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Wind tunnel study on correlation of aerodynamic forces on a tapered circular cylinder in a yawed flow

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SUMMARY:
The present study aims to study the correlation of wind pressures and aerodynamic forces on a stationary tapered circular cylinder through wind tunnel testing in a smooth, uniform, and yawed flow. In the present paper, the surface pressure measurements are conducted at different locations along the span and across the span for a stationary tapered circular cylinder with a large taper ratio in the AABL Wind and Gust Tunnel at Iowa State University. The results in the forms of pressure and force coefficients and spanwise correlation of these forces (lift and drag) are showed for different yaw angles of attack which are characterized for different aerodynamic regimes. It was found that maximum Cp at leading edge occurs at 0° yaw angle, and the distribution is different when yaw angle switches sign. Also, the Correlation of pressures along the model cross-section is maximum at 45° and decreases with decreasing yaw angle.

Keywords: Force correlation, Wind tunnel test, Tapered circular cylinder.

1. INTRODUCTION

Wind effects on structures have a great influence on its design. Because of its simplicity in design and construction, circular cross-section is widely used in civil engineering applications such as chimneys, bridge cables, traffic signal mast arm, luminaires, wind-turbine towers and so on. However, the aerodynamical behavior of these structures is quite complex and hard to model, especially for structures with a varying cross-section along the span. Moreover, flow past these structures falls under the category of bluff body aerodynamics and are gaining significant importance as an architectural choice for modern construction practices as in high-rise buildings. The focus of the present study is to improve the resilience of tapered circular slender structures subjected to wind loads which may lead to significant structural vibrations and high-cycle fatigue stresses leading to damage or failure.

To evaluate the aerodynamic performance of structures, section-model testing in wind tunnel is a general methodology accepted worldwide. However, often section-model testing ignores the spanwise correlation of aerodynamic forces, which is another key factor in the precise evaluation of structural responses. The lack of correlation of aerodynamic forces on these structures may arise due to the turbulence in the oncoming wind or three-dimensional vortices generated by the structure which in turn excite the structure (Simiu and Scanlan, 1996). The spanwise and streamwise distributions of aerodynamic forces on structures are important parameters in wind-assessment studies, ignoring which may underestimate the total wind loads on the structures and its fatigue life. Although there exists an extensive amount of literature concerning the problem of the flow past circular and rectangular cylinders (Simiu and Scanlan, 1996; Ricciardelli, 2010), a little has been accomplished regarding the flow over the tapered structures (Bosch and Guterres, 2001; Han et al., 2021).

Although several studies have made significant efforts to study the wind flow characteristics around tapered structures, the present study attempts to study the aerodynamic behavior of tapered circular cylinders while considering the effects of taper ratio, turbulence, yaw angle and Reynold's number. In the present paper, the surface pressure measurement results are shown for a static tapered circular cylinder with a large taper ratio in smooth, uniform and yawed flow conditions using wind tunnel tests conducted in the Aerodynamic/Atmospheric Boundary Layer (AABL) Wind and Gust Tunnel at Iowa State University (ISU). The effects of taper ratio, oscillation amplitude, turbulence and Reynolds number on the spanwise correlation of the aerodynamic forces from static and 2DOF (degree of freedom) dynamic section model tests of uniform and tapered cylinders with different taper ratios in uniform and yawed flow are not presented here for brevity.

2. WIND TUNNEL TEST

2.1. Experimental Setup

In the present study, all experiments were performed in the aerodynamic test section of the AABL Wind and Gust Tunnel (2.44 m W x 1.83 m H) located at ISU. The wind tunnel blockage ratio was less than 5% for all tests. A tapered cylinder section model with a circular cross section having a central diameter of 0.127 m and length 1.5 m was tested in uniform, smooth and yawed flow to obtain the static mean load coefficients as shown in Fig. 1.

