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COMPUTATIONAL FLUID ANALYSIS OF FLOW AROUND A FINITE HEIGHT CIRCULAR CYLINDER USING SPLITTER PLATE

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By

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COMPUTATIONAL FLUID ANALYSIS OF FLOW AROUND A FINITE HEIGHT CIRCULAR CYLINDER USING SPLITTER PLATE

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Reducing drag force over non-streamlined bodies and controlling shedding of vortices behind them has been known as two major problems concerning flow control and aerodynamic studies. In the present study circular cylinder was chosen as the bluff body under investigation in a subcritical flow regime with Re = 3000. The cylinder is mounted to the surface, and possess variety of heights relative to its diameter, D, defined as cylinder aspect ratio AR with four variations of 3, 6, 9, and ∞ which is same as an infinite cylinder. Two Splitter plates are used as passive control apparatuses in the form of detached and mounted to the surface with no oscillation just with the same height as the cylinder and are mounted upstream and downstream of the cylinder. Splitter plates' length were relative to the cylinder diameter specified as L_1/D and L_2/D. Likewise the gap between plates and the cylinder were defined relative to D as G_1/D and G_2/D. Variation of plates' length and gap ratio resulted in different combinations in which the best possible choice for each AR has been sought in this study. This optimum state was defined as a combination where the most drag reduction and vortex suppression was found.

Numerical solution has been deployed to measure the mean drag coefficient, Strouhal number and power spectra at the cylinder mid-height point. The effectiveness of the splitter plates were found in (i) reducing the drag which was mostly resulted by the upstream plate with its relative position as the dominant factor (comparing to its length ratio) and (ii) weakening or in some cases suppressing the vortex shedding, primarily as the result of implementation of downstream plate, while the key variable determined to be its length ratio unlike the upstream plate. Due to the presence of upstream plate at its optimum position (G_1/D = 1.5) a reduction of 7.9% up to 16.8% has been achieved depending on the cylinder aspect ratio. Speaking about the aspect ratio, the longer the cylinder was, the more effect it took concerning drag reduction.

Downstream plate however acted less efficient in diminishing the drag force as in dual mode in which both plates are present, the maximum drag reduction reached 9.4% up to 18.5%. As regards of the vortex shedding suppression though, shorter cylinders found to be easier in controlling the shedding, the necessity of employing longer plates to suppress the shedding behind cylinders with higher aspect ratio is a proof to this fact, as for the short cylinder with AR=3 a plate with $L_2/D=1.5$ is enough to suppress the vortices, while a lengthier plate with $L_2/D=5$ is required to suppress the vortices in a cylinder with AR=9.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Master Sains

ANALISIS PENGKOMPUTERAN BENDALIR BAGI ALIRAN SEKITAR SUATU KETINGGIAN TERHINGGA SILINDER BULATAN MENGGUNAKAN PLAT PEMBELAH

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Pengurangan daya seretan terhadap badan bukan garis arus dan pengawalan vorteks tumpahan di belakangnya merupakan antara dua masalah utama bagi kawalan aliran dan kajian aerodinamik. Kajian masa kini memilih silinder bulat sebagai badan tipuan dimana kajian dilakukan dalam rejim aliran dengan Re = 3000. Silinder dipasang di atas permukaan dan mempunyai pelbagai tahap relatif diameter,D, dimana ianya ditakrifkan sebagai nisbah silinder aspek AR dengan empat variasi 3, 6, 9, dan ∞ yang sama sebagai silinder tak terhingga. Dua plat pemisah digunakan sebagai radas kawalan pasif dalam bentuk berkembar dan dipasang dipermukaan tanpa ayunan hanya dengan ketinggian yang sama dengan silinder. Ianya dipasang di hulu dan hilir silinder. Panjang plat pemisah adalah relatif kepada garis pusat silinder yang dinyatakan sebagai L_1 / D dan L_2 / D. Jurang antara plat dan silinder pula telah ditakrifkan relatif kepada D sebagai G_1 / D dan G_2 / D. Perubahan panjang dan jurang nisbah plat menghasilkan kombinasi yang berbeza di mana pilihan yang terbaik bagi setiap AR telah dicari dalam kajian ini. Keadaan optimum ini telah ditakrifkan sebagai gabungan di mana pengurangan seretan yang paling tinggi dan penindasan vorteks ditemui.

