Journal of KONES Powertrain and Transport, Vol. 25, No. 3 2018

ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/01.3001.0012.4357

EXPERIMENTAL STUDIES OF LEADING EDGE VORTEX CONTROL OF DELTA WING MICRO AERIAL VEHICLE

Krzysztof Sibilski, Andrzej Żyluk

Air Force Institute of Technology
Ks. Boleslawa Street 6, Warsaw, 01-494, Poland
e-mail: krzysztof.sibilski@itwl.pl, andrzej.zyluk@itwl.pl

Wiesław Wróblewski

Wroclaw University of Technology
Wybrzeże Wyspiańskiego 27, 50-370 Wroclaw, Poland
e-mail: wieslaw.wroblewski@pwr.edu.pl

Abstract

It is known, that small disturbances generated by the micro actuators can alter large-scale vortex structures, and consequently, generate appreciable aerodynamic moments along all three axes for flight control. In the current study, we explored the possibility of independently controlling these moments. We perform analytical simulations showing optimal position of LEX generators, and water tunnel measurements showing effectiveness of MEX generators as MAV control devices. We applied array of actuators located on either the forward or the rear half section of the leading edge. Both one- and two-sided control configurations have also been investigated. Experimental results showed that asymmetric vortex pairs were formed, which leads to the generation of significant torques in all three axes. The article presents typical vortical flow over a delta wing, water tunnel at Wroclaw University of Technology, experimental setup and procedures, static test results on water tunnel testing including normal forces, pitching and yawing moments, maximum values of rolling, pitching, and yawing moment coefficients, effectiveness of pitching and yawing control.

Keywords: *Micro Aerial Vehicles, Unconventional control effectors*

Nomenclature

A_s – reference area (wing area),
b – wing span,
c_a – medium aerodynamic chord,
C_N – coefficient of normal aerodynamic force,
C_m – coefficient of pitching moment,
C_n – coefficient of yawing moment,
F_N – component of aerodynamic force normal to 5th component balance axis (normal aerodynamic force),
M – pitching moment,
N – rolling moment,
Re – Reynolds number,
q – dynamic pressure,
f, g – generic functions.

1. Introduction

Follows over delta wings have been studied extensively in the literature [1-5]. Even at small angles of attack, a pair of spiral vortices originating from the leading edges characterizes the flow on the leeward side of the wing (Fig. 1). Peckham [6] reported that leading-edge vortices could be observed at an angle of attack (AOA) as low as 2° for delta wings with sharp leading edges. For wings with rounded leading edges, the vortex pairs occur at higher angles of attack due to delay of flow separation.

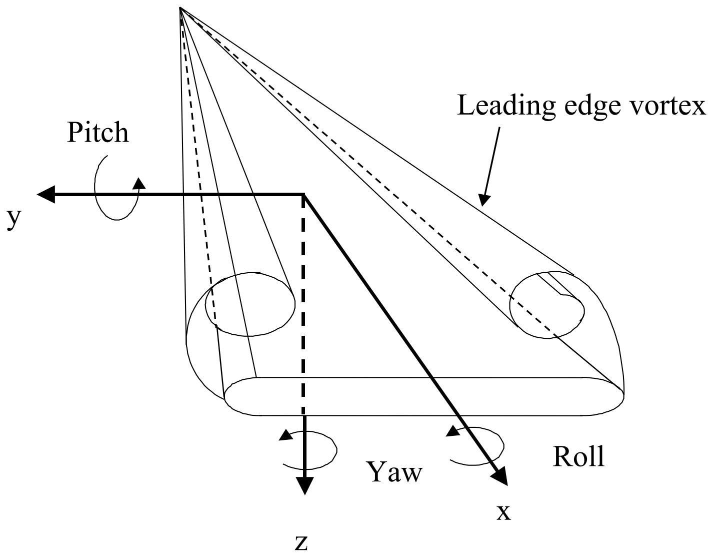

Fig. 1. Typical vortical flow over a delta wing (with round leading edges) at moderate angles of attack [39]

