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# The Effect of Inclination Angle on the Flow Characteristics of Tandem Bluff Plates

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## Abstract

The flow around bluff bodies in tandem is of significant interest due to its broad range of applications. Past studies have investigated the effect of common geometry configurations such as bluff plates and cylinders and found that flow characteristics varied significantly dependent upon certain geometrical parameters such as bluff body size or spacing ratios. This work explores an unobserved area to determine the effect of inclination angle on the flow around tandem bluff bodies due to an expected change in the pattern of the shed vortices. Specifically, key flow characteristics such as velocity fluctuations and drag are investigated for a pair of flat plates with equal dimensions at a Reynolds number of 54,000. The results are complimented by numerical modelling through computational fluid dynamics using Large Eddy Simulation, where vortex structures are visualized and quantitative drag are validated for. Strouhal number plots show that the inclination angle has a significant effect on the flow interactions between tandem bluff plates, and that when inclined, known transitions between flow regimes no longer occur. The results show that when the shear layer from an upstream bluff body does not meet at the downstream body at any location, a drag reduction is not possible and no optimum gap ratios can be achieved to minimize drag.

## Introduction

The flow around tandem bluff bodies is complicated by the interaction of the downstream body with the wake flow from an upstream body. Flow characteristics and load analysis has been investigated in many configurations, such as coaxial disks by Morel & Bohn [11], normal flat plates by Auteri et al. [3], disk and cylinder by Koenig & Roshko [8], and tandem prisms by Sakamoto et al. [12]. One of the first studies on tandem bluff bodies conducted by Eiffel [4] showed that when the gap ratio is less than 1, the combination of the two disks experienced a smaller drag compared to a single disk, and when the gaps are increased the combined drag decreased to a minimum before increasing beyond the drag of a single disk. Furthermore, when the downstream disk was left free to slide along a sting, it was found that at these small gaps the disk moved towards the upstream disk, signifying a negative drag force. The same trend of results were reported by Morel & Bohn [11] as well as Koenig & Roshko [8], despite the latter using a disk and cylinder instead of two disks, showing that the relative effect on the flow due to a gap is present irrespective of the bluff body used. In addition to load analysis, through phase averaging techniques such as Laser Doppler Anemometry along with Hot Wire Anemometry, Auteri et al. [3] found that the vortices that are present between two bluff plates alternate. Furthermore, when a vortex enters the gap, the opposite vortex is pulled through to the wake region behind the downstream plate. This phenomenon appears to be periodic, leading to a synchronization of the vortex shedding mechanism described by Sakamoto et al. [12]. Numerical flow visualization by Auteri et al. [3] showed that the alternating vortices have a constant velocity and magnitude, implying constant frequency and phase lag between the plates. This result is in agreement with the Strouhal number plots presented by Sakamoto et al. [12] and Auteri et al. [3] where the Strouhal number remains almost constant within the flow regime.

In order to quantify the different flow regimes and observe critical gap ratios where transition occurs, Strouhal number plots have been used extensively in the studies of different tandem bodies. Results for tandem cylinders, squares, and other more complex bluff bodies have shown that there exists an optimum gap ratio where drag loads are minimized and this corresponds to an intersection of the Strouhal number where the flow regime transitions [6, 7, 13, 14]. Alam & Zhou [1] described three distinct flow regimes as follows, i) the extended body regime where the downstream body is close enough to the upstream body such that the shear layers overshoot the second body, resulting in vortex shedding occurring behind the second body, ii) the reattachment regime, where the downstream body is placed at a position where the shear layers from the upstream body reattaches it, and iii) the co-shedding regime, where the downstream body is placed sufficiently apart from the upstream body such that vortex shedding occurs behind both bodies. The reattachment flow regime, where the objects approach a critical gap ratio, is of particular interest as the Strouhal number experiences a large decrease as the extended body regime moves towards the co-shedding regime [2], and hence such a Strouhal number behaviour can provide a strong indication that the drag is minimized at such a configuration.

