# Aerodynamic forces acting on a circular cylinder with splitter plate at incidence

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**ABSTRACT:** Aerodynamic forces acting on a circular cylinder with splitter plate is experimentally investigated at the range of attack angle between 0° and 180° with an increment of 3° for Re = 20000. In order to show the relation between Strouhal number, lift and drag coefficient and Reynolds number, force measurements are also carried out for the range of Re between 9700 and 36500 at the attack angles of 0°, 45°, 90°, 135°. Lift and drag coefficient is largely independent of Reynolds number changing between 9700 and 36500 for these angles. The results showed that Strouhal number, drag coefficient and lift coefficient is widely independent of Reynolds number.

**Keywords:** *Circular Cylinder, Splitter Plate, Drag Coefficient, Lift Coefficient*

## Atak Açısında Ayırıcı Plakalı Bir Dairesel Silindire etki eden Aerodinamik Kuvvetler

**ÖZET:** Ayırıcı plakalı bir dairesel silindir üzerine etki eden aerodinamik kuvvetlerin deneysel olarak Re = 20000 için 3° artışlarla 0°-180° atak açısı aralığında incelenmiştir. Kuvvet ölçümleri Re = 9700 – 36500 aralığı için 0°, 45°, 90°, 135° ve 180° derece atak açılarında, Strouhal sayısı kaldırma ve sürükleme kuvveti, ve Reynolds sayısı arasındaki ilişkiyi ortaya koyabilmek için gerçekleştirilmiştir. Kaldırma ve sürükleme katsayıları Re = 9700 – 36500 aralığında Reynolds sayısından büyük ölçüde bağımsız olduğu görülmüştür. Sonuçlar göstermiştir ki, Strouhal sayısı, kaldırma ve sürükleme katsayıları Reynolds sayısından büyük ölçüde bağımsızdır.

**Anahtar Kelimeler:** *Dairesel Silindir, Ayırıcı Plaka, Sürükleme Katsayısı, Kaldırma Katsayısı*

## 1. INTRODUCTION

Circular and square cylinders called as bluff bodies are required to control the flow around them because of their some disadvantages such as fluctuating forces that can cause vibration and also resonance, wide wake region and vortex shedding. Therefore, these bluff bodies have been drawn attention by researchers in order to eliminate the unwanted effect with the help of flow control methods that can be classified as active and passive flow control methods. Active flow control methods, such as piston-cylinder mechanism[1], suction and blowing [2], dielectric barrier discharge (DBD) actuator [3,4] entail an external energy to control a flow. Whereas, in passive flow control methods, such as splitter plates [5,6], control rod [7–9], dimple[10], it needs only geometrical modification. Available literature, especially about flow control around a circular cylinder with splitter plate, has been summarised below.

Akansu et al. [6] investigated the effect of splitter plate on the flow around a circular cylinder at L /D = 1. Velocities via hot wire anemometer and pressure distributions around a splitter plate placed behind the circular cylinder at attack angle between 0 and 180 were measured. They obtained the vortex shedding frequency from velocity measurement and, drag and lift coefficients acting on the circular cylinder with the plate from pressure measurements at Re = 20000. They also showed that the Strouhal number is widely independent of Reynolds number changing from 8000 to 60000. Their results showed that the minimum drag coefficient is obtained at 75 degree. Apelt et al. [11] performed an experimental study to investigate the effect of splitter plate on the rear circular cylinder at L / D ≤ 2. In this study, vortex shedding frequencies and pressure distributions were measured in the range 10000 < Re < 50000 at the water tunnel. Their results showed that circular cylinder with splitter plate significantly decreased the drag coefficient due to augmentation in the base pressure and there was no significant change in Strouhal number. In another study of Apelt and West [12], they investigated the effect of a circular cylinder with splitter plate for the ratio of the length of splitter plate to the diameter of the circular cylinder (L/D) from

