Journal of Engineering and Applied Sciences 11 (11): 2465-2468, 2016
ISSN: 1816-949X

Flow Visualization Study of Vortex Formation for a Wing with Cavity

Tham Weng Hong, Noorfazreena Mohammad Kamaruddin and Zulfaa Mohamed-Kassim
School of Aerospace Engineering, Universiti Sains Malaysia,
14300 Nibong Tebal, Penang, Malaysia

Abstract: This study presents the feasibility of trapping vortex inside a cavity for various low aspect ratio wing configuration as a passive control mechanism. The vortex formation flow structures were investigated qualitatively at low Reynolds number of 26,000 at angles of attack of 0°, 5°, 10° and 15°. Three wing configurations were manufactured which consist of a solid wing model without any cavity, a wing model with a single cavity and a wing model with triple cavities. A smoke wire technique was employed to visualize the flow. The results revealed that the wing with cavity generally managed to trap stable vortex in a clockwise direction. The flow remained attached and delayed separation at high angles of attack compared to the non cavity wing model configuration. Triple cavities wing configuration has a higher vortex intensity which has the potential to enhance lift and ultimately improve the aerodynamic performance.

Key words: Vortex trapping, cavity, flow visualization technique, smoke, vortex

INTRODUCTION

The idea of vortex trapping was pioneered by Ringleb with the potential to delay flow separation and promote flow reattachment. This concept is known as passive control mechanism as it does not require any energy input. On the other hand, active control mechanism such as high lift device requires energy input (e.g., electrical) to operate. Manipulating trapped vortex has been identified to reduce the aircraft energy consumption with potential to increase lift as studied by Wadcock *et al.* (1999) and Yarusevych *et al.* (2009) the research team of VortexCell2050 (2005-2009). However, the challenge is to design an unconventional wing shape with cavity to trap the vortex, identify its strength, stability and ultimately understand the vortex flow physics inside the cavity.

Yeung (2006) has approached this concept numerically on a Joukowsky airfoil with single, double and triple cavities. He found the triple cavities configuration has the ability to generate 10% lift, higher than the conventional configuration. Donelli *et al.* (2010) further investigated this study by applying suction slot to confine the vortex inside the cavity. Recently, Shi *et al.* (2014) conducted a study on an NACA 0020 airfoil at Reynolds number of 5000 and observed the forming of trapped vortex by reverse flow inside the cavity instead of a typical shear layer. Tee (2015) then investigated this trapped vortex concept qualitatively on a low aspect ratio wing at high Reynolds number at around 43000. As the previous studies mainly covered for the airfoil case, the current study further investigates the work for a wing at lower Reynolds number of 26000 to identify the existence of trapped vortex inside the cavity within this range of Reynolds number and its potential to generate lift.

It is important to understand the fundamental concept of vortex trapping on a wing with cavity and the feasibility to enhance lift particularly for small aircrafts including Unmanned Aerial Vehicle (UAV). Instead of using active control mechanism which consumes energy and increases the structural complexity of the aircraft, vortex trapping may potential enhace lift without the additional complexity and energy. This concept can be employed for many small aircraft applications including cloud seeding to overcome haze in Asian region as the high life device can be replaced with a vortex trapping mechanism.

MATERIALS AND METHODS

Wind tunnel: The experiment was performed at the Wind Tunnel Laboratory, School of Aerospace Engineering, Universiti Sains Malaysia. The closed-loop wind tunnel has a maximum speed of 80 m sec^{-1}, a rectangular test section of 1.0×0.8×1.8 m, a contraction ratio of 10:1 and turbulence level of 0.1%. A wooden test section window is used to replace the original Perspex to minimize any reflection induced by the camera or halogen light. The airspeed and angle of attack of the wing model are controlled by National Instruments Data Acquisition (NI-DAQ) system. All 3 models configuration were tested at angle of attack of 0°, 5°, 10° and 15° with Reynolds number of 26,000 corresponding to speed of 1.5 m sec^{-1}.

