The Flow Around A Circular Cylinder Above A Plate

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Abstract

The flow around a Cylinder Above a Plate (CAP) is a canonical flow applicable to various engineering problems, such as, automotive roof racks and submarine pipelines. This paper presents some insights from two experimental campaigns of an ongoing investigation into the aeroacoustics of this flow. First, an acoustic survey was carried out, the results of which show no detectable Aeolian tone below a critical gap height normalized by cylinder diameter of $G/D = 0.3$. Next, the fluid mechanics of the $G/D = 0.5$ case was investigated using simultaneous hotwire-microphone measurements. The findings confirm CAP flows contain significant upwash in the cylinder wake.

Introduction

A typical CAP configuration is shown in Figure 1. The semi-infinite cylinder is constrained on one side with a planar boundary (‘bottom side’), and unbounded on the opposing side (‘top side’); flow is impinging on the cylinder in a direction perpendicular to the cylinder axis. The cylinder has a diameter $D$, the gap between the cylinder bottom and plate top is $G$. The incoming free-stream with a velocity of $V_∞$ creates a boundary layer height of $δ$ at the cylinder location; $δ$ is defined in the freestream (no cylinder) condition. In this publication, the Reynolds number (Re) is reported in terms of cylinder diameter $D$ and free-stream velocity $V_∞$ unless otherwise noted.

Vortex shedding can become irregular and intermittent when gap sizes are in the ‘medium’ range [1]. Intermittency is the possibility that single or multiple shedding cycles are missed, whereas irregularity is the occurrence of cycle-to-cycle changes in shedding behaviour. The transition from ‘medium’ gap sizes, to ‘small’ gap sizes - in other words, the process of vortex shedding cessation is the interest of much research. Reference [3] argued for a gradual process which “transitions over a range”, while Ref. [5] note that the cessation is “abrupt”.

When the cylinder is close to a plate, vortex shedding does not occur solely on the cylinder, but can also be induced on the plate surface due to the adverse pressure gradient created by the cylinder [2]; this is apparent in water-dye visualized flows [10], whilst the upstream stagnation point and gap flow characteristics were considered in Ref. [10]. Wake vortex dynamics was the subject of Ref. [7], whilst the upstream stagnation point and gap flow character were considered in Ref. [10].

Figure 1: Schematic of typical CAP configuration and experimental set up; cylinder of diameter $D$, placed at height $G$ above a plate surface, subject to free-stream velocity $V_∞$, and boundary layer height $δ$. The hotwire probe (red highlight) is absent during the acoustic survey. A position of $x = 0$ is a location on the plate surface, $x = 0$ is inline with the downstream face of the cylinder.

The first effect of adding a bounding plane (a plate in this case) near the cylinder, is the loss of symmetry in the wake. This asymmetry can be attributed to two factors: First, the plate interacts with the static pressure field about the cylinder, somewhat similar to a reflective boundary condition in potential flow; second, the boundary layer flow on the plate surface interacts with the cylinder flow, decreasing the vorticity of the ‘bottom’ shear layer, thereby reducing the coupling between the ‘top’ and ‘bottom’ vortex necessary for normal sustained vortex shedding [9].

The gap height $G/D$ is usually classified into several regimes. The critical gap height is defined as the smallest gap height at which von Kármán vortex shedding is still detectable. $G/D$ was classified into three regimes in Ref. [12], referred to as ‘large’, ‘medium’, and ‘small’ in this paper for brevity. In Ref. [12], a ‘large’ $(G/D ≥ 0.8)$ gap features little to no mutual interaction between the cylinder and plate flows, ‘medium’ $(0.3 ≤ G/D ≤ 0.6)$ corresponds to a strong influence, and ‘small’ $(G/D ≤ 0.2)$ forcing a dominant change. This ‘small’ gap size, is smaller than the critical gap height; hence, it is free of von Kármán vortex shedding [12]. In some cases, a classification into as many as 5 regimes [7] have been suggested. The criteria and value ranges used for these divisions are subject to the aspects of flow examined. Wake vortex dynamics was the subject of Ref. [7], whilst the upstream stagnation point and gap flow character were considered in Ref. [10].

