal number 0.15, which approximately corresponded to the established value for a primary helical structure behind a disk. The number was a slightly higher than 0.135 for thin disks reported by Berger et al, (1990) in air and by Balligand (2000) in water, and the discrepancy is likely due to the geometric difference. Though the analysis was for two-dimensional cylinders, Roshko's wake Strouhal number incorporated the wake width to unify the shedding frequencies behind various cylinders

(Roshko, 1954). The effect of afterbody length on axisymmetric bluff bodies is currently being studied.

In the actuator-disk experiment, tabs were actuated at x1, x2, x3 of the frequency given above corresponding to m=1 fundamental frequency, f_1 (e.g., fe=9Hz, 18 Hz and 27 Hz at 6m/s.) When the free stream velocity was changed, the dimensionless frequencies of the excitations were kept constant. As shown schematically in Fig. 4, three modes of actuator sequence were used, in addition to the stationary mode as a control. These modes are termed T0: no actuation, T1: axisymmetric actuation (m=0 mode), T2: neighboring actuators moving in sequence with $\pi/3$ phase in clockwise (-) or counterclockwise (+) direction viewed from downstream (m=1 mode). No clear distinction was seen between the T2- and T2+ cases during the earlier test, thus the helical excitation for T2+ will be included here.

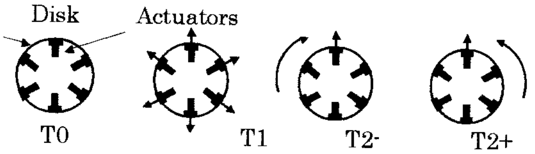


Fig. 4 Schematic of Tab Actuation

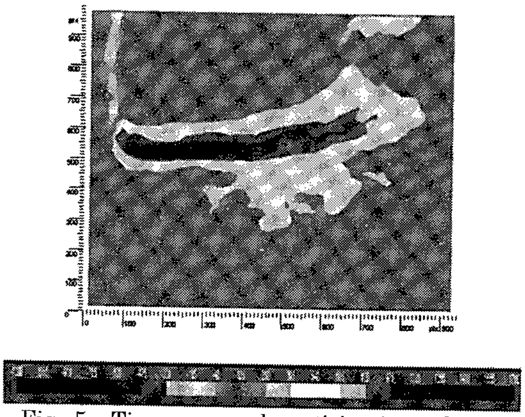


Fig. 5a Time-averaged vorticity immediately behind the non-actuated disk (1/s). Re=34,000