Corresponding Author: Noorfazreena Mohammad Kamaruddin, School of Aerospace Engineering, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia

Wing model: The 3 wing models configuration as shown in Fig. 1 were made of Aluminum which consisted of solid flat plate without cavity with single cavity and with triple cavities. The models were designed by Tee (2015) with an aspect ratio of 2, chord of 0.25 m, wingspan of 0.5 m, wing thickness of 0.03m and the cavity shape is based on Yeung (2006)'s configuration. The solid flat plate without cavity will serve as a baseline to identify and compare the effectiveness of vortex trapping capability. All cavities are designed to have a length-to-depth ratio of 2.75 with distance between cusp to cusp of 0.055 m and a maximum depth of 0.02 m. The ratio of horizontal curvature length to vertical height ratio for the first cusp design is 7.5 with a vertical height of 0.0028 m, measured from the upper surface of the flat plate wing model.

Smoke wire set up: Smoke wire system was initially developed by Nazri (2015) to visualize the vortex formation. Current study, several improvements were made to improve the quality of the images that involved single Nichrome wire with diameter of 0.25 mm. It was installed vertically in the wind tunnel test section as shown in Fig. 2 to heat and evaporate the Safex oil to generate smoke lines. Nichrome wire was placed at 4 cm from the wing tip to provide clear images of the flow structures across the models. Safex oil was dripped on the wire manually from the top of the wind tunnel test section by using a syringe. Halogen bulbs with 240 V and 50 W were installed and clamped by retort stands above and below the test section to capture and illustrate the flow structures. The top and bottom background wall of the test section was covered with black paper to avoid any reflection. A camera was placed at the outside of wind tunnel test section, perpendicular to the direction of smoke to capture and record the formation of vortices inside the cavities.

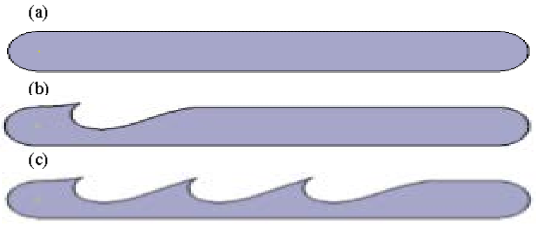

Fig. 1: Model configuration: a) Without cavity; b) With single cavity and c) With triple cavities

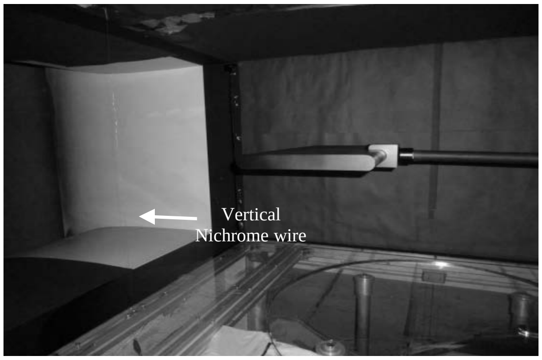

Fig. 2: Vertical Nichrome wire set up in the test section

RESULTS AND DISCUSSION

The flow structures of the smoke patterns across the models for solid, single cavity and triple cavities were captured at angles of attack of 0°, 5°, 10° and 15°. The images are illustrated in Fig. 3-5 for Reynolds number of 26,000 corresponding to 1.5 m $\sec^{-1}$. The flow direction is from left to right.

Effect of angle of attack for a solid wing model without any cavity: Figure 3a shows that the smoke wire produced smooth streamlines which means the flow remained attached for the solid flat plate wing model with a stagnation point (zero velocity) exactly on the nose of the leading edge. The flow was evently

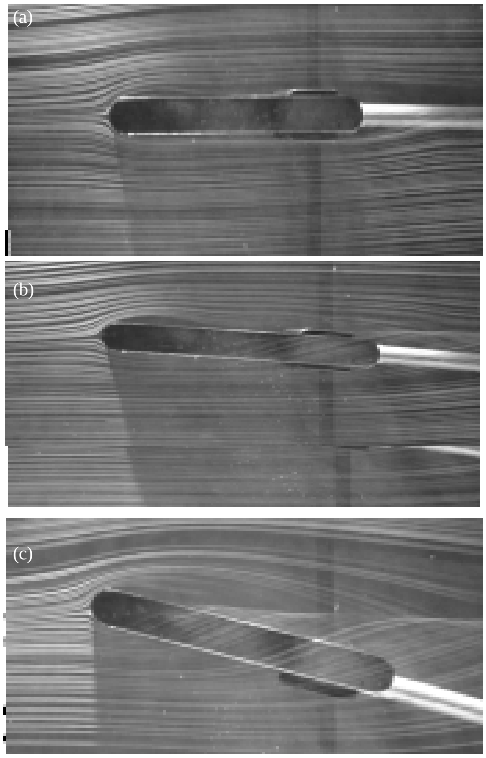

Fig. 3: Flow pattern across a solid wing model without cavity for angle of attack of: a) 0°; b) 5°; c) 10° and d) 15° at Reynolds number of 26,000