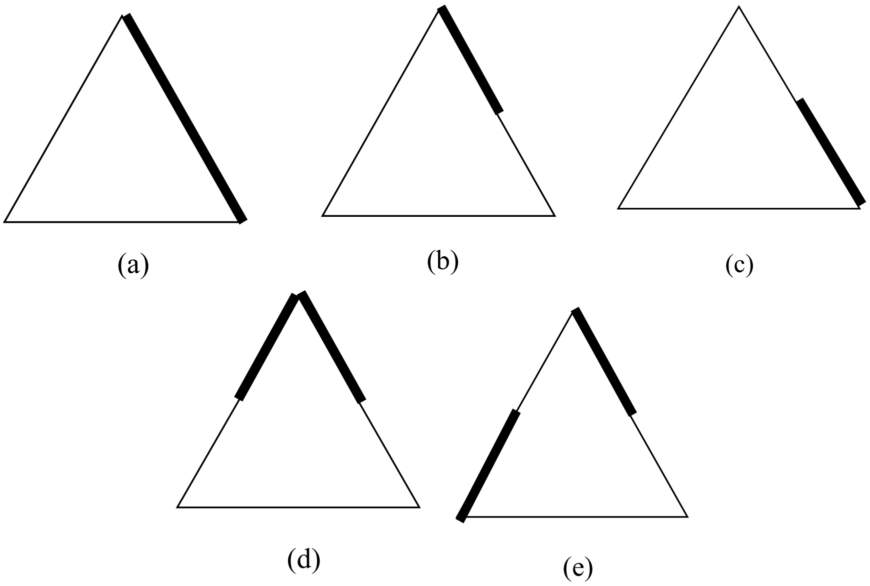

Fig. 2. Schematically all different actuator configurations used in the article. A detailed discussion of these results will be presented in the results and discussion section (a) a-t actuator, (b) forward h-a-t actuator, (c) rear h-a-t actuator (d) two-sided h-a-t actuators for pitching control, and (e) two-sided h-a-t actuators for yawing control (note actuators are represented by the thicker line segments [39]

Earnshaw and Lawford [7] found that these vortices start to appear at an angle of attack of 5°. The boundary layer flow separating from the leading edges will form a free shear layer, which will roll up into a core of high vorticity residing above the leeward side of the wing. The vortex core grows in radius along the downstream direction and the transverse size of the vortex is on the order of half the wingspan at high angles of attack. In addition to the swirl velocity component, each of the two leading-edge vortices contains an axial flow component in the central core region. As the vortex convects downstream, vorticity is continuously fed into the core region, and the circulation about the core increases. Thus, a low-pressure region will be generated by the leading-edge vortices. “Vortex lift”, which is distinguished from potential lift, is created as the result of the presence of this low-pressure region. At high angles of attack, the cores of leading-edge vortices on the wing tend to “burst” or “breakdown” [8]. Before vortex breakdown occurs, a significant portion of the total lift is attributed to the emergence of these leading-edge vortices [9]. It implies that we can generate a torque for flight control if we can break the symmetry of these two vortices. The majority of vortex control techniques discussed in the literature falls into four categories: (a) *blowing* [10-23], (b) *suction* [24-25], (c) trailing edge jet control [26-27], (d) *large mechanical flaps* [28-32], and (e) *heating* [33]. These approaches achieve vortex control by either altering the vorticity generation near the leading edges or manipulating the vorticity convection along the vortex core. In the paper [39] has shown that if the deflection amplitude of the actuators is comparable to the boundary layer thickness near the leading edge separation point, it is possible to perturb the separated flow and break the symmetry of the primary vortex pair. For this purpose, we used to control delta wing micro actuators with out-of-plane deflection length on the order of 3 mm. A significant increase in rolling, pitching, and yawing moments has been observed. It has also been found that the optimum angular location of actuators for the maximum torque generation is closely related to leading edge flow separation [27].

In order to investigate the interaction between the micro actuators and the vortices, a fundamental understanding of the flow field is essential. In light of this, we conducted a series of aerodynamic tests, including direct force measurements and flow visualization experiments, with and without the flow control. The objective of this work is to investigate how the vortex structure is altered by the use of micro actuators and how an unbalanced vortex pair can be used to generate appreciable torques at high angles of attack.

2. Experimental Setup and Procedures

A delta wing model with a sweep angle of 60° was sting mounted in a low-Reynolds number water tunnel (Fig. 3). The model support rig has a pitch angle range of –60° to 60°, resulting in α +/-55° range in angle of attack. The wing has a DF 101 airfoil (Fig. 4), wingspan 0.190 m and length 0.165 m (Fig. 5).

Fig. 3. Wroclaw University of Technology water tunnel (Rolling Hills Research Corp. Water Tunnel model 2436) [40]