The current study attempts to further explore the area concerning tandem bluff bodies by investigating the effects of inclining the angle of thin flat plates on the flow behaviour over a range of gap ratios. The significance of the study arises due to the lack of practical cases where bluff bodies are placed perfectly perpendicular to the flow, and through changing the angles on one axis of rotation the results may be inferred when the angles are altered in other planes. The study was primarily motivated by fast developing fields in the concentrating solar power (CSP) industry where large numbers of heliostats must be placed in tandem to harness solar energy. Although in much closer proximity to the ground, it is expected that the flow behaviour investigated over the top of the plates are still applicable to heliostats irrespective of the suppression of horseshoe vortices that may occur below. Emes et al. [5] found that within CSP systems, heliostats have the largest direct contribution to the capital costs, and that it is directly related to the design wind speed and the affected aerodynamic loads such as drag. Therefore, it is highly beneficial to understand the effects of angular changes on tandem body flow as it would allow for optimization of heliostat design and field layouts.

## Methodology

### Experimental Setup

The study was conducted via wind tunnel experiment using a closed return test section. The tunnel is fan driven and has turning vanes at each corner to minimize losses. A series of mesh screens along with a 6:1 contraction ahead of the test section accelerates the flow and reduces the turbulence as it reaches the test section with dimensions of $500 \times 500mm$. The maximum speed achievable at the test section is approximately $30m/s$ with a turbulence intensity of 0.5%. An experimental rig consisting of thin square flat plates mounted on a sting was produced for this test section where the plates are of equal dimensions with length $L = 100mm$ and thickness $t = 3mm$, resulting in a blockage ratio of 4% when the plates are perpendicular to the flow. Design considerations included the requirement for both plates to vary in inclination angle as well as gap ratios. One upstream plate is designed to allow the inclination angle to be set freely, whilst the downstream plates are fixed at angles of $90^o$, $60^o$, $45^o$ and $30^o$ from the horizontal, where $90^o$ inclination represents perpendicularity to the flow. Mounting points for the downstream plates are positioned so that each increase in the gap ratio $d/L$, where $d$ is the gap length, represents $0.5L$, up to a total of $4L$ to determine the gap effects. Figure 1 shows a schematic of the setup.

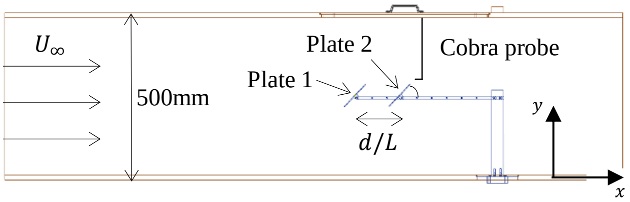


Figure 1. Schematic of the experimental setup.

Velocity measurements were taken with a cobra probe which is a multi-hole pressure probe capable of measuring all three components of velocity. The tests were conducted at a free stream velocity of $8m/s$ which gives a Reynolds number of 54,000. Auteri et al [3] found that the Strouhal number dependency on Reynolds number is negligible for $Re \leq 70{,}000$. Points of interest were in between the two tandem plates within the shear layer as well as behind the downstream plate in order to capture wake effects behind both plates. The cobra probe has a maximum velocity of $90m/s$ in the $x$-direction, has a sampling frequency of $2kHz$, and is able to measure up to $\pm 6kPa$ pressure. In order to satisfy the Nyquist criterion the oversampling frequency was set to $10kHz$ with a ratio of 8 to ensure data accuracy. A Matlab code was used to zero the cobra probe before each test run, whilst the reference temperature was taken from a thermometer mounted in the lab. Five seconds of data were recorded per run in order to minimize random errors associated with the setup and instruments.

Due to difficulties in pinpointing the exact location of the shear layer at each plate location, several measurements were taken at $5mm$ intervals beginning from the top edge of the plate. In order to maintain consistency across all measurements, the locations where the cobra probe was placed were always equal to the distance half way between where the two plates are situated. The same distance is used when measuring downstream. Hence the relative distance ratio between cobra probe measurement and the gap ratio is maintained at 0.5.