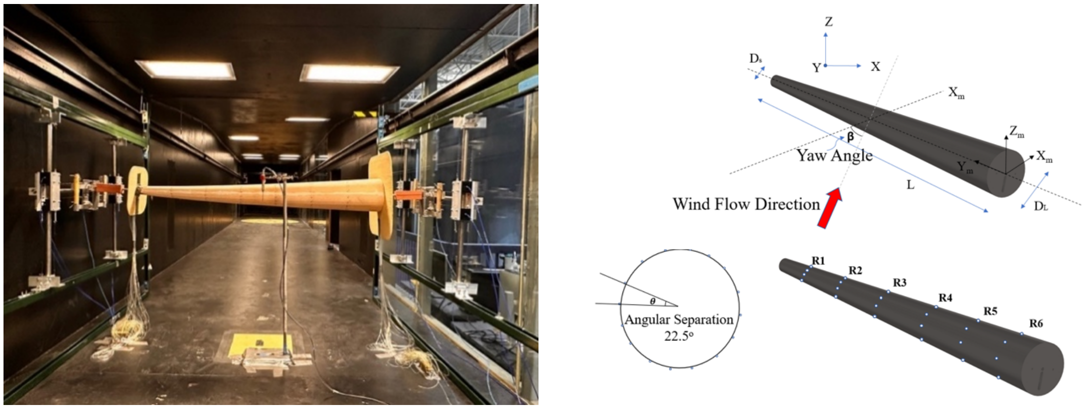

Figure 1. Experimental setup at AABL wind tunnel and coordinate system with definition of AOA.

The taper ratio of the model, defined as $(D_L-D_s)/L$, is 0.1. Two 64-channel pressure transducers (Scanivalve ZOC33/64 Px) were used to measure the surface pressures on the model at 96 pressure taps. To quantify the spanwise and streamwise correlation effects, the pressure taps were located at 6 different locations (denoted as pressure tap rings R1-R6 in Fig. 1) at equal distance along the span of the model with 16 taps at each of these six spanwise locations along the cross-section of the model with an angular separation of 22.5^o between the two adjacent pressure taps. The pressures at each tap were simultaneously recorded for 62.5 sec at a sampling frequency of 250 Hz. Cobra Probe (®Turbulent Flow Instrumentation) was used to measure the velocity and the turbulence of the upstream flow for a sampling period of 120 sec and a sampling frequency of 2500 Hz. The mean wind speed was 14 m/s and the turbulence intensity was less than 0.25% in all the tests which made the flow condition as smooth.

2.2. Aerodynamic Loads and Correlation Coefficient

To measure the mean pressure coefficient Cp and load coefficients C_D and C_L, the yaw angle of attack (β) of the model in the horizontal plane was changed from 45° to –45° where 0° yaw angle denotes the wind along perpendicular to the model and positive yaw angle represents wind with a spanwise component towards the thicker end of the model. Surface pressures at each pressure tap (P_i) on the model were recorded at three different mean wind speeds and were integrated to calculate the time varying aerodynamic forces, Lift (L) and Drag (D), that are defined as,

$$L(t) = -\sum_{i=1}^{N} P_i A_i sin\theta_i \tag{1}$$

$$D(t) = \sum_{i=1}^{N} P_i A_i cos\theta_i \cos\beta_i \tag{2}$$

where N is total number of pressure taps, θ is the angle between the vector normal to the surface of the cylinder at a pressure tap and the horizontal plane (parallel to the wind tunnel floor).

Correlation was calculated between lift and drag force time histories at different spanwise positions as well as between individual pressure signals at different streamwise (section-wise) positions (Fig. 1). The correlation of lift was expressed as a cross-correlation lift coefficient (Haan et al., 2016) defined as,

$$\rho_{L_1L_2}(\tau) = \frac{C_{L_1L_2}(\tau)}{\sigma_{L_1}\sigma_{L_2}} \tag{3}$$

where $\rho_{L_1L_2}(\tau)$ is the cross-correlation coefficient function with a time delay of τ for fluctuating lift $L_1(t)$ and $L_2(t)$. $L_1(t)$ and $L_2(t)$ are time-varying lift at two spanwise locations, $C_{L_1L_2}(\tau)$ is the cross-covariance function (taken for zero-time delay, $\tau = 0$) where σ is standard deviation. $L_1(t)$ and $L_2(t)$ are replaced by $P_1(t)$ and $P_2(t)$ to represent pressure signals and by $D_1(t)$ and $D_2(t)$ to represent drag time-histories in Eq. 3 while calculating correlation coefficients of pressures and drag force at different spanwise positions.