distributed over the model and a small separation bubble can be observed (although not significant) at the upper surface. The flow started to separate when the attached laminar boundary layer experienced an adverse pressure gradient and then curved back to form a small region of reverse flow, creating the separation bubble. The separated layer will reattached again where the momentum transfer had occurred. This laminar separation bubble modified the effective shape of the plate which might influence the air flow field and aerodynamic performance. Similar separation bubble phenomenon was also observed by Saxena (2009) due to low speed and low Reynolds number.

As the angle of attack increased to 5° and 10° as illustrated in Fig. 3b, c, respectively the flow separated closer towards the leading edge. The stagnation point shifted towards the lower surface of the model. The increase in the angle of attack delayed the flow reattachment after the formation of laminar separation bubble. Due to the pressure difference between the upper and lower surfaces of the wing, the air circulated from the high pressure region to the low pressure region, creating a wingtip vortex.

When the wing model pitched to 15° as illustrated in Fig. 3d, flow separated completely as vortex shedding developed on the upper surface of the flat plate without any reattachment. This phenomenon is known as the stall condition where the wing experiences a sudden loss of lift due to flow separation. This condition occurs due to a stronger adverse pressure gradient on the upper surface of the flat plate while the flow does not have adequate energy to overcome it. The adverse pressure gradient occurred and the flow lost its kinetic energy due to shear stress, resulting in the deceleration of flow. The intensity of wingtip vortices increased due to the increasing pressure difference between the top and bottom of the flat plate.

Effect of angle of attack for a single-cavity wing model: Figure 4a shows that the flow remained attached with the stagnation point maintained at the leading edge similar to the baseline model at zero angle of attack. There is no existence of laminar separation bubble as observed in the previous baseline case. Based on our recorded video, the flow was observed to enter the cavity in a clockwise direction to generate the trapped vortex. The vortex was found to be stable inside the cavity and managed to promote flow reattachment which is consistent with the numerical results by Yeung (2009). This clockwise flow direction and stable trapped vortex inside the cavity has the potential to generate lift as similar phenomenon was also observed in Shi *et al.* (2014) case study.

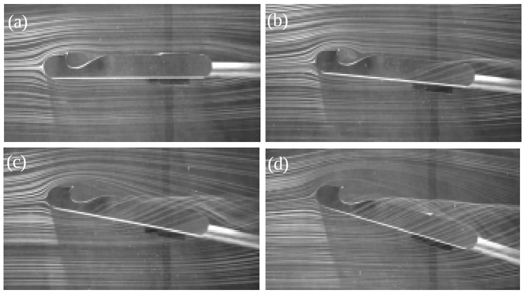

Fig. 4: Flow pattern across a wing model with single cavity for angle of attack of: a) 0°; b) 5°; c) 10° and d) 15° at Reynolds number of 26,000

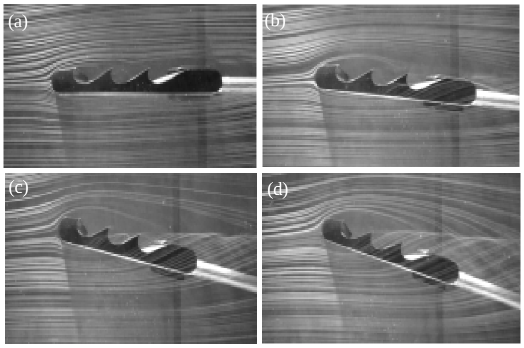

Fig. 5: Flow pattern across a wing model with single cavity for angle of attack of: a) 0°; b) 5°; c) 10° and d) 15° at Reynolds number of 26,000

As the angle of attack increased to 5° (Fig. 4b) the stable trapped vortex was observed to be rotating in a clockwise direction and the flow remained attached with wingtip vortices observed closer towards the trailing edge. As the wing is pitched to 10° (Fig. 4c), the flow still remained attached over the model. However, no vortex was observed to enter the single cavity. This could be due to a high intensity of kinetic energy of trapped vortex inside the cavity which could not be captured with the current set up. Further, quantitave study can be conducted in the future to verify this phenomenon.the leading edge. No trapped vortex was observed in the cavity and stall condition occurred at this stage. The intensity of wingtip vortices was higher based on the motion captured by the video as compared to the case with the 10° angle of attack.

