IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 13, Issue 1 Ver. VI (Jan- Feb. 2016), PP 46-52
www.iosrjournals.org

A CFD study of the performance characteristics of vented cylinders as vortex generators

Kishan Ramesh Kumar, Sumant Morab, Suhas Shekar, Arun Mahalingam
Mechanical Department, National Institute of Technology Karnataka- NITK, India

Abstract: *This paper mainly researched on influence of vortex generator on lift coefficient and drag coefficient, when vortex generator is mounted on a flat plate. Vented cylinders were used as vortex generators which intensify vortex shedding in the wake of the vented cylinder as compared to base line circular cylinder which ensures more attached flow and increases lift force of the system. Firstly vented cylinders were analyzed in commercial CFD software which is compared with baseline cylinders for different angles of attack and further variation of lift and drag forces were studied by varying Reynolds number to account for influence of turbulence and boundary layer in the flow. Later vented cylinders were mounted on a flat plate and variation of lift and drag coefficients was studied by varying angles of attack and studying the dependence of Reynolds number and dimensions of vortex generator on the coefficients. Mesh grid sensitivity is studied to check the convergence of the results obtained It was found that usage of vented cylinders as vortex generators increased lift forces with small variation in drag forces by varying angle of attack.*

Keywords: *CFD analysis, drag coefficient, lifts coefficient, vortex generators and vortex shedding*

I. Introduction

Vortex shedding in the wake of the cylinder is still one of the main research topics in fluid dynamics. Controlling vortex shedding and identifying methods to use vortex shedding for our benefit is an important issue. Using immersion boundary method [1] vortex shedding is studied in flat plates numerically where vortex shedding was considered as a travelling-wave nature and the trend of vortex shedding was discussed using this method. Vortex shedding was studied by many people by using many theories in different types of objects trying to make the theories more generic. Vortex shedding from yawed cylinders [2] was studied by conducting various experiments to quantify vortex shedding frequency in the wake of the yawed cylinder and verifying the dependence of yaw angle of the cylinder and vortex shedding frequency by changing normal velocity component of the medium.

Numerous theories and experiments were conducted to analyze vortex shedding in the wake of bluff bodies. Von Karman Street defines vortex shedding as staggered periodic chain of vortices with alternating rotational direction and where the spacing is derived from a stability consideration and differing Reynolds number. Based on this model many models have tried to find relation between Reynolds number and vortex shedding frequency [3] mathematically and found that as Reynolds number increases drag force decreases around bluff bodies and the relations between wake energy and vortex sizes was derived and proved Roshko's experiments around cylinders. Different types of designs of cylinders were studied to analyze vortex shedding where D-shaped cylinders [4] where it was found that flow separation does not change and drag is reduced and wake is steady by experimental analysis and numerical verifications. Numerical analysis when a cylinder is mounted on a flat plate [5] was studied with different parameters like aspect ratios, no slip condition, free slip conditions and accordingly the wake of the cylinder was studied for different Reynolds number and solved using PISO algorithm solution of the equations were solved with time step dependent courant flow number. For high Reynolds number vortex shedding was studied using large eddy simulation [6] the approach is to divide the flow field into smaller sub grid models for small scale and analyzing for large turbulent scales.

Few of the papers discussed modifications of cylinders with slits [7] where Particle image velocimetry was used to study vortex shedding and vortex shedding in slit cylinder was more regular than that of a baseline cylinder. This implied that slit modification resulted in enhancement of wake flow variation. Slit vent modification reduced boundary layer shed and can efficiently explain Karman vortex street phenomenon.

Few researchers have researched on vortex shedding from step cylinder [8] where, different diameter cylinders have been aligned to study nature of the vortex interaction in the split cylinder which mainly depends on the circulation of each vortices and its decay and more pronounced vortex shedding [9] was witnessed in vented cylinders for different angles of attack for vented cylinder and also oscillating cylinders [10].

The present study employs analyzing vented cylinders as vortex generators which ensure attached flow hence lift force increases for varying angles of attack when mounted on a flat plate.