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L/D = 2 to 7 at the similar Reynolds number in their previous study [11]. Their results indicated that Strouhal number and drag coefficient significantly changed with increasing the L/D up to 5. When L/D is bigger than 5, on the one hand, the drag coefficient is stable at 0.8, on the other hand, vortex shedding is suppressed. Cimbala and Garg [13] researched the effect of freely rotatable cylinder with splitter plate changing up to L/D = 5. They measured the velocity of air by using hot wire anemometer in order to determine the vortex shedding frequency and performed the smoke-wire flow visualization. Their results showed that the rotatable cylinder plate model stayed constant at 22 degrees for L/D = 1 because of pressure balance between upper and lower side of the plate. Nakamura [14] performed an experimental study for different shape bluff bodies with splitter plate in order to determine the vortex shedding frequency at the range of Reynolds number from 300 to 5000. These bluff bodies include circular, semi-circular with and without rectangular block and normal flat plate.

The aim of present study is to investigate the effect of the splitter plate on the rear of the circular cylinder at L/D = 1 for Re = 20000. The lift and drag force measurements are carried out by using a load cell at different attack angles between 0° and 180° with an increment of 3°. Moreover, the Strouhal number is calculated from these lift forces data.

## 2. EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUES

An experimental study is carried out at an open and suction type wind tunnel having a square test section 57 cm x 57 cm. The test section, having a divergence angle of 0.3 degree from its inlet to outlet, is composed of transparent Plexiglas. Free-stream turbulence intensity is smaller than 1%. Free stream velocity within the test section can be adjusted via using frequency inverter.

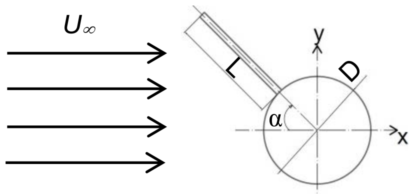


**Figure 1.** Schematic view of the circular cylinder with splitter plate

Figure 1 shows the schematic view of the circular cylinder with the splitter plate. The test model is composed of the circular cylinder, the splitter plate and two end plates that are manufactured from Plexiglas. The circular cylinder having a diameter of 40 mm and end plates having 300 mm diameter and 5 mm thickness were assembled in order to obtain uniform flow structure acting on the assembled model. The distance between the end plates with the bevelled angle of 45° is 400 mm. A blockage ratio of the cross section area of the circular cylinder with splitter plate to the cross section area of the test section is equal to 6 % at an incidence angle of 90°. The test model was centered on test section and mounted on ISEL ZD30 rotary unit so as to rotate it clockwise direction between β=0° and 180° with an increment of 3° for force measurements. For Reynolds number, based on diameter of circular cylinder (D), of 20000, force measurements were carried out by using a six axis ATI Gamma DAQ F/T load cell which is attached to the rotary unit and this force data was collected as 10000 data at a sample frequency of 0.5 kHz with the help of NI PCIe-6323 DAQ card. The load cell could measure forces up to ±32 N at the direction of x and y axis. Pitot tube placed in the test section is connected to ManoAir500 micromanometer in order to measure free stream velocity ($U_\infty$). All experiments were conducted twice so as to provide the repeatability. The uncertainties for the drag and lift coefficients were calculated as 6.2% and 6.8%, respectively.