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No prior publication (to the authors’ knowledge) other than Ref. [8] has examined the aeroacoustics of the CAP case. Thus, this work aims to fill this knowledge gap, by developing an initial dataset of acoustic measurements, for the circular CAP case at various $G/D$ settings. This work also aims to understand the complex fluid dynamics contained in the CAP wake.
Experimental Setup

Wind Tunnel Facility
The experiments were conducted in the open-jet Anechoic Wind Tunnel located at UNSW School of Mechanical and Manufacturing Engineering. With the use of a muffler, the maximum velocity of the free-jet is approximately 18.5 m/s, with a free-stream turbulence intensity < 1%. The test section has a maximum width and height of 455 mm; the room size is approximately 3.2 m wide, 2.9 m long, 2.0 m tall.

Test Rig and Model
The circular cylinder model is rigidly mounted between two end-plates spanning the maximum width of the test section. A rigidly mounted flat plate also spanned the same width. In this experiment, the cylinder has a diameter $D = 35$ mm. The leading edge of the plate begins 5.4$D$ upstream of the cylinder centre, whilst the trailing edge terminates 11.6$D$ downstream.

Equipment and Procedure
Two experimental campaigns are reported here: an acoustic survey, and hotwire-microphone measurements. A GRAS 40PH Freyfield microphone was used for both experiments. The Dantec 55P16 single hotwire probes used were connected to a Dantec 54N80 Multi-channel CTA. Measurements reported here were carried out at $V_{in} = 18$ m/s.

The experimental set up of the acoustic survey, and hotwire-microphone measurements is depicted in Figure 1; in both cases, the microphone was placed at a fixed position directly over the cylinder, oriented perpendicular to the flow, pointed at the midspan. The microphone position for the acoustic survey was $y = 21.3D$. Acoustic data was acquired on an NI PXIe-8135 (using a PXIe-4499 card) at a sampling frequency of $2^{19}$ Hz, for 32 seconds; both the CAP case, and the equivalent baseline unbounded cylinder case were recorded. On the other hand, the NI cDAQ-9178 (with NI 9215 module) was used for the hotwire-microphone measurements, sampled simultaneously at $51200$ Hz, for 32 seconds. The microphone remained at $y = 35.5D$ while the hotwire was traversed in the $y$ direction, at $x$ locations of $0D, 0.25D, 0.5D, 0.1D, 0.7D, 0.9D, 0.6D$, and $0D$. Similar measurements were repeated for the baseline unbounded cylinder case at distances $x = 0D, 5D$, and $7D$.

Results

Acoustic Survey
The Figures 2 (a) and (b) are spectral maps showing the power spectral density of acoustic frequencies at various $G/D$ values, for $0.05 \lesssim St \lesssim 1.0$. The Aeolian tone is located at $St \approx 0.19$. Figure 2(a) shows the Aeolian tone’s level decrease as $G/D$ decreases, until it is undetectable at $G/D = 0.2$. In contrast, Figure 2(b) indicates a strong tone for all cylinder positions. Reference [2, 4, 12], found the critical gap height to be $G/D = 0.3$ for circular cylinders, based on flow measurements; these acoustic measurements observe the same agreement.

The overall acoustic spectrum when $G/D = 0.2$ looks identical to the $G/D = 0.3$, and baseline case, with the exception of the absent tonal peak. This similarity can be observed in Figure 3. This acoustic spectrum drastically changes character when $G/D \leq 0.1$: here the spectrum features 3 low strength broadband peaks, centred at approximately $St = 0.13, 0.29, \text{and } 0.55$. This is somewhat similar to acoustic data from [8], who also found 3 broadband peaks, when there is no gap between cylinder and plate. These findings differ with [8] in the broadband centre frequencies reported.

In summary, tonal noise represents a large contribution of the overall radiated noise from the CAP case, when the cylinder is far enough from the plate. Broadband noise becomes dominant when the cylinder is too close. These acoustic results suggest a quick transition between 3 regimes, tonal noise ($G/D \geq 0.3$), no tonal noise ($G/D = 0.2$), and broadband noise ($G/D \leq 0.1$).

The integrated spectra around the Aeolian tone peak (integrated between 75 Hz and 120 Hz) was compared between the baseline unbounded cylinder case and CAP case in Figure 4. The baseline case reveals that the overall level change between the largest and smallest $G/D$ tested was approximately 3.5 dB, as microphonie-cylinder distance decreases while $G/D$ increases. The levels of the CAP case shows a similar trend, with a more prominent slope at low $G/D$ values. Therefore, microphone-cylinder distance is not the primary factor to consider for the change in level of the $G/D$ case. The presence of the plate, even at relatively large gap heights ($G/D \geq 1.0$), leads to a significant loss in level of the Aeolian tone.