### Computational Fluid Dynamics

Numerical work via Computational Fluid Dynamics was also used in conjunction with the wind tunnel experiments to provide drag analysis of tandem inclined plates. Initial simulations focused on producing a well-defined mesh and setup such that the flow visualization and drag trends reflect those found in published papers and the current experimental results. Due to the inherent unsteadiness of the problem, an embedded large eddy simulation (ELES) was chosen as the optimum method of resolving the inevitable velocity fluctuations that would be present due to vortex shedding. As the geometry is simple, a fully structured mesh was produced using ANSYS ICEM. Convergence study was performed for both the mesh resolution and timestep size to ensure that the results are valid and has an error of less than 1%. Figure 2 and Table 1 show the domain and mesh statistics used in the analysis, including any requirements which the values were based upon.

| | |
|---|---|
| Nodes | 4,000,000 |
| Aspect ratio | <16 |
| Mesh type | Hexahedral |
| Cell size | 10mm ($< 0.05L$ where $L$ is the characteristic length of the plate [10]) |

Table 1. Mesh statistics for the ELES simulation.

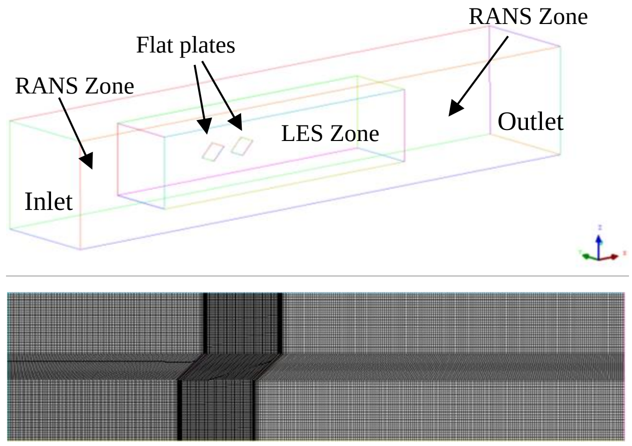


Figure 2a. Domain of computational setup and 2b. Fully structured mesh around the tandem plates with inflation close to the bodies.

The commonly used non-dimensional $y_+$ wall distance was not considered in this case as the plates are thin and the flow is certain to separate immediately aft of the bodies. Cell sizes were determined based upon Menter's guide to Scale-Resolving-Simulation [10] where the largest turbulent scales in the flow can be resolved if a minimum cell size was specified. Simulations were run in ANSYS Fluent for two angles, at $90^o$ and $45^o$, for a range of gap ratios from 0.5 to 4 in 0.5 increments. The Fluent setup is shown in Table 2.

| | |
|---|---|
| Inlet conditions | Velocity-inlet (velocity profile and $I_u$ generated via user defined functions) |
| Outlet | Pressure outlet |
| ELES interface – inlet | Velocity fluctuations generated from Vortex Method available in Fluent |
| ELES interface - others | Interface |
| Others | Wall (Floor roughness of $0.004m$ specified to maintain boundary layer characteristics) |
| Time step size | $0.0005s$ (CFL < 1 [10]) |
| Number of time steps | 6000 ($3s$ of flow) |

Table 2. Simulation setup in ANSYS Fluent.

## Results

Comparisons of the experimental measurements between configurations are on a relative scale therefore the effects of errors and solid blockage are not corrected as they remain consistent across all the results. To visualize the effect of the inclination angles on different gap ratios, the Strouhal number is computed by observing the peak in the power spectrum obtained by a Fast Fourier Transform (FFT) of the velocity measurements. The power spectral density (PSD) graph shown in Figure 3 illustrates this process.

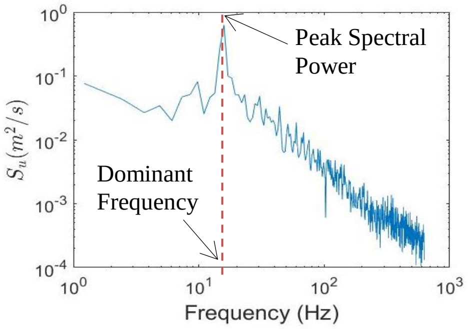


Figure 3. PSD of velocity signal showing the peak frequency used to calculate the Strouhal number.

The FFT was calculated for all measurement points and the dominant frequency was determined for each signal. Since each position has multiple measurements at different heights, the averaged representative Strouhal number was used for analysis.