3. PRELIMINARY RESULTS AND DISCUSSION

Fig. 2 shows the Cp distribution and the streamwise (section-wise) correlation of pressures at the central pressure taps ring of the tapered cylinder model for different yaw angles.

In Fig. 2(a), the Cp value is maximum at the leading edge ($\theta = 0$ °) when yaw angle is 0° (wind flow perpendicular to the model). Moreover, it is worth noting that the Cp distribution is not same when wind attacks at equal angles from two different sides (For example, Cp distribution is not same for yaw angles of 45° and –45°) as the structure is not symmetric along X_m axis. In Fig. 2(b) the streamwise correlation is maximum for 45° yaw angle and the streamwise correlation decreases with decreasing yaw from 45° to –45°. Fig. 3 shows the spanwise correlation of lift and drag forces, which were derived by integrating the surface pressures.

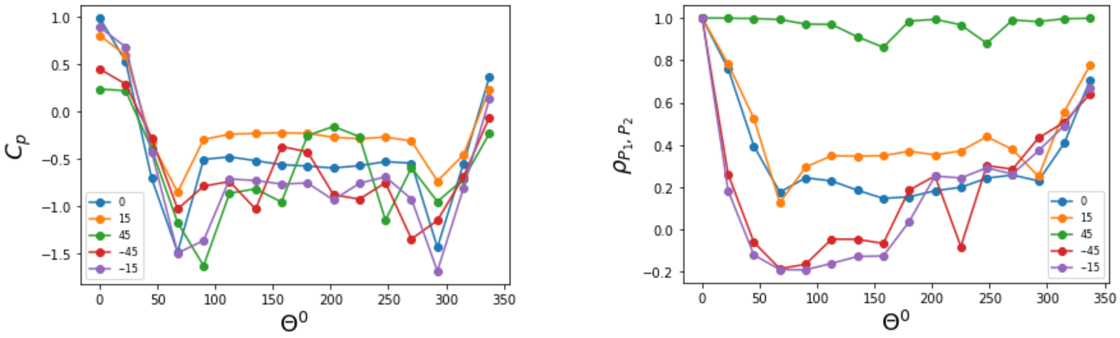

Figure 2. (a) Mean Cp and (b) streamwise correlation of pressures at central ring pressure taps for different AOA.

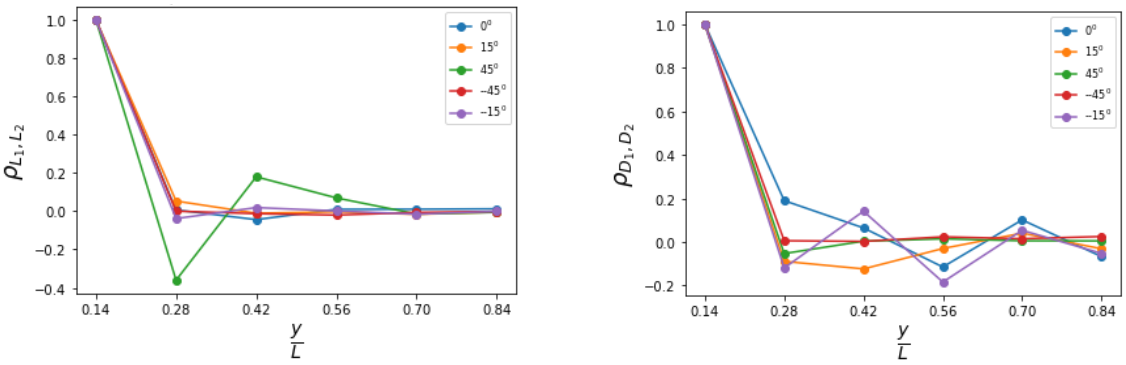

Figure 3. Spanwise correlation of (a) Lift and (b) Drag forces for a tapered cylinder for different yaw angles.

4. SUMMARY

In the present study, the pressure measurement results are presented for a stationary tapered circular cylinder considering the correlation effects through wind tunnel testing in a smooth, uniform and yawed flow. The results in the forms of pressure and force coefficients as well as spanwise correlation of aerodynamic loads are presented for different yaw angles of attack. It was observed that the maximum Cp at leading edge occurs at 0° yaw angle, and the distribution is different when yaw angle switches sign. Correlation of pressures along the cross-section of the model is maximum at 45° and decreases with decreasing yaw angle.

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