Nomenclature

D = Diameter of cylinder
D_v = Diameter of vented cylinder
C_D, C_L = Drag coefficient, Lift coefficient
Re = Reynolds Number
x = space coordinates in stream-wise direction
y, z = space coordinates in transverse direction
u, v, w, t = velocity of air in x, y and z direction and time
p = pressure
μ = kinematic viscosity
ν = dynamic viscosity
ρ = density of the medium
a = slit width
α = angle of attack
k, ε = turbulent kinetic energy, turbulent dissipation
CFD = Computational fluid dynamics
FVM = Finite Volume Method

II. Governing Equations and Solution Methodologies

Governing Equations

Vortex shedding in the wake of the cylinders is governed by time dependent continuity equation and set of Navier stokes momentum equations in all the directions in Cartesian coordinate system. k-ε Turbulence model was used to solve for the intense vortex shedding produced by the vortex generator. The governing equations are

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

Fluid properties like pressure (p) and fluid density (ρ) play a major role on the eddy size and frequency of vortex shedding.

Boundary Conditions and Solution Methods

Domain of the flow is always includes inlet and outlet boundaries along with the wall for the external flow over a cylinder. To verify the correctness of the results and to check for suitable pressure velocity coupling algorithm to govern vortex shedding in the wake. For the ease of validation, boundary conditions from [5] are used and checked for flow over a cylinder and compared with flow over a vortex generator for low Re=200. Similarly from [6] for high Re=1000000, vortex shedding is compared between a baseline cylinder and vented cylinder. Inlet turbulence intensity levels are considered in our study to check the sensitivity of results.

Flow domain for mounted vented cylinder over a flat plate was considered similar to [1] ensuring the dimensions of the domain big enough to avoid divergence of the solution and reverse flow due to negative gauge pressure near the boundaries of the domain along with no slip boundary conditions were considered over the system wall. The domain is as shown below. Vortex shedding is an unsteady phenomenon where Coupled pressure velocity coupling algorithm was used to solve transient in-compressible flow after rigorous study. An axis-symmetric model was considered for the ease of solving the coupled set of equations which govern the external flow and to check the periodicity of vortex shedding. To account for vortex shedding in wake a suitably low time step was considered in transient formulation.

Fig. 1. Domain of vented cylinder mounted on flat plate

III. Results And Discussions

Flow over a vented cylinder as vortex generator

Vortex generators are used to delay flow separation to the system which in turn increases lift forces accordingly for different angles of attack. Different types of Vortex generators could be used like prisms, delta shaped, vane type etc. which serve the main purpose to increase the lift force. Here we use vented cylinders as vortex generators which includes through slits in a normal baseline cylinder which increases turbulence in the wake of the cylinder and delays separation of turbulent boundary layer when compared with laminar boundary layer which further increase lift.

Simulating flow over a cylinder in [5] was studied, where a numerical approach was used to account for vortices and accordingly grid mesh sensitivity was conducted and readings were recorded. By applying similar boundary conditions, we obtain lift and drag coefficients per unit span of length for each angle of attack from below formulae

$$C_D = \frac{2F_D}{\rho v^2 D} \tag{4}$$

$$C_L = \frac{2F_L}{\rho v^2 D} \tag{5}$$

$$Re = \frac{\rho v d}{\mu} \tag{6}$$

Where F_D and F_L are drag and lift forces respectively. For the first case when D=10mm, Re=200 which is very low where it could be considered as laminar flow, lift and drag coefficients were found and compared with [5] where drag coefficients were approximately same as shown in Table I. Varying angle of attack lift and drag forces were calculated computationally and further from the above formulae lift and drag coefficients were calculated for a normal baseline cylinder. Since baseline cylinder is symmetric along x-axis and y-axis the lift and drag coefficients are independent of angle of attack.

TABLE I. Comparison of Experimental [5, 6] and Computed Results

Re	Experimental	Computed	Error
	C_D	C_D	
200	1.45	1.426	0.024
100000	1.2	1.278	0.078
1000000	0.4	0.535	0.135

By applying the same boundary conditions for simulating flow over a vortex generator, a vented cylinder in this case angle of attack plays a major role in the lift and drag forces. Here D_V=10mm for ease of comparison, applying same boundary conditions and having ratio of diameter of vented cylinder and slit width as 10 which is to ensure slenderness of the slit compared to diameter. Now varying the angle of attack we obtain lift and drag forces and accordingly obtain lift and drag coefficients. As angle of attack increases lift force increase and accordingly lift coefficient also increases. We observe from Fig.2 that rate of change of lift coefficient w. r .t angle of attack is very less and drag coefficient almost remains constant for α less than 20 degrees which is our area of interest.