Two Strouhal number plots are presented in Figure 4, the first is for velocity measurements between the plates at various gap ratios and inclination angles, whilst the second is for velocity measurements downstream of the second plate at the same configurations. Limitations to the experimental setup meant that the dataset is slightly smaller for downstream measurements compared to in-between measurements.

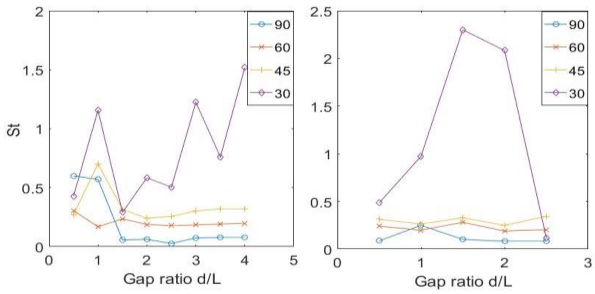


Figure 4a. Strouhal number between the plates at different inclination angles (left) and 4b. Strouhal number downstream at different inclination angles (right).

From Figure 4 it can be seen that as the inclination approaches to $30^o$, the Strouhal number experiences a significant change for the measured gap ratios. The increase of Strouhal number above 1 at this angle shows that the flow behaviour is no longer consistent with bluff body interactions and that the rapid build-up and shedding of vortices no longer occur. If the unrepresentative results for $30^o$ inclination is removed (Figure 5), then the remaining results show that the flow interactions remain in the form of bluff bodies however the critical gap ratio where flow regimes change is noticeably absent for angles $60^o$ and $45^o$.

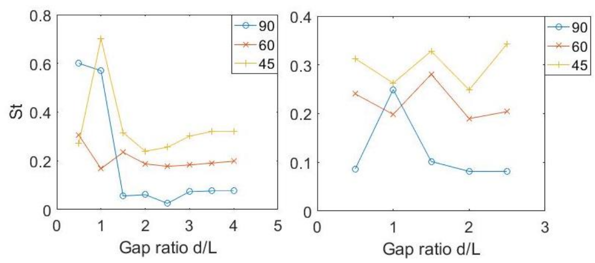


Figure 5: Strouhal number plots without $30^o$ inclination data.

The above experimental results are complimented by numerical results in the form of drag coefficients. A combined drag coefficient is investigated instead of for individual plates as the present analysis focuses upon the tandem plates as a system, and therefore it is of interest to observe the effects of flow interaction on the overall behaviour of the system rather than any individual body.

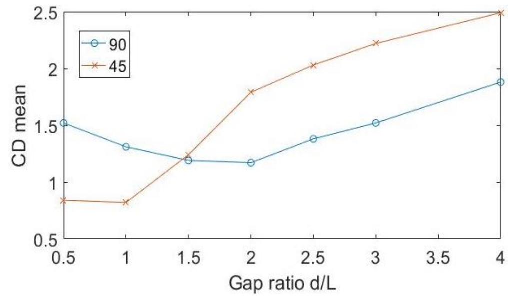


Figure 6: Mean drag coefficients from CFD, for $90^o$ and $45^o$ inclination angles at various gap ratios.

Figure 6 shows the drag coefficients calculated from CFD results. Pressure on the fore and aft surfaces of each plate were measured which was then used to determine drag coefficients based upon the free stream velocity. Simulation results were validated against published data such as the combined drag coefficients reported by Eiffel [4] and Koenig & Roshko [8], as well as current experimental data, where the drag coefficient for perpendicular plates sees a noticeable decrease as gap ratio increases, reaching a minimum around $d/L = 2$ before increasing, whilst the drag coefficient for $45^o$ inclined plates behave in no obvious pattern as the gap ratio increases. The minimum drag coefficient observed at a gap ratio of 2 is higher than the critical gap ratio reported from experimental results, however this can be attributed to numerical errors where the mesh defines the smallest scales resolvable via LES. As noted in the Methodology, the mesh size for the simulation was chosen such that the largest turbulent scales in the flow were resolvable within a reasonable timeframe and therefore it is possible that the reattachment length of the shear layer is overestimated, resulting in the increased gap ratio for optimum drag.