## 3. RESULTS AND DISCUSSION

For a circular cylinder with and without splitter plate, lift and drag coefficient results are presented. Force measurement experiments were carried out by using a load cell. The lift coefficient ($C_L$) is expressed as $C_L = (2F_{Lnet})/\rho AV^2$ where $F_{Lnet}$ is net lift force acting on the model, $\rho$ is density of air, $A$ is the cross-section area of the model based on $D$ and $V$ is the velocity of air. Figure 2 shows the variation of lift coefficient as a function of attack angle for a circular cylinder with and without a splitter plate at Re = 20000. As seen in this Figure, lift coefficient changes significantly with the angle of incidence. $C_L$ starts to augment with increasing the angle of attack up to 12° and reaches a maximum value of 3.1. Lift coefficient has zero values at 72°, 153° and 180°. This can be explained with a pressure balance between upper and lower side of splitter plate. When this present study results are compared with Akansu et al. [6] for a circular cylinder with a plate at L/D = 1, the lift coefficient results shows significant differences. This is because Akansu et al. [6] calculated the lift coefficients from the surface pressure measurement data of the circular cylinder only, that is, they did not take into account of the pressures acting on the plate for Re = 20000. The maximum difference in $C_L$ between the present and Akansu et al. [6] studies is occurred at 12°. The lift coefficient decreases with increasing the angle of incidence from 33° to 120°. This decrease is due to the increased pressure on the upper side of the circular cylinder with the plate. Due to the pressure increment on the lower surface of the model, lift coefficient increases up to 162° again. At this angle, the value of $C_L$ is 1.36 and after this angle, it starts to decrease again.

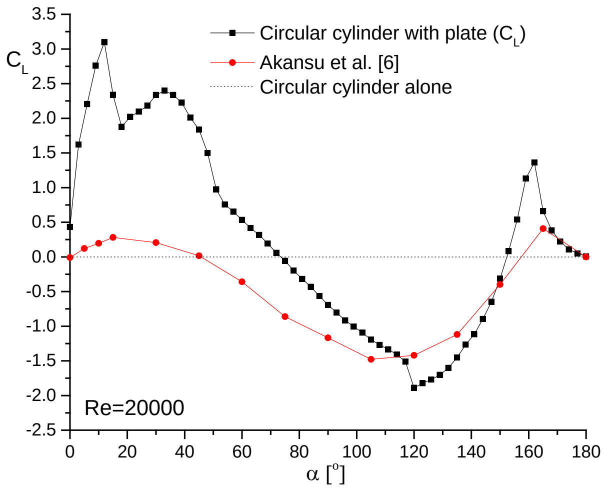


**Figure 2.** Lift coefficient versus angle of attack

The drag coefficient ($C_D$) is expressed as $C_D = (2F_{Dnet})/\rho AV^2$ where $F_{Dnet}$ is net drag force acting on the model, $\rho$ is density of air, $A$ is the cross-section area of the model based on $D$ and $V$ is the free stream velocity of air. Figure 3 shows the variation of drag coefficient as a function of attack angle for a circular cylinder with splitter plate at Re = 20000. When these $C_D$ results are compared with those of Akansu et al. [6], as it was in lift coefficient plot, there are considerable differences among them because of the same reason mentioned above. $C_D$ is obtained as 0.86 at α = 0° and starts to decrease with the angle of incidence up to 9°. Maximum drag reduction is 48.3% at this angle. From 9° to 45°, the drag coefficient increases abruptly owing to increasing the cross section area of the test model with the angle of incidence. Maximum drag coefficient is obtained as 2.9 at 45° and 2.6 at 84°. For α <18° and α >150°, the drag coefficients of a circular cylinder with the plate are smaller than those the bare circular cylinder.

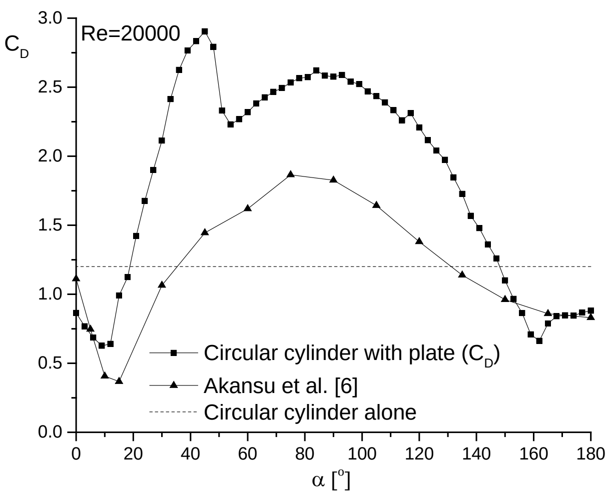


**Figure 3.** Drag coefficient variation versus angle of attack

For α >165°, $C_D$ of the present study shows a similar trend with that of the study of Akansu et al. [6], because the splitter plate within the flow around the model at these angles doesn't produce significantly the pressure drag or friction drag. In this case, the splitter plate only eliminates any interaction of the separated shear layer, therefore the drag reduction is obtained as 30% between 165° to 180°. There is an apparent drag reduction (45%) at 162°.