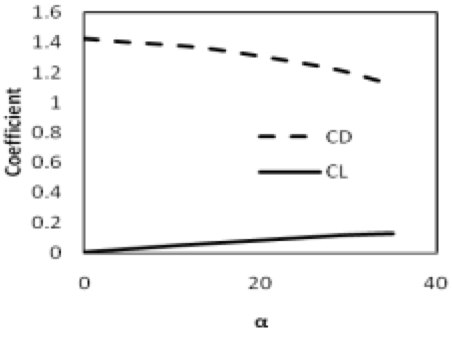

Fig. 2 Lift and Drag coefficient v/s α for Re = 200

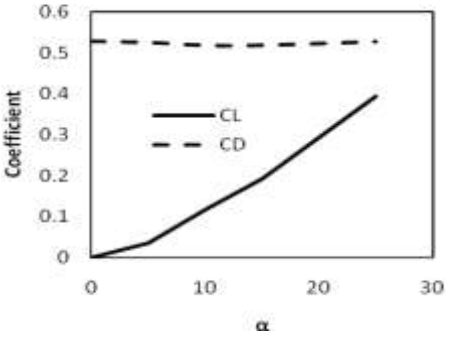

Fig. 3 Lift and Drag coefficient v/s α for Re = 10^6

This shows that at low Re, though there is vortex shedding it is not prominent to be used for flow attachment of the body and increase the lift forces.

Simulating the flow over a cylinder for two more Re cases Re=100000, 1000000 [6] where experimental approach and numerical approach to study vortex shedding was shown. Applying same boundary conditions and studying the flow in commercial CFD FVM code, for Re=1000000, we obtain lift and drag forces where we obtain lift and drag coefficients respectively as shown in Table I. Applying same boundary conditions to analyze vented cylinder using same dimensions D_V = 10mm and ratio of diameter of vented cylinder and slit width as 10 we obtain Fig. 3 which Lift and Drag coefficients v/s angle of attack. Here we observe that rate of increase in Lift coefficient w. r. t angle of attack as compared to Fig. 2 is more which shows the turbulence nature of the flow. In Fig. 3 Drag coefficients remains constant for every angle of attack. This proves that as Re increases drag coefficient decreases and lift coefficient increases with the increase in angle of attack.

As Re increases Drag crisis phenomenon was observed where sudden decrease of drag force associated with point of separation of flow in the case of flow over cylinder. Similarly the same phenomenon was witnessed, hence the optimum Re is always below 350000 to avoid drag crisis. Hence for further analysis Re= 275000 is considered to analyze flow over a cylinder or vortex generator mounted on a flat plate.

Flow over a Vented Cylinder Mounted On Flat Plate

Most of the applied aerodynamic research occurs to increase lift force and trying to control the flow at moderately high speeds by delaying or fixing the point of separation of the flow. Lots of research has occurred in vortex shedding in flat plates [1] trying to understand shedding phenomenon. Aerodynamic research began with flat plates and drifted towards more streamline airfoil shape for better control over flow. In our study we analyze normal baseline cylinder mounted on flat plat and compare the same with mounting vented cylinders on flat plate of same dimensions with a definite slit width at the same position on the plan-form area. From the previous section we observed that to avoid drag crisis phenomenon, the considered Reynolds number is lower than limiting value. Considering Re = 275000, the flow was considered transient to account of for shedding using same k-ε model similar to previous case and solving using coupled pressure velocity solution methodology. Reynolds number is calculated from the formulae shown where d in the formula is the characteristic length of the system which is the ratio of four times the area of body and perimeter of the body. The study of the flow was considered with flat plate having aspect ratio 10:1 and ratio of the breadth of flat plate and diameter of the cylinder is 10:3. The latter ratio is considered to ensure boundary layer length dependence on the dimensions of the vortex generator and to study the effects of the same. The cylinder was mounted at a distance 1/8th from the leading edge of the flat plate and dependence of the placement of the cylinder is studied later. The flow domain was considered similar to [6] where the ratios of the domain w. r. t the dimensions of flat plate were big enough to avoid divergence and reverse flow characteristics. The flow is analyzed and accordingly lifts and drag coefficients are calculated from lift and drag forces respectively. Similarly repeating the same conditions and replacing normal base line cylinder with vented cylinder and keeping the same ratio of diameter and slit width as 10:1 we study the flow and observe more intense vortex shedding compared to previous case. In the wake of the vortex generator, intense turbulence levels are witnessed with very low pressure and velocity values which indicate more circulation of the velocity which serve the basic purpose of the vortex generators.

