Experimental analysis on vortex-induced vibration of a rigid cylinder with different surface roughness

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Abstract. This project presents an experimental work on vortex-induced vibration (VIV) of a short rigid cylinder to obtain its dynamic responses in cross-flow directions with different cylinder surface roughness. In order to enable the rigid cylinder to suspend and vibrate freely upon excitation of wind speed, a supporting structure has been designed and fabricated. This paper aims to investigate the effect of cylinder surface roughness on the characteristics of VIV. The surface roughness was differentiated by using two grade sizes of sandpapers. This self-designed experiments were conducted using Wind Blower at Aeronautical and Wind Engineering Laboratory (AEROLAB), UTM Kuala Lumpur. By using the accelerometer, the raw amplitude readings were recorded and processed using LMS TestXpress 12 software. The data was recorded in the range from 1 m/s to 8 m/s of wind speed, with an interval of 1 m/s. Analysis on the data in terms of amplitude and frequency responses was conducted to identify the effect of cylinder surface roughness on the characteristics of VIV. The lock-in region is found at the low reduced velocity range, where the amplitude value is slightly higher. At Vr=8 lock in phenomena is occurred. From the results obtained, the amplitude increases as the vortex shedding frequency close to the natural frequency of the cylinder, where the frequency ratio =1. Amplitude reduction is found to be 86.7% and 3.43% for the highest and middle surface roughness respectively. The higher the surface roughness, the higher the amplitude reduction.

1. Introduction

In fluid dynamics, fluid can be categorized in many forms, for example water and air. Ranjith et al [1] explained in their research that when fluid flows past an object with different size and shape of the body at certain velocities, an oscillating flow is created. It is called Vortex shedding. In fact, Ranjith et al [1] and Zhou et al [2] stated that one of the key problems in pipeline and riser is the vortex-induced vibration faced by the bluff structures. The vibration may cause the structural failure and also accelerate the fatigue failure. Lock-in phenomenon can be said to occur when the frequency of vortex shedding become closer to the natural frequency of the cylinder. The reduced velocity range (Vr) for lock-in or large amplitude vibration is normally occurred at 3 < Vr < 8. Tao et al [3] discussed about the result of amplitude ratio versus reduced speed of wind in his study and found that maximum amplitude occurred at Vr = 7. Gabbai et al [4] investigated vortex-induced vibration (VIV) of circular cylinder. He explained that the range of reduced velocities over which the vortex-shedding frequency coincides with the natural frequency of the body depends on the oscillation amplitude. In additions, reduced velocity is non dimensional. Therefore it can be referred generally in other field, not only constrain on particular
velocity. Recent research described the “lock-in” as a dynamic equilibrium of flow-structure interaction by Dahl [5]. In his research, the vortices are formed because of the instability of flow wake located at the behind of bluff body. The vortex shedding and excitation cannot be avoided once the vortices are triggered by the flow perturbations. The vortex-induced forces can cause to a difference in the wake frequency and lastly resulted the vortex shedding frequency to be closed to the effective natural frequency of structure.

From the above factors, industries have to bear a higher cost of investment on the structures and expenses for maintenance and pipeline replacement. Large effect on the flow pasts a circular cylinder can be found as the roughness is applied on the cylinder surface. With the presence of surface roughness, the separation angle of boundary layer is also affected. Chakroun et al [6] studied about the effect of surface roughness on flow around a circular cylinder. In his research, roughness causes an increase in the near-wall velocity defect. The peak in the turbulence intensity for the rough wall spreads farther from the wall than for the smooth and continues into the outer region of the boundary layer.