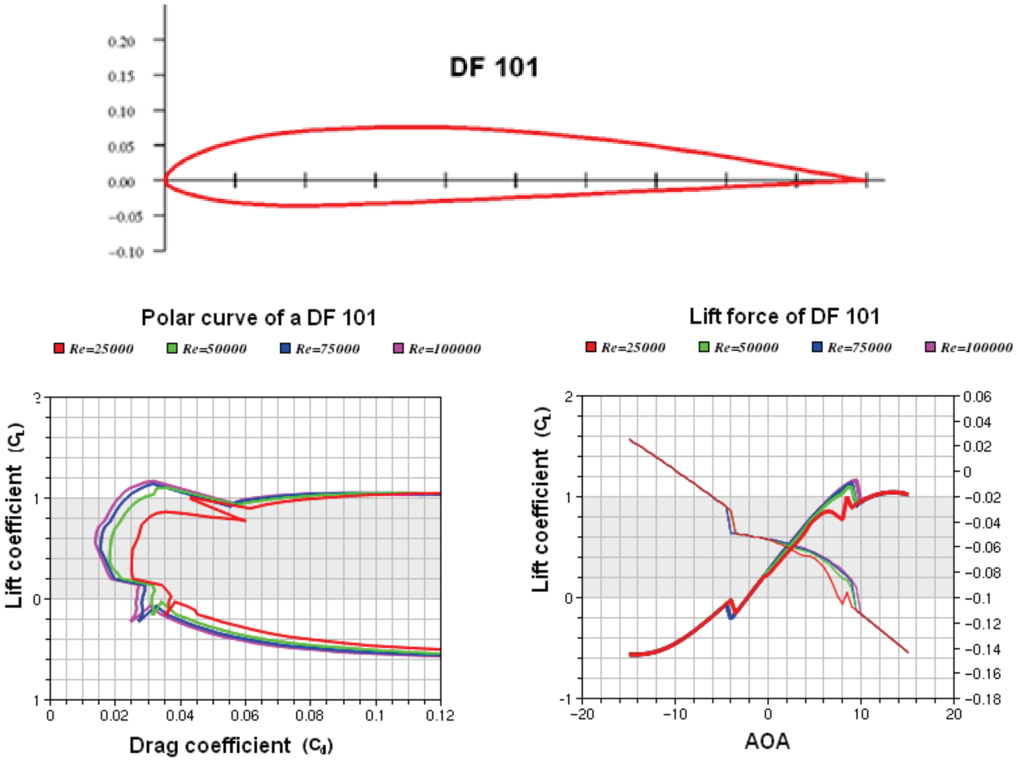

Fig. 4. Aerodynamic data of DF101 airfoil

Due to the limited supply of micro actuators in water tunnel, we used miniature mechanical actuators for water tunnel tests. Basically, the mechanical actuator has the same deflection length as micro actuators except that the stiffness of the mechanical actuator is larger. The effects caused by using miniature mechanical actuators were found to be comparable.

Fig. 5. Delta wing model

3. Results and Discussion

Normal and side force and 3-axis moment data were measured using a 5-component balance system and RHRC support system. This balance was used to record changes in torques induced by the use of micro actuators. Data were digitized by an analogue-to-digital converter and processed by a personal computer (PC) – by using LabViev computer software.

3.1. Water tunnel testing (static tests)

Figures 6-11 show the results of measurements normal force and pitching moment of delta wing without actuators at different angles of attack. This data was obtained from the five-component transducer system.