Varying the angle of attack to the body and calculating lift and drag forces for each angle of attack for both the above cases and accordingly the calculated lift and drag coefficients are plotted in Fig 4 and Fig 5 respectively. From Fig 4 we see that compared to normal baseline cylinder vented cylinder mounted on flat plate generates more lift which shows the delay in flow separation and since the width of the slits are very less the drag forces experienced are same which is shown in Fig 5. The angle of attack is varied up-to 16 degrees considering stall phenomenon. After 16 degrees the solution starts diverging and which signifies the stall phenomenon. Vortex generators also ensure that less noise is produced especially during take-off considering research in aero-acoustics. Many parameters decide the frequency of vortex shedding like slit width, angle of slits with x-axis, dimensions of vented cylinder w. r. t the flat plate, Reynolds number, position of the vented cylinder on the plan-form area of the flat plate etc.

To check the boundary layer development on the flat plate i.e. transition from laminar boundary layer and significant development of turbulent boundary layer the position of vortex generator is shifted from 1/8th to 1/4th of the length away from the leading edge of the flat plate. Applying the same boundary conditions similar to the previous one and using same solution methodology lift and drag forces were calculated, accordingly lift and drag coefficients were calculated. Fig 6 shows the results of the simulation where compared to Fig 4 the lift coefficient has increased for every angle of attack and rate of change of lift coefficient with angle of attack is also increased. After $\alpha=16^0$ we observe that lift coefficient saturates and solution diverges which signifies stall phenomenon where sudden reduction of lift force is observed. The drag force is slightly reducing with the rise of angle of attack as shown in Fig 7 yet it remains the same compared to cylinder case. There is slight reduction of drag coefficient from Fig 5 compared to Fig 7 after $\alpha=10^0$ which shows the delay in the separation of turbulent boundary layer which tend to increase with rise of angle of attack. Similar to lift coefficient drag coefficient also saturates after angle of attack exceeds 14^0 in both baseline cylinder and vented cylinder.