Effect of angle of attack for a triple-cavity wing model: At zero angle of attack as shown in Fig. 5a, the flow remained attached with stagnation point occurred exactly on the nose at the leading edge similar to the previous cases without any separation bubble. Based on the recorded video, the flow was observed to enter the first two cavities in clockwise direction with strong intensities to trap a vortex in each cavity. However, as the vortex intensity grows stronger in the third cavity, the camera could not capture the trapped vortex image. Stable clockwise vortices were trapped in all three cavities and lift enhancement is expected to occur as shown numerically by Yeung (2009).

As the angle of attack increased to 5° as illustrated in Fig. 5b, the flow separated earlier than the previous case closer towards the leading edge and no vortex was found to be trapped in the first cavity. But, the separated shear layer entered the second and third cavities to form clockwise vortices, promoting flow reattachment at the trailing edge of third cavity. The vortex motion in the third cavity was also contributed by the wingtip vortices.

As the wing is pitched to 10° (Fig. 5c, there is no vortex captured in the first cavity, similar to the previous case. However, the clockwise vortices in the second and third cavities were observed to be generated by the wingtip vortices that entered the cavity. At the angle of attack of 15° as illustrated in Fig. 5d), the flow separated completely which was similar to the case for the baseline model at the same angle of attack. No vortices were captured in the cavities as stall condition occurred at this stage. Although, there were wingtip vortices circulated and entered the second and third cavities, no vortices were found rotating inside the cavities.

CONCLUSION

The formation of vortices trapped inside a single and triple-cavity wings with low aspect ratios (AR = 2) were investigated by using a smoke wire technique at Reynolds number of 26,000. The research aims to generate trapped vortices inside the cavities as an alternative technology for passive control mechanism to enhance lift. Flow streamlines for single and triple cavity were observed to remain attached at high angles of attack compared to those of a no-cavity wing configuration. Vortices formed in clockwise direction inside the cavities for lower angles of attack are stable and has the potential to enhance lift. Load measurement can be conducted in the future to quantify the amount of lift generated by the trapped vortices for single and triple-cavity wings configuration.

ACKNOWLEDGEMENTS

The researcher acknowledge financial support from Universiti Sains Malaysia under the Short Term Grant (304.PAERO.60312043), technical supports from Mr. Mohamad Najhan Awang and Mr. Mahmud Isa, wing designs by Ms. Tee Yi Hui and experimental setups by Mr. Anuar M. Nazri from the School of Aerospace Engineering USM.

REFERENCES

Donelli, R.S., D.G. Fabrizio and P. Iannelli, 2010. Flow separation control by Trapped Vortex. Proceeding of the 48th AIAA Aerospace Sciences Conference on Including the New Horizons Forum and Aerospace Exposition, January 4-7, 2010, AIAA, Orlando, Florida, pp: 1-19.

Nazri, A.M., 2015. Development of smoke system for USM wind tunnel flow visualization study. MA Thesis, Universiti Sains Malaysia, George Town, Malaysia.

Saxena, A., 2009. The laminar separation bubble. Maryland., 1: 1-6.

Shi, S., T.H. New and Y. Liu, 2014. On the flow behaviour of a vortex-trapping cavity NACA0020 aerofoil at ultra-low Reynolds number. Proceeding of the 17th International Symposium on Applications of Laser Techniques to Fluid Mechanics, July 7-10, 2014, Shanghai Jiao Tong University, Lisbon, Portugal, pp: 1-12.

Tee, Y.H., 2015. Development of smoke wire system for Vortex trapping application. MA Thesis, Universiti Sains Malaysia, George Town, Malaysia.

Wadcock, A.J., J. Tso and R.M. Cummings, 1999. An experimental analysis of vortex trapping techniques. J. Fluids Eng., 121: 555-559.

Yarusevych, S., P.E. Sullivan and J.G. Kawall, 2009. On vortex shedding from an airfoil in low-Reynolds-number flows. J. Fluid Mech., 632: 245-271.

Yeung, W.W.H., 2006. Lift enhancement on unconventional airfoils. J. Mekanikal, 22: 17-25.

Yeung, W.W.H., 2009. Vortex trapping on a surface with an indentation and corrugations. Math. Comput. Simul., 79: 3243-3257.