In order to determine the effect of the Reynolds numbers over the circular cylinder with plate at incidence, force measurement experiments were carried out at Re = 9700, 13000, 16500, 19600, 23000, 26300, 29700, 33000 and 36500 for 0°, 45°, 90°, 135° and 180°. Figure 4 indicates the variation of lift coefficient as a function of Reynolds number for these incidence angles. The variations of lift coefficient considerably depend on the angle of attack and there is no significant effect of Reynolds number between 9700 and 36500 over the lift coefficient. Therefore, lift coefficient is widely independent of Reynolds number in contrast to the angle of attack.

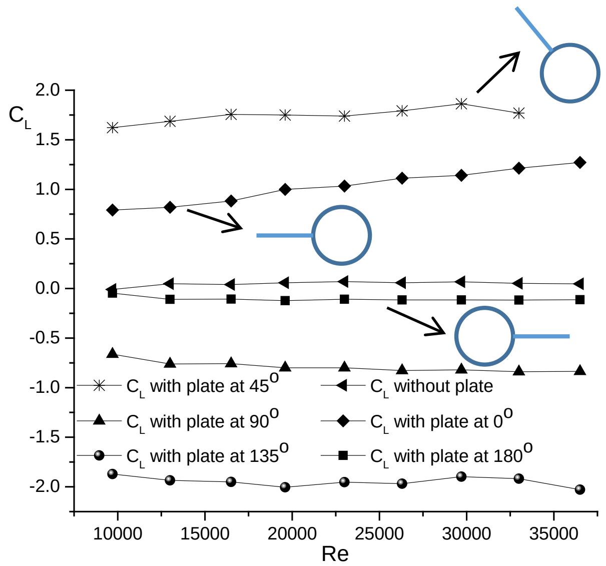


**Figure 4.** The variation of lift coefficient with Reynolds number for different angles of incidence

The variation of the drag coefficient versus Reynolds number for the circular cylinder with/without splitter plate is plotted in Fig. 5. Drag coefficient acting on the circular cylinder with/without splitter plate shows significant variation with changing attack angle at 0°, 45°, 90°, 135° and 180°. But when Reynolds number increases from 9700 to 36500, the drag coefficient is nearly constant for each attack angle. It can be concluded that drag coefficient widely depends on the angle of attack.