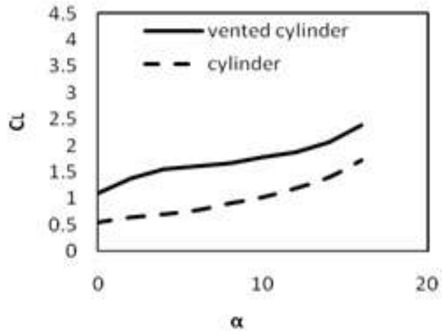

Fig. 4 Coefficient of lift v/s angle of attack

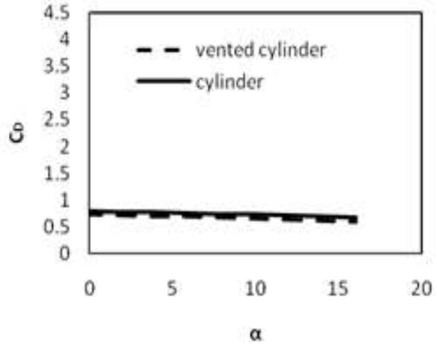

Fig. 5 Coefficient of drag v/s angle of attack

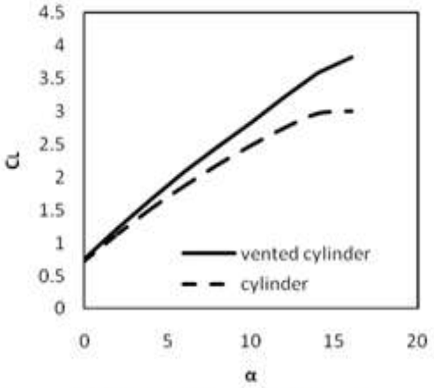

Fig. 6 Coefficient of lift v/s α for 1/4th position

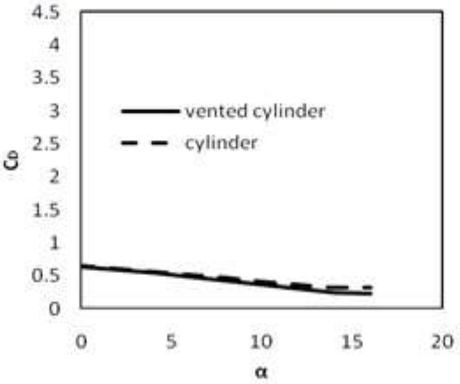

Fig. 7 Coefficient of drag v/s α for 1/4th position

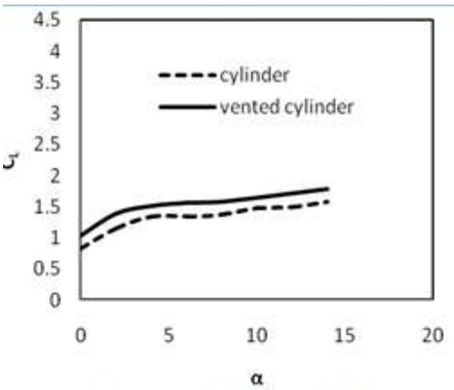

Fig. 8 Coefficient of lift v/s α for Re=10^6

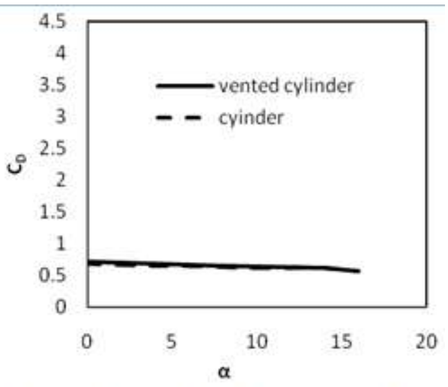

Fig. 9 Coefficient of drag v/s α for Re=10^6

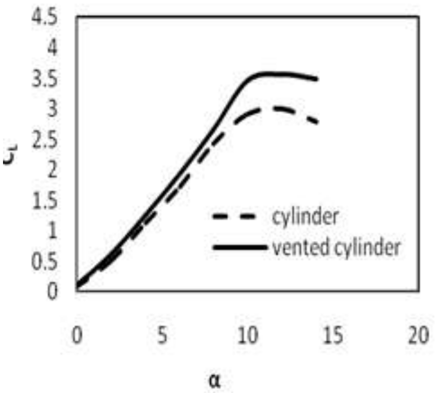

Fig. 10 C_L v/s α when D_v is reduced by 2

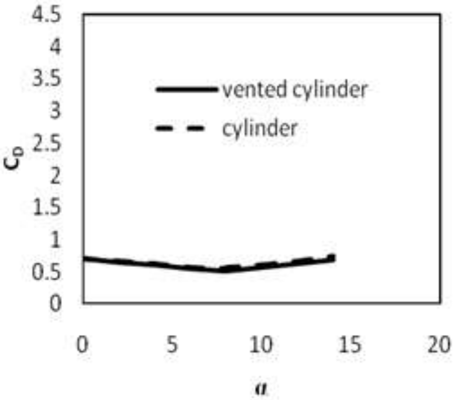

Fig. 11 C_D v/s α when D_v is reduced by 2

Increasing Reynolds number decreases lift and drag coefficients since vortex shedding does not occur at a distinct single frequency but over a narrow band of frequency along with position of wake formation. In our study we changed Re=10^6 and analyzed the lift and drag coefficients by varying angle of attack keeping other parameters same as Fig 4. We observe from Fig 8 and when compared to Fig 4, the lift coefficients have decreased by a constant factor and trend of the variation remains approximately same. The drag coefficient Fig 9 has also decreased but by a very small amount to quantify yet we observe that there is no variation between vented cylinder and normal baseline cylinder.

The dimensions of the vortex generator w. r. t bluff body we consider also influences lift and drag coefficient where there are types of vortex generators like low profile, high profile vortex generators etc. Dimensions include slit width which help in reduction of boundary layer shed and make the shedding of vortices more regular and increased frequency of shedding compared to normal baseline cylinder. In our study for studying dependence of dimensions, 'D_V' and 'a' is reduced by factor 2 from the original case. Comparing Fig 10 and Fig 4 we observe that lift coefficient has increased by a considerable amount for rise in angle of attack. As slit width decrease, more regular vortex shedding is observed and increase in lift forces at early stages of angle of attack along with decrease in stall angle of attack compared to original case.