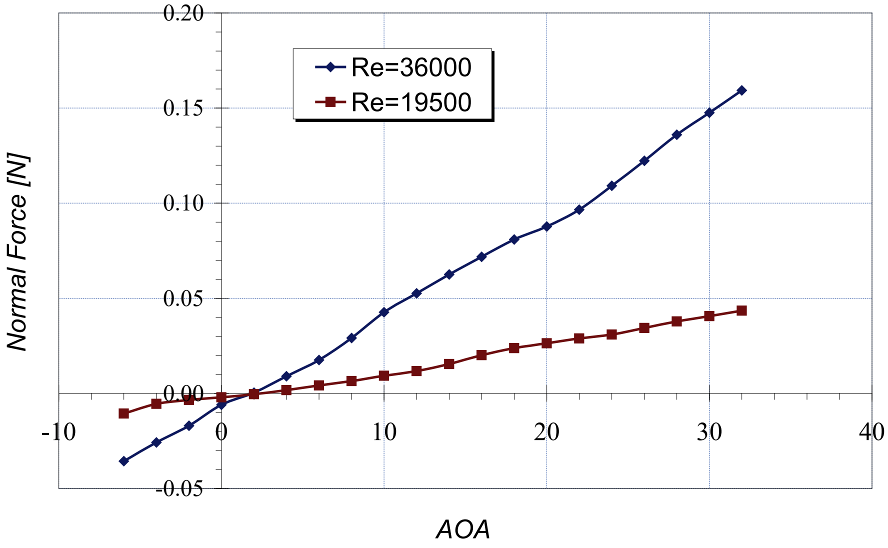

Fig. 6. Clean configuration. Normal force in [N] vs. Angle of Attack

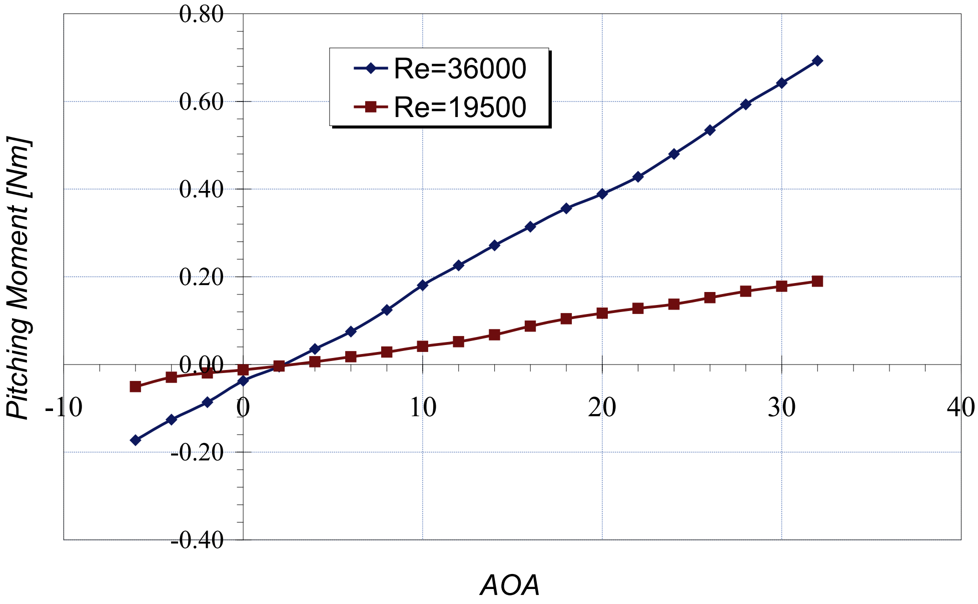

Fig. 7. Clean configuration. Pitching moment in [Nm] vs. Angle of Attack

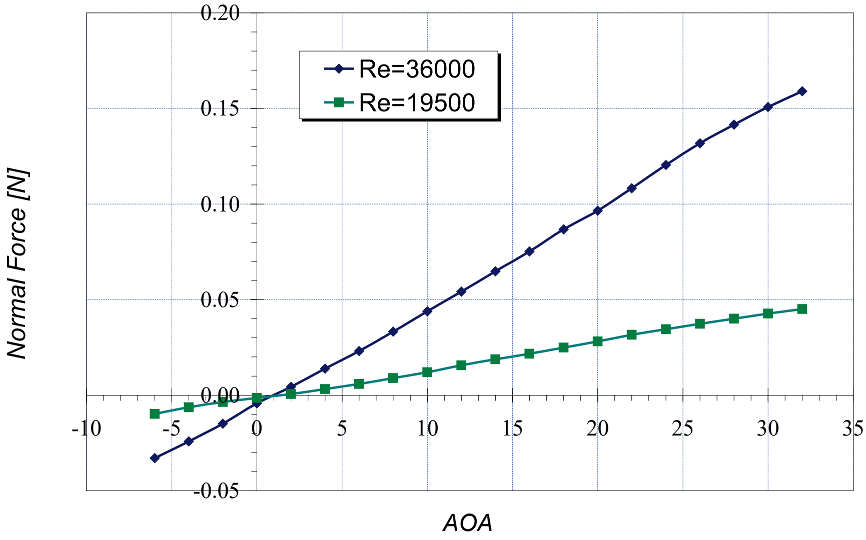

Fig. 7. Actuators on – pitching control configuration. Normal force in [N] vs. Angle of Attack

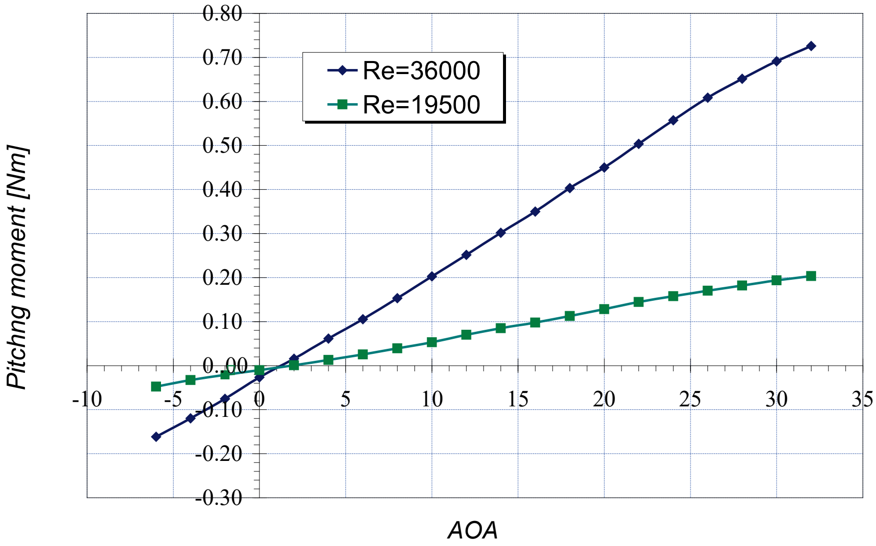

Fig. 8. Actuators on – pitching control configuration. Pitching moment in [Nm] vs. Angle of Attack