From the previous researches related to the effect of surface roughness, experiments had been conducted by Achenbach et al [7]. They showed that for smooth cylinder, the drag coefficient at transcritical Reynolds number was increased. Kahraman et al [8] investigated the vortex formation in shallow water for a cylinder based on the influence of the localized roughness elements. The formation of vortex was characterized using a method, which is called high-image-density, PIV. Cheung et al [9] conduct a study in supercritical turbulent flow to identify the influence of surface roughness on a cylinder in circular shape. They conducted experiment in the wind tunnel by increasing the turbulence intensity level. The study showed that the increasing of Reynolds number flow affected the VIV response. Besides, by roughening the cylinder surface, the pressure distribution and separating region of a cylinder can be developed to be similar to a smooth cylinder at higher equivalent Reynolds number. Zhang [10] also stated that influence due to the surface roughness is still exists at very large Reynolds numbers. However, the research on the surface roughness of the cylinder is very limited. Therefore, the main objective of the present study is to identify the effect of surface roughness towards the VIV of the cylinder.

2. Methodology
The experiment was conducted in the Aeronautical and Wind Engineering Laboratory (AEROLAB), UTM Kuala Lumpur using a wind blower. The supporting structure of the cylinder is of 41.5 cm in length, 36 cm in height and 34 cm in width (Figure 1). A PVC cylinder is used to be tested in air flow. The mass ratio \( m^4 = 4m/ \rho \pi D^2 \) = 300.6 of the cylinder is high as the fluid medium that flows around the cylinder is air. Internal fluid is not considered in the study as the focus is only concentrated on the influence of external flow towards the response of the cylinder. The properties of test cylinder is mentioned in Table 1. At each corner of the cylinder, a hole is made to place the coiled spring. The spring with stiffness of 0.3374 kN/m is placed in order to suspend the cylinder on the supporting structure.

![Figure 1. Measurement of support structure.](image-url)
Table 1. Properties of the test cylinder.

| Items              | Properties |
|--------------------|------------|
| Total length (m)   | 0.20       |
| Outside diameter (m) | 0.022     |
| Wall thickness (m)  | 0.002      |

2.1. Surface roughness
Sandpaper is one of the methods to create different surface roughness as it has various grade sizes. Two different sandpapers with the properties as shown in Table 2. are applied on the surface of the cylinder to identify the influence of surface roughness towards the VIV of cylinder. Figure 2 indicates the circular cylinder is fully wrapped with the sand paper to create different surface roughness. Double sided tape is used to attach the sandpaper on cylinder. An accelerometer is attached at the middle of the outer surface of the cylinder using superglue to measure the vibration of the cylinder. Only the first natural frequency is identified in the present study as the cylinder used is short and rigid. Siemens LMS Scadas XS is connected to the accelerometer to record the raw acceleration data. The data is then converted into displacement by using double integration method. The same steps are repeated for different grade size of sandpaper. The mass of the sandpaper is assumed to be negligible. The experiment is conducted with the stated speed condition and the data is recorded.

Table 2. Properties of sandpaper.

| Type of sandpaper | Grade size of sandpaper |
|-------------------|--------------------------|
| 1                 | 36                       |
| 2                 | 80                       |

Figure 2. Cylinder fitted with sandpaper.
2.2 Experimental set up

Figure 3 shows the experimental set-up of the present study. The wind blower is placed at the front centre of support structure. The wind speed of the experiment is ranged from 1 m/s to 8 m/s, with an increment of 1 m/s. Once the cylinder vibrates uniformly, the data is recorded for 20 seconds. This is to ensure the data obtained for cylinder vibration are in stable conditions.

![Figure 3. Experimental setup.](image)

3. Results and discussions

Before starting the experiment, free decay test is conducted to obtain the natural frequency of the cylinder. A free decay test can be done by pulling the cylinder downwards and allowing it to vibrate freely until it stops. It was analyzed using LMS TestXpress 12 software. From the graph as shown in Figure 4, the power spectral can be obtained by converting the time series data to frequency domain using Fast Fourier Transform function.

![Figure 4. Raw amplitude data.](image)

Then, the natural frequency can be obtained from the graph as shown in Figure 5. The natural frequency of the cylinder is found to be 5.48 Hz. The natural frequency of a rigid cylinder is very
important to the present study, as it is used to calculated reduced velocity and is used to identify the lock-in condition of a cylinder.