Dependence of many factors were studied on lift and drag coefficients and compared with normal baseline cylinder, where it clearly demonstrates that more lift is produced in the case of vented cylinder.

Grid Mesh Sensitivity

In a commercial CFD solver using FVM code, analysing grid mesh sensitivity is very important as it proves the convergence of the results obtained. Grid Mesh Sensitivity Results were checked with increasing refinement relevance centres from 1 to 3 and percentage variance of lift and drag forces compared with original case were obtained and error was found to be within 2 % hence it proves convergence of the solution.

IV. Conclusion And Future Scope

From the above cases we can conclude that as Reynolds number increases lift and drag forces decrease and also frequency of shedding spreads over a band of frequencies. The dimensions of the vented cylinder and slit width also play a major role which decides the boundary layer involvement in the study. The position of the vortex generator influences the delay in the flow detachment and accordingly increases lift coefficient depending on the boundary layer regime.

Usage of vented cylinders as vortex generators which could be mounted on wing and analyzing the flow in the future and its dependence on symmetric nature of airfoil and position of vortex generator with dimensions could be further studied.

References

[1] Alexander Yakhot, and Heping Liu, “Vortex Shedding from Rectangular Plates”, AIAA journal, Vol 42, NO 7, Technical Notes.

[2] A R Hanson, “Vortex Shedding From Yawed cylinders”, AIAA Journal, Vol 4, NO 4.

[3] Boye Ahlborn, Mae L. Seto and Bernd R. Noack, “On drag, Strouhal number and vortex-street structure”, Elsevier Journal, Fluid dynamics research, 30 (2002) 379–399.

[4] Chandrakant D. Mhalungekar and Swapnil.P.Wadkar, “CFD and Experimental analysis of vortex shedding behind D- shaped cylinder”, International Journal of Innovative Research in advanced engineering (IJIRAE), ISSN: 2349-2163, Vol 1 Issue 5, 2014.

[5] K. Satpathy , K. Velusamy , B. S. V. Patnaik and P.Chelapindi , “Numerical Investigation of Vortex shedding Past a finite Circular cylinder Mounted on flat plate”, Taylor Francis Journal, Numerical Heat transfer Applications ISSN: 1040-7782.

[6] P. A. B. de Sampaio and A. L. G. A Coutinho, “Simulating Vortex shedding at high Reynolds number” International Offshore and polar engineering conference, International Society of offshore and polar engineers, ISSN 1098-6189.

[7] Wang Junwei, Yang Jinwen, He Yi, Bao Feng, “Experimental Study of slit cylinder vortex shedding in circulating water Channel”, IEEE conference, 2012 International Conference on Measurement, Information and control, 978-1-4577-1604-.

[8] C Morton and S yarusevych, “Vortex dynamics in the Turbulent wake of single step cylinder” Journal of fluids Engineering – ASME, Vol 136, March 2014

[9] Suryanarayana, G. K, Meier G. E. A and Pauer Henning, “Vented circular cylinder as Vortex generator”, Journal Of visualization, Vol 8, No 3 2005.

[10] M Tutar, A E Holdo and A. P Lewis, “Simulation of Vortex Shedding from an oscillating circular cylinder”, AIAA journal 98-3021

[11] H Veersteeg and W. Malasekra, “An Introduction to Computational Fluid Dynamics”, Finite Volume Method Book, Second Edition.

[12] John C Lin, “Review of research on low profile vortex Generators to control boundary layer separation”, Elsevier Journal, Progress in Aerospace sciences, 38 (2002) 389-420.

[13] M.Tutar, A.E.Hold and A.P.Lewis, “Simulation of vortex shedding from an oscillating circular cylinder”, AIAA journal, 98-3021.

[14] Marinos Manolesos and Spyros G.Voutsinas, “Experimental investigation of the flow past passive vortex generators on an airfoil experiencing three-dimensional separation”, Journal of wind engineering and industrial aerodynamics, 142(2015)130-148.

[15] Behzad Ghadiri Dehkordi and Hamed Houri Jafari, “On the suppression of vortex shedding from circular cylinders using detached short splitter plates”, Journal of fluids engineering- ASME, Vol. 132 / 044501-1.

[16] Bruce J. Wendt, “Parametric Study of Vortices Shed from Airfoil Vortex Generators”, AIAA JOURNAL Vol. 42, No. 11, November 2004.