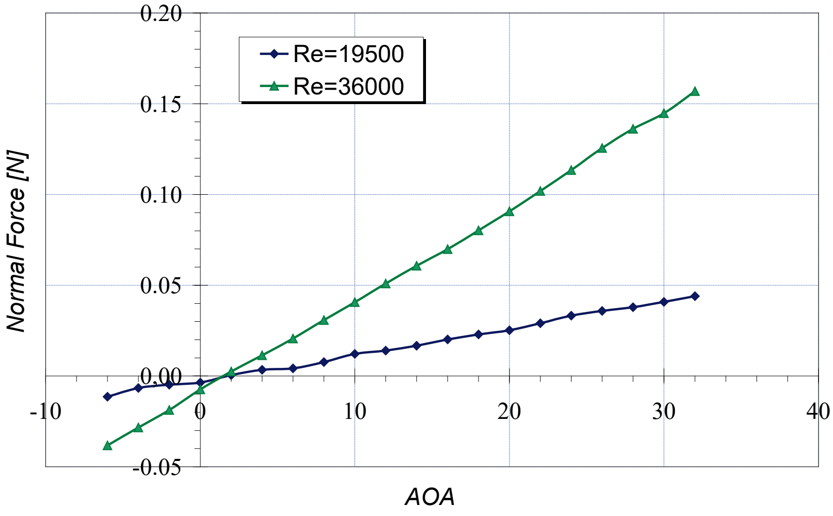

Fig. 9. Actuators on -rolling control configuration. Normal force in [N] vs. Angle of Attack

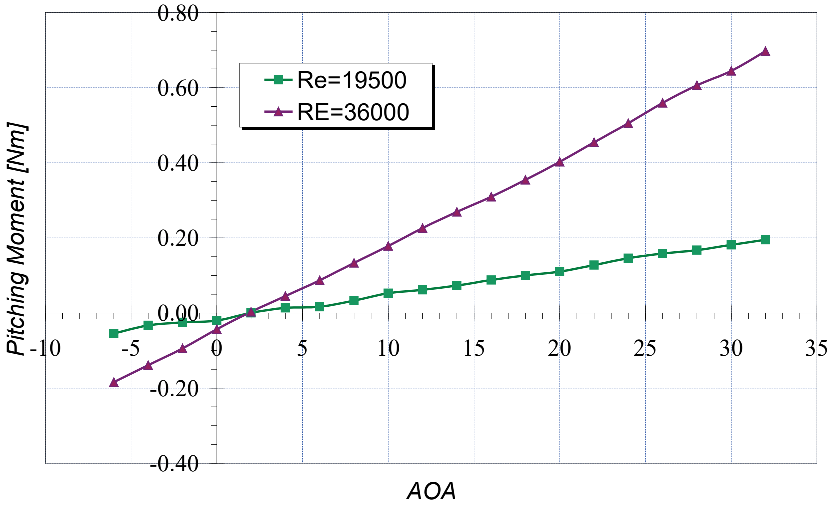

Fig. 10. Actuators on -rolling control configuration. Pitching moment in [Nm] vs. Angle of Attack

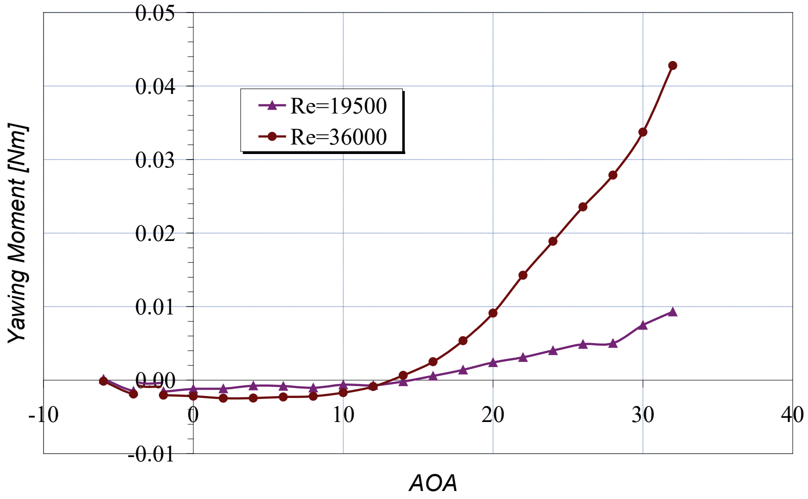

Fig. 11. Actuators on -rolling control configuration. Yawing moment in [Nm] vs. Angle of Attack

3.2. Pitching and yawing moments

The data from 5-component balance were also converted into moment coefficients as shown in Fig. 6-11. The increasing of pitching, yawing, and rolling moment coefficients are defined, respectively, as:

$$\Delta C_{N,m,n,l} = \frac{\left(C_{N,m,n,l}\right)_{actuators\ on} - \left(C_{N,m,n,l}\right)_{actuators\ off}}{\left(C_{N,m,n,l}\right)_{actuators\ off}} 100\%,$$

where $\Delta C_{N,m,n,l}$ normal force, pitching moment, yawing moment, and rolling moment coefficients respectively.