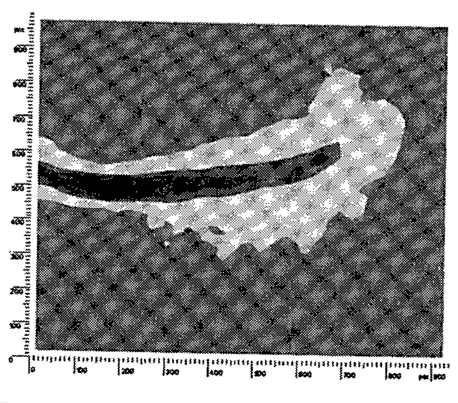
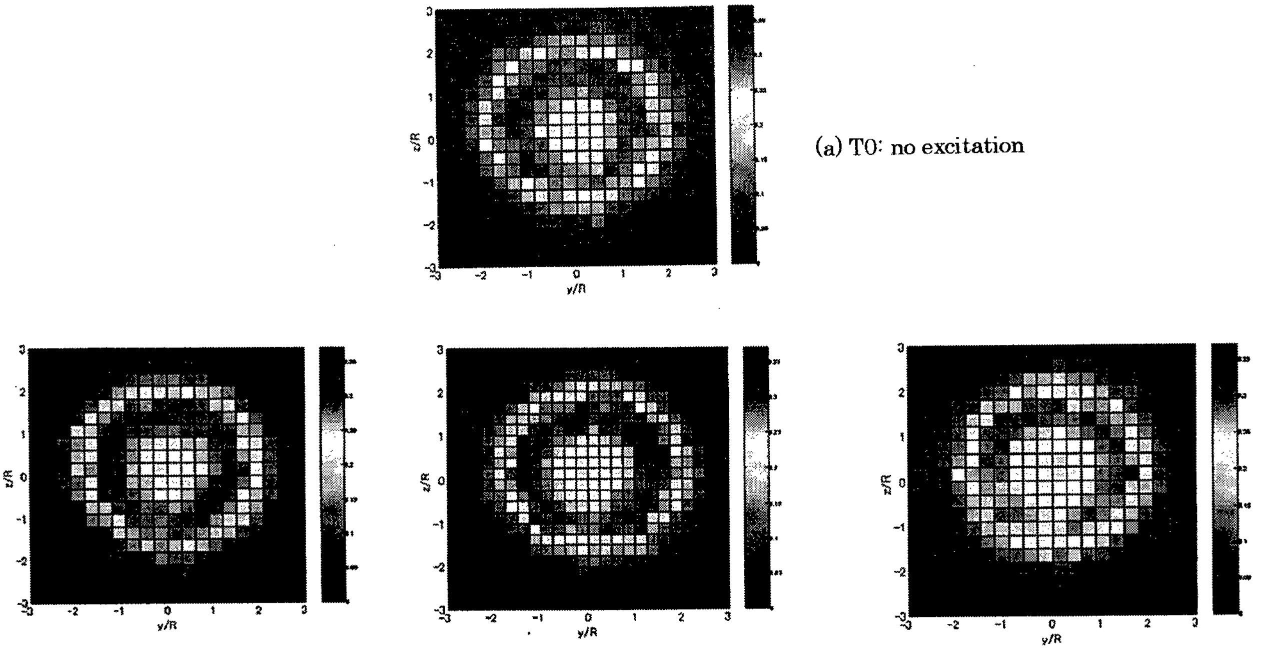


Fig. 5b Time averaged vorticity immediately behind the actuated disk (1/s) (T1 at fe=3* f_1) Re=34,000

Velocity fluctuations in the wake under the tab excitations were surveyed in air with hot-wire anemometry in the Tohoku wind tunnel and with particle image velocimetry in the Syracuse wind tunnel. The latter was conducted in air with the time-resolved PIV system. The velocity vector field was obtained at 250 frames per second using the time interval between the double pulses of 500 micro second that enabled the tracking the shear layer instability waves in the separating shear layer, though the field of view had to be significantly reduced compared to the experiment in water due to the seeding particle size and reduced laser power in faster double pulses. Only the axisymmetric tab motions were tested for convenience at different excitation frequencies. With actuator movement, the instantaneous vorticity contour showed the high shear region dynamically responding to the motion of the tab. The time-dependent depiction of vorticity countour heuristically resembled a flexible rope being held at a moving end. The time averaged vorticity distributions are compared among various excitation modes in Figs. 5. For this study the thin film was removed and tabs were exposed to the flow. This enabled the tab actuation at lower voltage, but it is believed that the overall effects remained the same. The field of view is X=0.06D to 0.93D and the disk edge is at the lower left corner, where the downstream distance is measured from the front surface of the disk. The natural wake with tabs at retracted position is shown in Fig. 5(a) as a reference. (Some minor secondary effect of glare from the model within the incoming flowfield is left untouched.) With the symmetric tab actuation, the time-averaged vorticity contour showed the earlier shear layer vortex formation. On the other hand, the overall vorticity level is reduced in the order of 2* f_1 and 3* f_1 excitations. The peak vorticity region is closer to the model and the shear layer diverges less from the disk centerline. The 3* f_1 symmetric excitation is shown in Fig. 5(b) with smaller magnitude of vorticity.

The time-series analysis of the velocity fluctuations was performed with the hot wire data. Analysis of the time-resolved PIV data in space-time domain is also being planned, including in the reverse flow region.

Figures 6 show the turbulence intensity in the x/D=3 plane obtained from the hot-wire measurements. Reasonable axisymmetry of the wake was also established in all cases, though the minor presence of the strut can be traceable in the profile. Figure 6(a) is for without any excitation.