The Aeolian tone Strouhal number is also compared between the CAP and baseline cases in Figure 5. The frequency remains effectively unchanged until the point of cessation. At the Reynolds number examined, $St$ is unaffected by $G/D$. The literature generally agrees with the lack of dramatic $St$ change.
Figure 3: Power spectral density plot of the CAP cases $G/D = 0.1, 0.2, 0.3$ as well as the baseline case, between for $0.05 \leq St \leq 1.0$.

Figure 4: Integrated spectra around the Aeolian tone for the baseline case, and the CAP case. Note, baseline case $G/D$ values represent the same cylinder-microphone distance as the CAP case at the same $G/D$, since microphone and plate position remain static, whilst cylinder position changes for changing $G/D$.

Figure 5: Aeolian tone frequency as a function of $G/D$. Hotwire data reproduced from Ref. [2].

Figure 6: (a) Velocity profile of the CAP case, and (b) turbulence intensity profiles, at locations downstream from the cylinder back. Profile values are offset by 0.3 $V/V_\infty$ in (a); profiles values are offset by 20% turbulence intensity in (b). Data points where turbulence intensity exceeded 25% were excluded. The legends represent values of $x/D$.

Figure 7 (a) and (b) show a spectral map, coloured by hotwire-microphone coherence levels, at $x/D = 7.0$. At all locations in the wake examined (where turbulence intensity did not exceed 25%), only at the Aeolian tone frequency was high coherence between acoustic and velocity signals observed. When examining coherence of the Aeolian tone, a loss in coherence is observed, seen as a ‘dip’ at $y/D = 1$ for the baseline cases (Figure 7 (b)). This corresponds to the centre of the cylinder wake. The same ‘dip’ is also observed with the CAP cases (Figure 7 (a)), but at different $y/D$ positions. The ‘dip’ moves up in $y/D$ position, as the hotwire migrates in $x/D$ downstream. This phenomenon is shown more dramatically in Figure 8 (a), which is in stark contrast to Figure 8 (b). Both Figures 8 (a) and (b) show the coherence of the Aeolian tone with fluctuating velocity signals, as a function of $y/D$, at downstream $x/D$ locations. These plots show the plate creating an upwash effect on the cylinder wake, demonstrated through the movement of the minimum coherence zone away from the plate. The CAP case contains no symmetry around the cylinder centre, unlike the baseline cylinder case. The minimum coherence zones are likely regions in the wake outside the trajectory of the ‘top’ and ‘bottom’ vortices. The plate also decreases the maximum coherence of the CAP case by approximately 0.2, in comparison with the equivalent baseline case.

Hotwire Measurements

The velocity and turbulence intensity profiles for the CAP case are shown in Figures 6 (a) and (b) respectively. These profiles are substantially different to the baseline case. The cylinder wake appears to have merged with the boundary layer flow on the plate. The velocity and turbulence intensity profile shapes of this experiment are somewhat comparable to similar measurements of Ref. [4].

Conclusions

The findings of this study have shown some interesting and important aspects of CAP aeroacoustics and fluid dynamics. The reduction in level between the baseline and CAP case exceeded 6 dB when the cylinder was close to the plate, but never equalized, even at the largest gap size. Coherence between acoustic and velocity signals was found only at the Aeolian tone frequency. A significant upwash effect was observed in the wake. Future experiments will attempt to better understand and clarify these phenomena.
Figure 7: Coherence map of the cylinder wake between hotwire and microphone, for the CAP case (a), and baseline case (b), at $x/D = 7.0$ downstream. The cylinder centre is at $y/D = 1$, a circle superimposed onto the chart indicates the size and position of the cylinder, relative to the $y/D$ axis. The color scale shows coherence levels. Data for $G/D < 0.4$ in (a) omitted due to technical limitations.

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References

Figure 8: Coherence of Aeolian tone to velocity for the CAP case (a) and baseline case (b). Profiles offset from each other by 0.4 coherence levels in (a); and by 0.5 coherence levels in (b). The offsets were applied to clearly display profile shapes. The maximum coherence level for $x/D = 7.0$ is 0.428, not 1.628. The legends presents values of $x/D$, and the cylinder centre is at $y/D = 1$, highlighted by the dashed line.