The maximum values of pitching, yawing and rolling moment coefficients as function of Reynolds number is shown in Fig. 12. The maximum value of pitching moment coefficient is 0.02683bat Re number = 20 000. The maximum value of rolling moment is 0.0263 at Re=70 000, and the maximum value of yawing moment coefficient is 0.00787 at Re=70 000. Those exemplary data are measured at Angle of Attack=25 deg.

Figures 13 and 13 show the increasing of steering moments caused by LED generators. It is clear, that it is possible to attain effective MAV control using LEV generators.

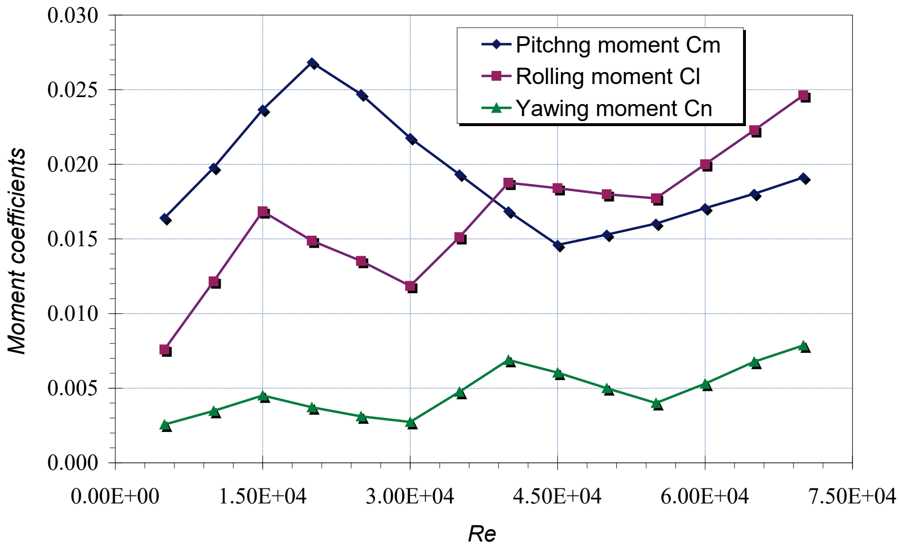

Fig. 12. Maximum values of rolling, pitching, and yawing moment coefficients at AOA=25 °