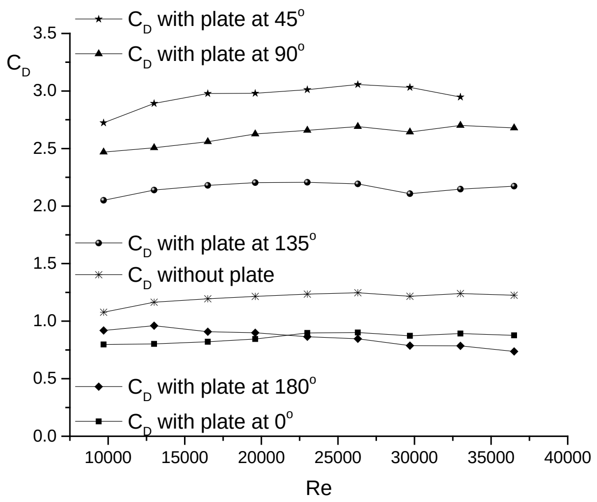


**Figure 5.** The variation of drag coefficient with Reynolds number for different angles of incidence

The vortex shedding frequency around the test model for each measurement is obtained from Fast Fourier Transform (FFT) analysis of the lift force data at a wide Reynolds number range. Time histories of lift force data for bare circular cylinder are shown in Figure 6 (a). The lift force date is collected as 10000 during 20s in order to use in the FFT analysis. Figure 6 (b) shows the vortex shedding frequency (f) obtained from FFT analysis. The dominant vortex shedding frequency acting on the bare cylinder is 46.35 at Re = 20000. The Strouhal number (*St*) is defined as $St = (f\ D)/V$ here, St is Strouhal number calculated based on D, $D$ is the diameter of the circular cylinder, $V$ is the velocity of air. According to this equation, Strouhal number for bare circular cylinder is calculated as 0.195. This result is almost the same the result of Akansu et al. [6] that is 0,193 for the same Reynolds number.

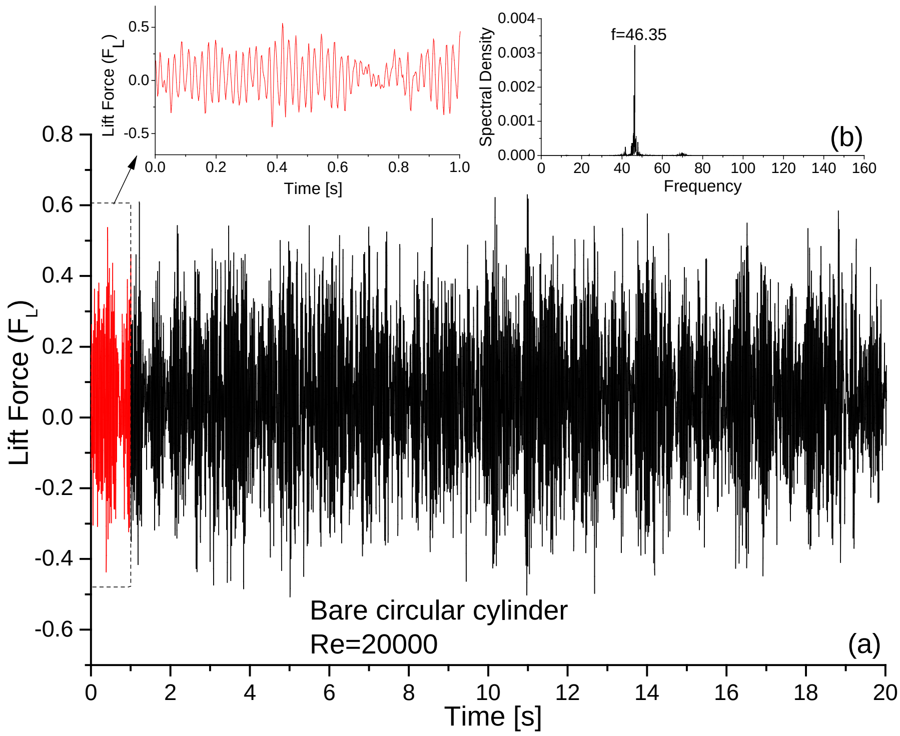


**Figure 6.** (a) Fluctuating lift force data as a function of time and (b) the vortex shedding frequency obtained from FFT analysis for bare circular cylinder at Re = 20000

Figure 7 shows the variation of Strouhal number as a function of the attack angle for a circular cylinder with splitter plate at Re = 20000 and also includes the data of the study of Akansu et al. [6] in order to compare the results. While attack angle is increased from 0° to 180° with an increment of 3°, there is a significant variation in Strouhal number. This variation can be attributed to changing geometry of circular cylinder with plate related to incidence. Strouhal number results of the present study show a similar trend with those of the study of Akansu et al. [6]. Strouhal number reaches a peak value at two attack angles that are 6° and 162°. St diminishes in the range $6° \leq \alpha \leq 51°$, this decrease can be attributed to the flow separation from the splitter plate without reattachment over the cylinder and the wider wake region occurred with the increasing incidence. Strouhal number remains constant with increasing the angle of attack between 54° and 120° owing to constant vortex shedding frequency. After 162°, Strouhal number starts to decrease because splitter eliminates interaction of the separated shear layer and suppress the vortex shedding. Therefore the vortex shedding frequency is reduced between $162° < \alpha < 180°$.