(a) T0: no excitation

(b) T2 (3* f_l : 27 Hz) (c) T1 (2* f_l : 18 Hz) (d) T1 (3* f_l : 27 Hz)

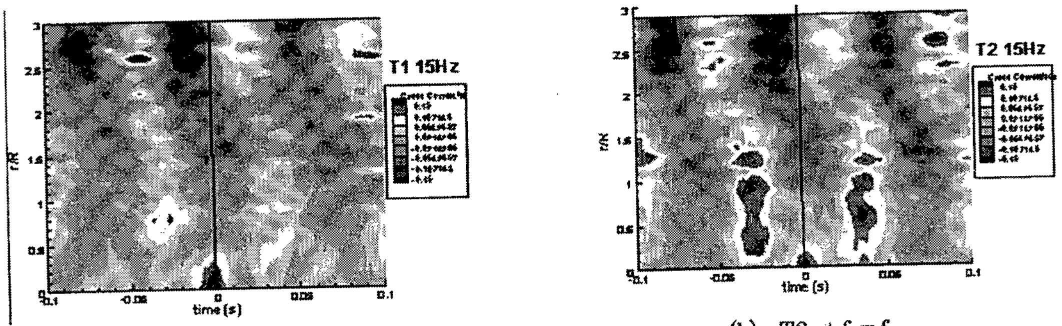
Fig. 6 Axial velocity fluctuations (u'rms/U) at X/D=3. Re=40.000

The helical excitation (T2, 3* f_l) at three times the fundamental frequency exhibited the increased turbulence level (Fig. 6b). On the other hand, the axisymetric excitation (T1) was most effective at fe=2* f_l (Fig. 4c), but at 3* f_l the turbulence level decreased below the stationary case (Fig. 6d.).

The cross-correlations at X=2D between the two opposite radial position in Figs 7a and 7b compare effect of two types of forcing on the wake structure. Due to the physical space limitation, the reference probe was placed somewhat too close to the centerline. Nonetheless, compared to the axisymmetric tab motion (Fig. 7a), the anti-phase helical structure is clearly seen at T2 mode both excited at f_l.

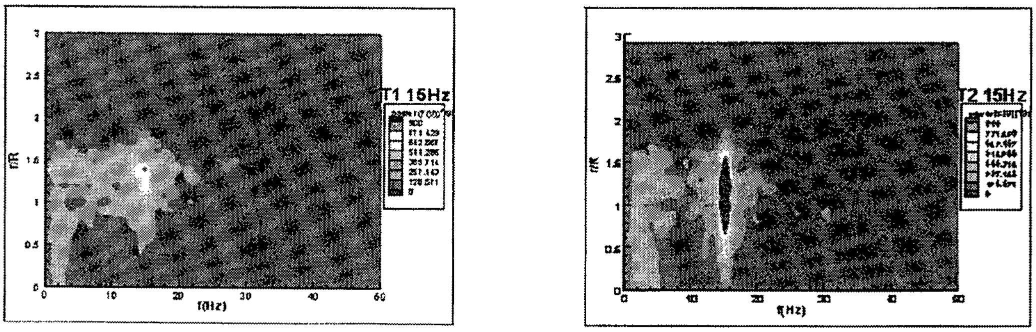
Berger et al. (1990) demonstrated a dramatic effect of the disk oscillation in a nutation mode at an excitation frequency corresponding to the helical mode. There, the separation line itself is expected to be helical, while the present tab movement in circumferential sequences appeared to have a less dramatic effect in enhancing the helical mode.

The power spectrum density of the axial velocity fluctuation was measured as the probe was placed at X/D=2 and traversed in the radial direction. The fundamental frequency corresponding to St=0.15, as noted earlier, was clearly shown in the natural wake. With axisymmetric tab excitation (T1), the spectral peak was significantly reduced at fe= f_l (Fig. 7a), increased significantly in a wider radial range at 2* f_l (Fig. 7b), then reduced at 3*f_l. The helical tab excitation, on the other hand, increased the spectral peak over a wide radial range at fe= f_l (Fig. 7c), but significantly reduced at 2* f_l (Fig. 7d) and a moderate spectral peak was observed at 3*f_l. It is to be noted that the excitation mode and frequency reduced or enhanced the fundamental