Penyelesaian berangka telah digunakan untuk mengukur min pekali seret, nombor Strouhal dan kuasa spektrum dibahagian titik tengah silinder. Keberkesanan plat pemisah ditemui dapat (i) mengurangkan seretan yang kebanyakannya disebabkan oleh plat huluan dengan kedudukan relatif sebagai faktor dominan (berbanding dengan nisbah panjang) dan (ii) melemahkan atau dalam beberapa kes menekan vorteks tumpahan, terutamanya hasil daripada pelaksanaan plat hiliran, manakala pembolehubah utama yang ditetapkan sebagai nisbah panjangnya tidak seperti plat huluan. Oleh kerana kehadiran plat pemisah hulu pada kedudukan yang optimum (G_1 / D = 1.5) pengurangan 7.9%

sehingga 16.8% telah dicapai bergantung kepada nisbah aspek silinder. Bercakap mengenai nisbah aspek, semakin panjang silinder itu, semakin berkesan ianya mengambil mengambil masa bagi pengurangan seretan. Plat hiliran adalah kurang berkesan dalam mengurangkan daya seretan. kerana dalam mod dual, pengurangan drag maksimum ialah 9.4% sehingga 18.5%. Berhubung dengan vorteks tumpahan penindasan, silinder lebih pendek didapati lebih mudah dalam mengawalan penumpahan itu, keperluan dalam menggunakan plat yang lebih panjang untuk menindas tumpahan dibelakang silinder dengan nisbah aspek yang lebih tinggi menjadikan bukti kepada hakikat kajian ini. untuk silinder pendek dengan AR = 3 plat dengan L_2 / D = 1.5 adalah cukup untuk menyekat vorteks, tapi plat yang lebih panjang dengan L_2 / D = 5 diperlukan untuk menekan pusaran dalam silinder dengan AR = 9.

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This is to confirm that:

- The research conducted and the writing of this thesis was under our supervision;
- Supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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LIST OF ABBREVIATIONS

AR Cylinder aspect Ratio (Cylinder's length to its diameter ratio)

a Acceleration, m/s^2

C_d Mean drag coefficient, $2F_d/$[illegible]

C_L Mean lift coefficient, [illegible]

C_P Mean pressure coefficient, [illegible]

C_{Pb} Mean pressure coefficient at cylinder's base point

C_{Ps} Mean pressure coefficient at cylinder's stagnation point

C_v Special heat capacity in constant volume, J/kg.K

D Cylinder diameter, m

δ Plate's thickness, m

F Force, N

F_b Body force, N

F_D Drag force, N

F_L Lift force, N

f_s Vortex shedding frequency, 1/s

G_1 Gap between upstream plate's trailing edge and cylinder's stag point, m

G_2 Gap between cylinder's base point and downstream plate's trailing edge, m

Γ Viscous dissipation

H Cylinder height

K Fluid thermal conductivity

L	Characteristic length, m
L_1	upstream plate's length, m
L_2	Downstream plate's length, m
μ	Fluid dynamic viscosity, Pa.s
P	Fluid pressure, Pa
P_∞	Free stream pressure, Pa
[illegible]	Fluid density, kg/m^3
Re	Reynolds number, [illegible]$U_\infty D/\mu$
St	Strouhal number, [illegible]
σ	Normal stress, pa
t	time, s
T	Fluid temperature, K
TS	Time step
[illegible]	Tangential stress, pa
[illegible]	Fluid shear stress, [illegible], Pa
U	Velocity, m/s
U_∞	Free stream velocity, m/s
u	Velocity component in x direction, m/s
v	Velocity component in y direction, m/s
w	Velocity component in z direction, m/s

CHAPTER 1

INTRODUCTION

1.1 Overview

Generally, there are two types of immersed bodies that become subjects of study for flow control, namely streamlined and non-streamlined bodies. Streamlined bodies are those that are aligned with the flow passage while non-streamlined bodies which are also known as bluff bodies, resist the fluid flow and this resistance results in the production of undesirable forces. Variety of features related to flow around bluff bodies including drag forces, vortex shedding behind the body, generation of downstream wakes and flow separation are considered in the study of flow control. The above mentioned features associate this scope of fluid dynamic to engineering applications, some of which are industrial stacks, bridge pillars, large and slender buildings and submerged pipelines, etc.

A comprehensive understanding of flow characteristic around these body is required, so that a proper solution to this problem can be established. The non-streamlined shape of the body causes a blockage in the fluid flow results in creation of pressure difference between two sides of the body as shown in the Fig 1.1. A high pressure point that is formed at the upstream of the body is called stagnation point while this point's low pressure counterpart exists just at the opposite side of the body denominated base point (Rathakrishnan, 1999). The differentiation between those mentioned points generates a resisting force known as pressure drag which requires a counterbalance force to compensate the movement disorder.