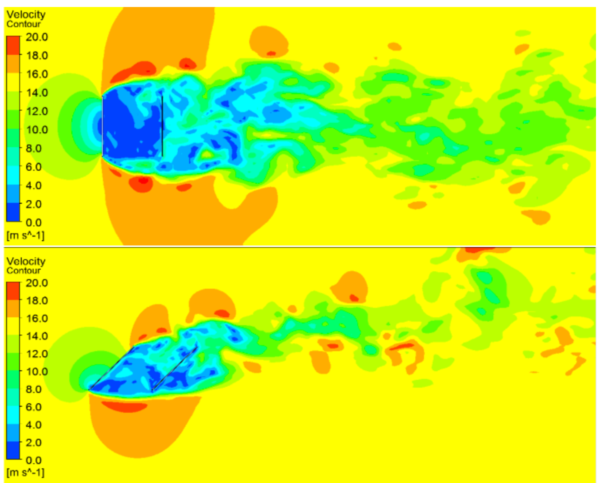


Figure 7: Velocity contours of tandem plates at $90^o$ (top) and $45^o$ (bottom) inclination angle and gap ratio of 1.

The velocity contours shown in Figure 7 provide some insight into the difference in flow characteristics as well as the lack of transition between different flow regimes shown by the Strouhal number analysis when the plates are inclined on an angle. At a gap ratio of 1, the bottom shear layer for the inclined plates can be evidently seen to almost reattach towards the second plate, however due to the inclination angle, the upper shear layer is raised further away from the edge of the second plate, resulting in shed vortices away from the central region behind the second plate. This creates a higher pressure region as evident by the velocity magnitude between the plates. The high pressure region combined with the low pressure region induced by the vortex shedding along the bottom edge results in a higher pressure differential and hence, higher drag coefficients.

## Discussion

Strouhal numbers for perpendicular plates from experiments match those published by Auteri et al. [2] where a peak appears at a gap ratio of 1 before dropping below the value for an isolated plate. This shows that the required gap where the shear layer of a first plate reattaches to the second plate is approximately equal to the characteristic length of the plate. This can be considered the critical gap ratio for tandem flat plates as the rapid change of Strouhal number suggests a transition from the extended body regime to the co-shedding regime, or 'mode I' to 'mode II' as defined by Liu & Chen [9]. The familiar Strouhal number trend is also observed in the velocity measurements taken between plates, further reinforcing this theory for plates in the perpendicular configuration. When moved to inclination angles of $45^o$ and $60^o$, the same behaviour is not seen with the exception of $45^o$ at a gap ratio of 1. Due to the singular peak value and a lack of support from data downstream of the plates at the same gap ratio, it is possible that such a peak is an outlier to the dataset rather than providing conclusive evidence of flow transition. Observation of the downstream data shows that, aside from a small increase in Strouhal number across all gap ratios, there appears no evident deviation to suggest that different flow regimes occur over the investigated gap ratios.

Numerical results confirmed the experimental findings through simulations of tandem plates at two different inclination angles and demonstrated that inclination angle has the possibility to negate all positive effects of exploring for an optimum gap configuration between tandem bluff bodies. Extending this result to further applications that are not confined to simple geometries such as bluff plates, it is hypothesized that when investigating tandem bluff body configurations, the shear layers of the upstream body must be able to reattach to some position on the downstream body in order for a flow regime transition to occur and hence for aerodynamic loads such as drag to be minimized.

## Conclusion

Experimental analysis using wind tunnel measurements along with numerical analysis through CFD of tandem bluff plates showed that inclination angles have a significant effect on the drag and flow regimes present. Specifically, results across a number of gap ratios for two equally sized bluff plates show that the shear layer moves away from the downstream plate when inclination angle is introduced, and a lack of reattachment to the downstream plate results in increased drag through all gap ratios. Moreover, due to a lack of reattachment of the shear layer towards the second plate, different flow regimes do not occur and this was reflected in the Strouhal number plots showing no significant behavioural trends. Results for the perpendicular bodies were comparable with published data which provided validation of current experimental and numerical methods. This analysis provides critical insight into the design and placement of tandem bluff bodies, showing that tangible benefits in drag may not be achievable if the flow passes a body that is inclined at an angle.


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