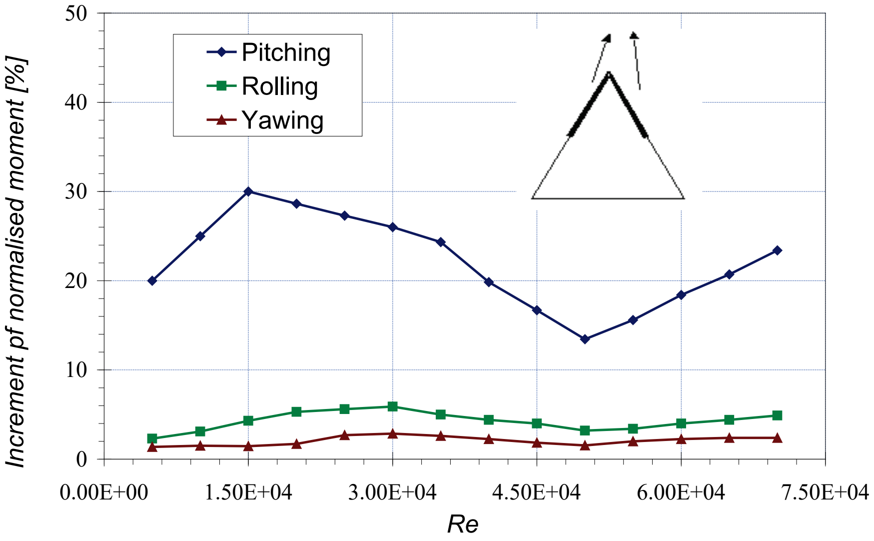

Fig. 13. Effectiveness of Pitching Control vs. Reynolds number at AOA=30 deg

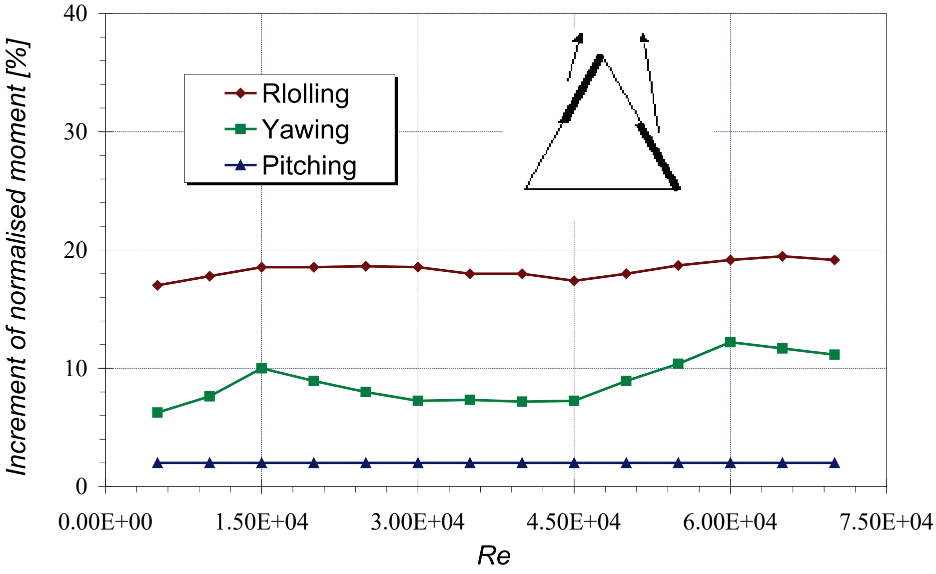

Fig. 14. Effectiveness of Yawing Control vs. Reynolds number at AOA=30 deg

4. Conclusion

A pair of nearly symmetric vortices separating from the leading edge characterizes the flow over a delta wing. At high angles of attack, these vortices make a significant contribution to the total lift of the wing. Hence, if the symmetry of these vortices can be broken by using micro actuators, it is possible to generate appreciable moments for flight control.

References

[1] Ericsson, L. E., Reding, J. P., *Approximate Nonlinear Slender Wing Aerodynamics*, AIAA Journal of Aircraft, Vol. 14, No. 12, pp. 1197-1204, 1977.

[2] Payne, F. M., Ng, T. T., Nelson, R. C., *Visualization and Wake Surveys of Vortical Flow over a Delta Wing*, *AIAA Journal*, Vol. 26, No. 2, pp. 137-143, 1988.

[3] Fink, P. T., Taylor, J., *Some Early Experiments on Vortex Separation*, Aeronautical Research Council, R & M., No. 3489, 1967.

[4] Lambourne, N. C., Bryer, D. W., *The Bursting of Leading-Edge Vortices-Some Observations and Discussion of the Phenomenon,* Aero. Res. Council, Reports and Memoranda, No. 3282, pp. 1-37, 1961.

[5] Lee, M., Ho, C. M., *Lift force of delta wings*, Applied Mech. Rev, Vol. 43, No. 9, pp. 209-221, 1990.

[6] Peckham, D. H., *Low-speed Wind-Tunnel Tests on a Series of Uncambered Slender Pointed Wings with Sharp Edges*, Aeronautical Research Council, R. & M. No. 3186, 1958.

[7] Earnshaw, P. B., Lawford, J. A., *Low-Speed Wind-Tunnel Experiments on a Series of Sharp Leading-edged Delta Wings*, Aeronautical Research Council, R. & M., No. 3424, 1964.

[8] Hall, M. G., *Vortex Breakdown*, Annual Review of Fluid Mechanics, Vol. 4, pp. 195-218, 1972.

[9] Polhamus, E. C., *Predictions of Vortex-Lift Characteristics by a Leading-Edge Suction Analogy*, *AIAA Journal of Aircraft*, Vol. 8, No. 4, pp. 193-199, 1971.

[10] Bradley, R. G., Wray W. O., *A Conceptual Study of Leading-Edge-Vortex Enhancement by Blowing*, *AIAA Journal Aircraft,* Vol. 11, No. 1, pp. 33-38, 1974.

[11] Wood, N. J., Roberts, L., *The Control of Vortical Lift on Delta Wings by Tangential Leading Edge Blowing*, AIAA, paper No. 87-0158, 1987.

[12] Campbell, J. F., *Augmentation of Vortex Lift by Spanwise Blowing*, *AIAA Journal of Aircraft,* Vol. 13, No. 9, pp. 727-732, 1976.

[13] Greenwell, D. I., Wood, N. J., *Roll Moment Characteristics of Asymmetric Tangential Leading-Edge Blowing on a Delta Wing*, AIAA Journal of Aircraft, Vol. 31, No. 1, pp. 161-168, 1994.

[14] Johari, H., Olinger, D. J., Fitzpatrick, K. C., *Delta Wing Vortex Control via Recessed Angled Spanwise Blowing*, AIAA Journal of Aircraft, Vol. 32, No. 4, pp. 804-810, 1995.

[15] Gu, W., Robinson, O., Rockwell, D., *Control of Vortices on a Delta Wing by Leading-Edge Injection*, AIAA Journal, Vol. 31, No. 7, pp. 1177-1186, 1993.

[16] Miyaji, K., Fujii, K., Karashima, K., *Enhancement of the Leading-Edge Separation Vortices by Trailing-Edge Lateral Blowing*, *AIAA Journal*, Vol. 34, No. 9, pp. 1943-1945, 1996.

[17] Meyer, J., Seginer, A., *Pulsating Spanwise Blowing on a Fighter Aircraft*, AIAA-92-4359-CP, pp. 188-197, 1992.

[18] Gad-el-Hak, M., Blackwelder, R. F., *Control of the Discrete Vortices from a Delta Wing*, AIAA Journal, Vol. 25, pp. 1024-1049, 1987.