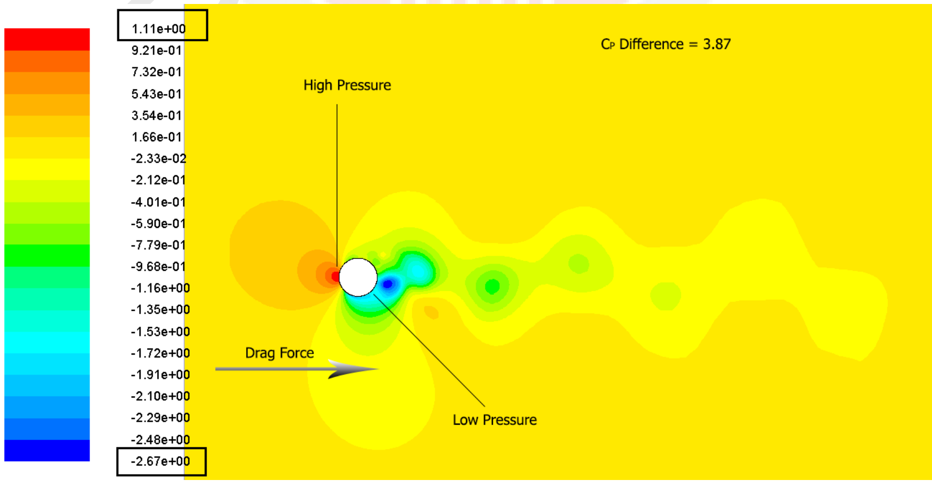

Figure 1-1. Pressure coefficient distribution around a non-streamlined body

Moreover flow separation is another undesirable phenomenon which results in inefficient operations in submarine and air applications of bluff bodies. A positive pressure gradient in the direction of the fluid movement leads to deceleration of the moving fluid while passing the body, causing an unwanted reduction in the flow kinetic energy in the boundary layer until the flow reaches a zero or sometimes negative velocity relative to the direction of the flow (Braza, Chassaing, & Minh, 1986). This type of pressure distribution which is known as adverse pressure gradient triggers the most unpleasant consequences in moving fluid such as the above mentioned phenomenon, flow separation (Batham, 1973). This sort of gradient is dominantly observed in flows over non-streamlined bodies. Negative aspects of flow over bluff bodies are not merely limited to pressure forces to the body itself as a type of oscillating flow forms behind the body called vortex shedding (P. W. Bearman, 1984; Perry, Chong, & Lim, 1982). These vortices detach periodically and form a low pressure area downstream of the body which helps the improvement of the pressure drag as well (P. W. Bearman & OWen, 1998).

Shedding of vortices also leads to the formation of Kármán Vortex Street behind the body in the wake area, this may also lead to undesirable motions called flow-induced vibration (Chen, 1987). Development of new research works follows the purpose of weakening or even suppressing these unwanted motions and forces. Many strategies and devices have been developed and applied to alter the flow behavior over these bodies in order to lessen negative features.

1.2 Flow Control

Generally, flow control is applying strategies in order to positively alter the behavior of flow motion. There have been numerous flow control methods, however all of them are categorized in two different types namely active and passive controls. Active flow control, in which the flow is controlled by inducing external forces such as blowing, suction and sound waves exertion, demands complicated equations and systems due to the presence of extra motors, pumps or speakers. Alternatively by modifying the shape of the body, attaching additional elements, changing the roughness, or varying the flow incident degree it becomes easier and less costly to control flow over the body, which are considered as passive flow control. Many attempts have been made to achieve a proper and effective method in the area of passive control. Their main purpose is to use aerodynamic means in front of or behind the blockage and reduce flow-induced forces by controlling the separation of shear layers (Murakami, Mochida, & Sakamoto, 1997). Varying the inlet flow regime, using end-plates, control cylinders, hinged or detached splitter plates or grooving the bluff body are some of the examples of passive control. Roshko's study can be referred as one of the earliest investigations in the scope of passive aerodynamic control

(Roshko, 1954).

The initiative of using control cylinders and splitter plates in his studies broadened new horizons in regards to passive flow control, mostly to infinite length bodies. The mentioned devices were mainly used to suppress vortex shedding and reduce drag over the bluff bodies. Those researches were then followed by Apelt where in his studies a circular cylinder was used as the controlled body and splitter plates were used downstream of the body to control vortices as well (Apelt, West, & Szewczyk, 1973; Apelt & West, 1975). Tripping rod were also applied in Alam's experiment over 2 cylinders with tandem arrangement to control aerodynamic forces (Alam, Sakamoto, & Moriya, 2003).