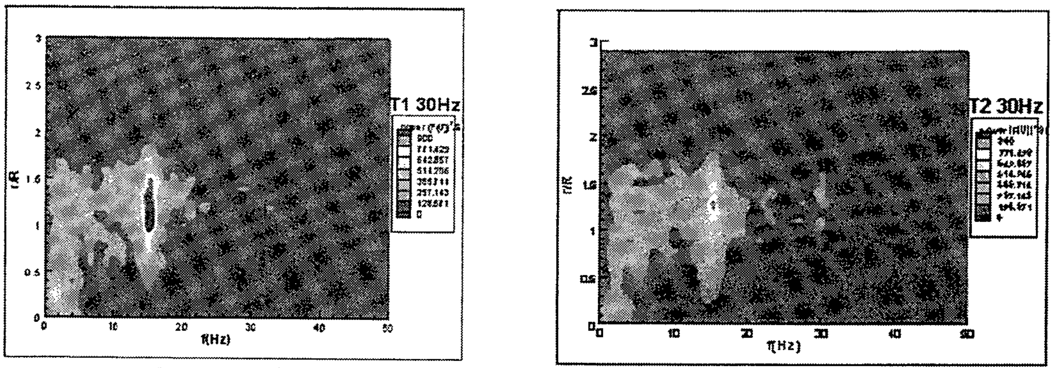
(a) T1 at fe= f_l (b) T2 at fe= f_l

Fig. 7 Radial cross-correlations of velocity at x/D=2,



(a) T1 fe= f_1

(c) T2 fe= f_1



(b) T1 fe=2* f_1

(d) T2, fe=2* f_1

Fig. 8 Power spectral density at X/D= 2D, $0<r/D<1.5$ Re=67,000

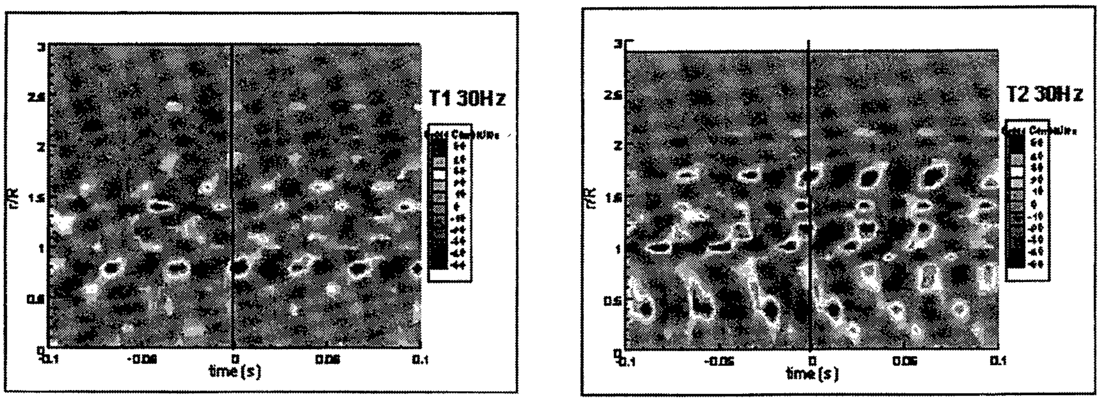
frequency peak, but it did not alter the peak frequency. The actual waveform of the tab movement was closer to a rounded triangular wave rather than being purely sinusoidal, involving harmonics, but the enhancement and suppression of turbulence by the axisymetric and helical excitations appear to be consistent. Siegel (1999) applied controlled suction and injection at the blunt tail of the sting model in water and surveyed the wake response in detail. When the forcing frequency was scanned, the results at Reynolds number 1500 indicated the maximum spectral peak at the natural frequency as well as lock-in frequency to the forcing.

In order to examine the time relationship between the excitation and the velocity fluctuation in the shear layer of the wake, cross-correlation between the actuator motion and the hot-wire signal in the wake was calculated and the result in one mode of excitation is presented in Figs. 9. (The actuator input signal was corrected for the calibrated tab movement and used for the correlation. The hot-wire signal was not affected by the operation of actuators themselves.) The wake motion responded to the actuator movement, and that the helical mode correlates across the wake including the wake center region, in particular at f_1 and $2{*}f_1$ (see Fig. 9a), while the axisymmetric mode was limited to the highest shear region (see Fig. 9b). Note that these lock-on frequencies were overshadowed by the fundamental frequency in the overall power spectra as shown in Fig. 8.