![Figure 5. The value of natural frequency.](image)

3.1 Analysis on surface roughness

Before starting the experiments on the surface roughness, the vibration of bare cylinder is compared with the previous researcher, Koide et al [11] as shown in Figure 6. The amplitude ratio is attained by taking the standard deviation of the displacement data in time series over the cylinder diameter. To obtain the displacement of the data, the acceleration obtained from the accelerometer is pre-processed using double integration through LMS TestExpress software.

The Reduced velocity (Vr) can be calculated by:

\[ V_r = \frac{U}{f_n \cdot D} \]  \hspace{1cm} (1)

Where U is the flow velocity, \( f_n \) is the natural frequency of the cylinder and D is the diameter of the cylinder.

Based on Figure 6, both studies show an increment in amplitude ratio as reduced velocity increases. However, the amplitude ratio of existing experimental data is higher compared to the present study. It is mainly due to the dispersity of the flow from the wind blower. A self-made wind tunnel is proposed to be used in the future to improve the concentration of the wind blow and increase the validity of the present study.

In the present study, two different grade size of sandpapers are used to investigate the effect of surface roughness towards the VIV of rigid cylinder. The mass of sandpaper is assumed to be negligible in the experiment because the mass of the sandpaper is too low. Therefore, it is expected that it will not affect the natural frequency of the cylinder.
Figure 6. Comparison of graph pattern.

Figure 7 shows the amplitude ratio of a bare cylinder and cylinder with different surface roughness. From Figure 7, it can be seen that in the range of \( V_r = 8 \), where lock-in occurs for bare cylinder and cylinder fitted with middle roughness of sand paper. This can be explained the amplitude ratio increases as the frequency close to the natural frequency, as we refer to the frequency ratio of 1 in Figure 8. This observation is in agreement with Zeinoddini [12] that maximum amplitude ratio results in lock-in phenomena. Tao [3] also reported that lock-in region can be found when the frequency ratio is closed to 1.

After applying a higher roughness of sandpaper, the amplitude ratio at low reduced velocity \( (V_r = 8) \) is reduced to 0.001726. This shows that rough surface is able to reduce amplitude value. The higher the surface roughness the higher the amplitude reduction. The average amplitude reduction for middle and high surface roughness of cylinder is 3.33% and 86.7% respectively.

Figure 7. Amplitude ratio of surface roughness.

Besides amplitude response, the frequency response is also investigated in the present study. To obtain the frequency value, Fast Fourier Transform function (FFT) was implemented in order to convert the time series data into frequency domain. The time series data can be obtained from the accelerometer. The frequency data of experiments need to be normalized with its natural frequency to obtain frequency ratio. Figure 8 shows the frequency ratio of different surface roughness. Based on the Figure 8, the frequency ratio of the cylinder with middle roughness is equal to 1 throughout the whole reduced
velocity range. Cylinder with highest roughness is able to alter the frequency ratio to closely 0.5 at low reduced velocity range ($8 < V_r < 16$), indicating the highest surface roughness is able to suppress lock-in phenomenon, and hence reduce the vibration amplitude at low reduced velocity.

![Figure 8. Frequency ratio of surface roughness.](image-url)

4. Conclusion

In this research, analysis of vortex-induced vibration and investigation on the effect of surface roughness towards the VIV of rigid cylinder has been conducted at AEROLAB UTM Kuala Lumpur. LMS TestXpress 12 software is used to analyze the raw amplitude readings from the accelerometer.

The objective of this research have been successfully attained. From the experiment, the vortex-induced vibration effect at low reduced velocity is successfully simulated on the short rigid cylinder. The lock-in region is found at the low reduced velocity range. The amplitude ratio increases as the frequency close to the natural frequency which is frequency ratio $=1$ at low reduced velocity. For the surface roughness, the higher the surface roughness, the higher the amplitude reduction. It can be concluded that high surface roughness is able to suppress the lock-in condition where the amplitude ratio is reduced to a lower value compare to the others.

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