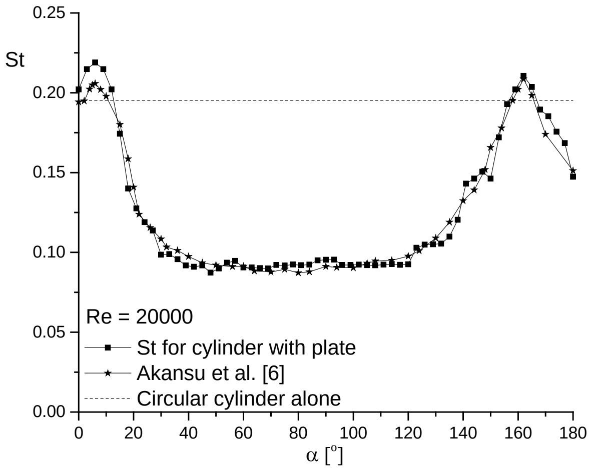


**Figure 8.** Strouhal number vs. the angle of incidence at Re = 20000

The variation of Strouhal number with Reynolds number is given in Fig. 8 for 5 different angles of incidence. When the Strouhal numbers examined in this figure, St is largely independent of Reynolds number between 9700 and 36500 for attack angle of 0°, 45°, 90°, 135° and 180°. The Strouhal numbers of the present study show a similar trend with those of the study of Akansu et al. [6] for all attack angles.

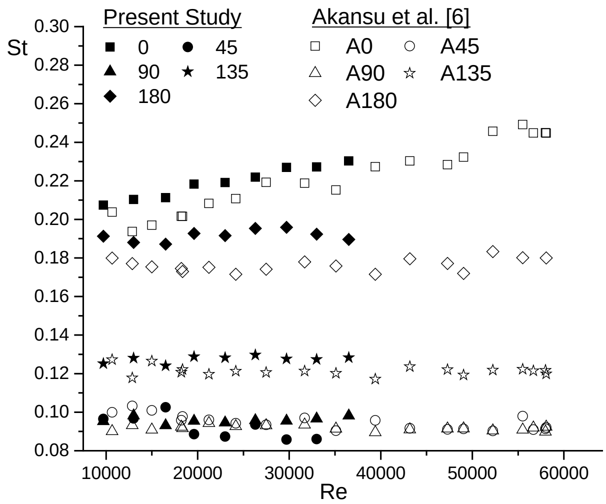


**Figure 8.** Strouhal number vs. Reynolds number for different angle of incidence

## 4. CONCLUSIONS

An experimental study is carried out to investigate the aerodynamic forces acting on a circular cylinder with splitter plate having L/D = 1 at Re = 20000 for the angle of incidence changing between 0° and 180° with an increment of 3°. Forces acting on the circular cylinder such as lift and drag are measured in order to reveal the relation between the Strouhal number, lift and drag coefficient and Reynolds number at wide Reynolds number range changing between 9700 and 36500 for the angles of attack of 0°, 45°, 90°, 135°. Vortex shedding frequency is obtained from the lift force data by using FFT analysis. Remarkable results on the flow around the circular cylinder with/without splitter plate are summarised below;

I. Strouhal number is widely independent of Reynolds number changing between 9700 and 36500 for the angles of attack of 0°, 45°, 90°, 135°. Strouhal number is nearly constant in the range of 54°-120° for Re = 20000.

II. Maximum drag reduction is 48.3% at the incidence angle of 9°. The drag coefficient of a circular cylinder with the plate is smaller than that of the bare circular cylinder, while the incidence angle is smaller than 18° and higher than 150°.

III. Lift coefficient has a maximum value of 3.1 at 12°. $C_L$ has a value of 0 at the angles of 72°, 153° and 180°.

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