Among the mentioned studies in which different apparatuses were identified in order to modify the fluid flow, there were some other researches involved with similarities between characteristics of wake behind various bluff bodies, such as the size of formation region, and the rate of shed vortices (Gerrard, 1966). These studies which are known as universal parameter formulation were later continued in two forms of analytical empirical models (P. Bearman, 1967; Griffin, 1981). In most of universal parameter formulations there are common scales which are defining equations. As an example, the forming parameters of Strouhal number, which is the product of a frequency scale in a length scale over a defined velocity scale. These scales were chosen differently in various studies, as in some of them freestream velocity corresponded to characteristic velocity (Fage & Johansen, 1928), while shear-layer velocity replaced the same scale in another study (Griffin, 1981). Meanwhile Roshko constructed his parameters using wake width as length scale and shedding as frequency characteristic (Roshko, 1954).

There are several add-on devices which have been employed in order to delay flow separation, suppress vortex shedding, narrow wake width and eliminate flutter effects. One of these add-on devices is splitter plates which have been applied in some studies as an attached apparatus (Akilli, Karakus, Akar, Sahin, & Tumen, 2008; Sudhakar & Vengadesan, 2012), hinged to the cylinder (Shukla, Govardhan, & Arakeri, 2009) or in the form of detached as it has been in the most recent studies (Dehkordi & Jafari, 2010; Hwang, Yang, & Sun, 2003; Hwang & Yang, 2007; A Igbalajobi, McClean, Sumner, & Bergstrom, 2013).

1.3 Problem Statement and Hypothesis

The main problems arise from the cylinder flow namely the drag force and the vortex shedding. The solution is sought by employing splitter plates. Many studies have been conducted using splitter plates, while there were a number of gaps in those researches which are being covered in this study. Different cylinder height to diameter ratio, which is known as aspect ratio are investigated in the current study.

Although previous studies of flow control over cylinder by splitter plate has covered a wide range of Reynolds numbers, there are still flow regimes which has not been comprehensively covered by those studies. On the other hand an overview to the Application of splitter plates clarifies that most of the researches apply either upstream of downstream plate as the controlling device, to achieve one of the objectives of current study; drag reduction (Apelt & West, 1975) or vortex suppression (Apelt et al., 1973). While by placing both plates at the same time both objectives can be obtained (Hwang & Yang, 2007). The use of splitter plate has been examined primarily for the two-dimensional bodies, still many engineering applications involve flow around finite bodies. Those few researches which include both plates, however, are conducted in the 2-dimensional domain in which the effect of cylinder aspect ratio is disregarded. The author of this manuscript intends to combine the techniques in the mentioned studies in order to fill the gap in this area. By applying both plates in a 3-dimentional domain, this study seeks a solution to overcome both drag and vortex shedding issues in a subcritical flow regime.

The research hypothesis is based on the anticipated outcome of the study which is the reduction of drag forces and elimination of vortex shedding behind a circular cylinder by two splitter plates as control devices.

1.4 Aims and Objectives

The thesis mainly concerns numerical investigation on the effect of splitter plates on the enhancement of the flow over a surface-mounted circular cylinder. The study aims to examine the effectiveness of this supplement on the drag reduction and vortex elimination by mounting one of the splitter plates upstream and one on the wake region of the cylinder. The primary objectives of the study are listed below.

◎xTo assess the effect of placing splitter plates on the drag reduction, vortex suppression and flow enhancement; separately and both together.
◎xTo investigate the effect of cylinder aspect ratio (AR) on the flow and optimize the splitter plates' configuration of length and gap ratio in each cylinder AR.
◎xTo validate the study with the previous carried out researches. This phase includes the comparison of the calculated drag force, Strouhal number and also visualization of the flow in the Re = 3000.

1.5 Scope of the Study

The study is performed for flow with Reynolds number of Re = 3.0×10^3 in which a subcritical flow regime is defined for a finite heighted circular cylinder. The Reynolds number is defined based on freestream streamwise velocity and cylinder diameter. Circular cylinders has been considered surface mounted with free tip exposed to the flow.

The measuring parameters are drag coefficient (C_d), Pressure coefficient (C_P) and Strouhal number (St). Parameters to be varied are cylinder AR which leads to a dual domain analysis (two dimensional and three dimensional), plates' thickness (t), plates' length to the cylinder diameter ratio (L_1/D and L_2/D) and plates' gap ratio relative to the cylinder diameter (G_1/D and G_2/D). The effectiveness of upstream and downstream plate will be evaluated separately and will be compared for both finite and infinite case. Finite case refers to study over a cylinder with a specific aspect ratio.

1.6 Thesis Outline

Chapter 2 provides a comprehensive review on the previously conducted studies pertaining flow control over circular cylinders applying attached, detached or hinged splitter plates. Various literatures are criticized which contains flow analysis of finite and infinite cylinders in an approximately 60 years' time-span. Chapter 3 thoroughly discusses about problem setting, time, domain, and mathematical model which are used during this study. Results and further discussions over this study are embedded in chapter 4. Research conclusion, future scopes and recommendations are presented in chapter 5.

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