[19] Celik, Z. Z., Roberts, L., *Aircraft Control at High-Alpha by Tangential Blowing*, AIAA Paper 92-0021, Jan. 1992.

[20] Greenwell, D. I., Wood, N. J., *Static Roll Moment Characteristics of Asymmetric Tangential Leading Edge Blowing on a Delta Wing at High Angles of Attack*, AIAA 93-0052, 1993.

[21] Fitzpatrick, K., Johari, H., Olinger, D., *A Visual Study of Recessed Angled Spanwise Blowing Method on a Delta Wing*, AIAA Paper 93-3246, July 1993.

[22] Malcom, G. N., Skow, A. M., *Flow Visualization Study of Vortex Manipulation of Fighter Configurations at High Angles of Attack*, AGARD CP-413, 1986.

[23] Alexander, M., Meyn, L. A., *Wind Tunnel Results of Pneumatic Forebody Vortex Control Using Rectangular Slots on a Chined Forebody*, AIAA Paper 94-1854, June 1994.

[24] Hummel, D., *Zur Umstromung sharfkantiger shlanker Deltaflugel bei grossen Anstellwinkeln,* Z. Flugwiss, Vol. 15, No. 10, pp. 376-385, 1967.

[25] Ross, F. W., Kegelman, J. T., *Recent Explorations of Leading Edge Vortex Flowfields*, NASA CP 3149, Vol. 1, Pt. 1, pp. 157-172, 1990.

[26] Shih, C., Ding. Z., *Trailing-Edge Jet Control of Leading-Edge Vortices of a Delta Wing*, AIAA Journal, Vol. 34, No. 7, pp. 1447-1457, 1996.

[27] Helin, H. E., Watry, C. W., *Effects of Trailing-Edge Jet Entrainment on Delta Wing Vortices*, AIAA Journal, Vol. 32, No. 4, pp. 802-804, 1994.

[28] Wahls, R. A., Vess, R. J., Moskovitz, C. A., *Experimental Investigation of Apex Fence Flaps on Delta Wings*, AIAA Journal of Aircraft, Vol. 23, No. 10, pp. 789-797, 1986.

[29] Marchman, J. F., *Aerodynamics of Inverted Leading-Edge Flaps on Delta Wings*, *AIAA Journal of Aircraft*, Vol. 18, No. 12, pp.1051-1056, 1981.

[30] Rao, D. M. Buter, T. A., *Experimental and Computational Studies of a Delta Wing Apex-Flap*, AIAA paper no. 83-1815, 1983.

[31] Rao, D. M., Johnson, T. D. Jr., *Investigation of Delta Wing Leading-Edge Devices*, *AIAA Journal*, Vol. 18, No. 3, pp. 161-167, 1981.

[32] Spedding, G. R., Maxworthy, T., Rignot, E., *Unsteady Vortex Flows over Delta Wings*, Proc. 2nd AFOSR Workshop on Unsteady and Separated Flows, Colorado 1987.

[33] Marchman, J. F., *Effect of heating on Leading Edge Vortices in Subsonic Flow*, *AIAA Journal of Aircraft*, Vol. 12, No. 2, pp. 121-123, 1975.

[34] Lee, G. B., *Control of a Delta-Wing Aircraft by Using Micromachined Sensors and Actuators*, Ph.D. Thesis, University of California, Los Angeles 1998.

[35] Lee, G. B., Jiang, F., Tsao, T., Tai, Y. C., Ho, C. M., *Macro Aerodynamics Devices Controlled by Micro Systems*, *IEEE Aerospace Conference,* Snowmass, CO, Feb. 1-8, 1997.

[36] Ho, C. M., Tai, Y. C., *Micro-electro-mechanical-systems (MEMS) and Fluid Flows*, Annual Review of Fluid Mechanics, Vol. 30, pp. 579-612, 1998.

[37] Liu, C., Tsao, T., Tai, Y. C., Ho, C. M., *Surface Micromachined Magnetic Actuators*, An Investigation of Micro Structures, Sensors, Actuators, Machines, and Systems, Proc. 7th Ann. Int. Workshop MEMS, Oiso, Japan, IEEE, pp. 57-62, New York 1994.

[38] Lee, G. B., Ho, C. M., Jiang, F., Liu, C., Tsao, T., Tai, Y. C., *Distributed Flow Control by MEMS*, ASME International Mechanical Engineering Congress & Exposition, Atlanta, Georgia, USA 1996.

[39] Gwo-Bin Lee, Yu-Chong Tai, Fukang Jiang, Charles Grosjean, Chang Liu, and Chih-Ming Ho, *Robust Vortex Control of a Delta Wing by Distributed Microelectromechanical-Systems Actuators*, AIAA Journal of Aircraft, Vol. 37, No. 4, 2000.

[40] http://www.rollinghillsresearch.com/Water_Tunnels/Model_2436.html

Manuscript received 09 May 2018; approved for printing 31 August 2018