In the experiment by Berger et al. (1990) the rear stagnation point was reduced approximately from 2.5 D to 1.5 D by nutating the disk. They reported a small influence on the wake when the disk was oscillated in axial direction. At present, flow visualization indicated approximately 10% upstream shift in the rear stagnation point with tab actuation, though further study is needed to correlate it with the observed change in vorticity and turbulence level at various excitations.

CONCLUDING REMARKS

In spite of the small stroke due to the mechanical limitations of the selected actuator (corresponding to 2% of the disk diameter), the present experiment demonstrated the effectiveness of the motion of the disk edge by actuators in modifying the wake shear layer. As a comparison, when the actuators were fixed in the stationary mode the change in the wake turbulence was negligible. When stationary flaps of a length as large as 15% of the disk diameter were fixed at the edge, the wake turbulence was clearly modified. The present paper reported the effort to correlate the flow control and the instantaneous flowfield measurements. Future experiments will include further flowfield survey as well as the feedback control of the excitation. An active separation control over a wing is concurrently being



(a) T1, fe=2* f_1

(b) T2, fe=2*

Fig. 9 Cross-correaltion between actuator motion and velocity fluctuation Re=67,000.

conducted at Syracuse University. The PIV velocity field data will be used to ascertain the low-dimensional model of flow control (Young, et al, 2003). The result is expected to help in constructing the control strategy of the present disk wake.

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REFERENCES

Balligand, 2000, H. "Unsteady Wake Structure Behind a Solid Disk," Ph. D. Thesis, Syracuse University, Syracuse, NY.

Berger, E. Scholz, D. and Schumm, M., 1990, "Coherent Vortex Structures in the Wake of a Sphere and a Circular Disk at Rest and under Forced Vibrations", Journal of Fluids and Structures, Vol. 4, pp. 231-257.

Cannon, S., C., "Large -scale Structures and the Spatial Evolution of Wakes behind Axisymmetric Bluff Bodies," Ph.D. dissertation, University of Arizona, 1991.

Higuchi, H. and Balligand, H., 2001, "Circulation Time-history and Onset of Three-dimensional Vortex Shedding in the Wake behind a Disk," Proceedings, Second International Symposium on Turbulence and Shear Flow Phenomena, Stockholm, Vol. 1, pp. 301-306.

Higuchi, H., Zhang, J., Furuya, S. and Muzas, B.K., "Immediate and Near Wake Flow Patterns Behind Slotted Disks" AIAA Journal Vol. 36, No. 9, September 1998, pp. 1626-1634.

Higuchi, H., Anderson, R.W., and Zhang, J., "Three-Dimensional Wake Formations Behind Regular Polygonal Plates, " AIAA Journal, Vol. 34, No. 6, June 1996, pp. 1138-1145.

Kiura, T. and Higuchi, H., 2000, "Knuckleball Aerodynamics: Passive Alteration of Three-Dimensional Wake-Structure Interactions, " IUTAM Symposium on Bluff Body Wakes and Vortex-Induced Vibrations, Marseille, France.

Mehta, R. D., 1985, " Aerodynamics of Sports Balls" Annual Review of Fluid Mechanics, Vol. 17, pp. 151-189.

Park, J., Choi, H. and Jeon, W., 1998, "Active Control of Flow over a Sphere for Drag Reduction using Electro-magnetic Actuators," IUTAM Symposium on Bluff-Body Wake, Marseille, France

Roshko, A., 1955, "On the Wake and Drag of Bluff Bodies, " J. Aeronautical Sciences, pp. 124-132.

Siegel, S., 1999, "Experimental Investigation of the Wake behind an Axisymmetric Bluff Body," Ph. D. Thesis, University of Arizona, AZ.

Young, M. J., Glauser, M. N., Higuchi, H., and Taylor, J., 2003, "Towards Sensing and Control of Separation in Subsonic Slows," Proceedings of FEDSM03, 4th ASME-JSME Joint Fluids Engineering Conference, Honolulu, Hawaii, USA.