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FLOW INTERFERENCE BETWEEN TWO THREE-DIMENSIONAL CIRCULAR CYLINDERS IN TURBULENT FLOW

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ABSTRACT

The effect of free ends on flow interference between two circular cylinders has been examined, based on the measurements of mean and fluctuating base moments on one of the cylinders. Two cylinder arrangements were selected for the investigation, tandem($Y/D = 0$) and staggered ($Y/D = 1$) arrangements. The Reynolds number was set at 1.1×10^5 for a range of turbulence intensities from 0.4% to 11.5%. The influence of turbulence intensity on the free end effect has also been discussed.

INTRODUCTION

In the past, most of the research on flow interference between two circular cylinders has been conducted on 2D cylinders, ie. cylinders without free ends. Whilst the fundamental study of 2D interference is important for the understanding of various interference mechanisms, it is also of practical interest to obtain knowledge of the flow interference between 3D cylinders, ie. cylinders with free ends.

It is well known that flow on a single 3D cylinder can be significantly different from that on a 2D cylinder. Previous work by Okamoto(1973), Farivar(1981), Gerrard(1981), Kawamura(1984) and Zdravkovich(1989) shows that the presence of a free end introduces significant three dimensional flows at the free end. The separated flow from the free end is deflected into the wake, and thus affects the wake pressures. Okamoto et al.(1973) showed that the range over which the end effect reached could be the entire length of the cylinder if the aspect ratio (cylinder length to diameter ratio) was less than 6. If the aspect ratio was larger than 7, he observed that this end effect is limited to a range of 4 diameters from the free end. Moreover, this downwash also results in a disruption of the regular vortex shedding in that region, which can significantly affect the dynamic pressures and therefore the overall dynamic forces on the cylinder. As has been demonstrated by Zhang and Melbourne(1991), the interference between two 2D cylinders is, to a large extent, due to the interactions between vortices shed from the cylinders, hence, the effect of the free end on vortex shedding as described above, was expected to have a significant impact on flow interference.

It is the aim of this paper firstly to demonstrate the effect of free ends (3D effect) on flow interference for both tandem and staggered arrangements, and secondly to show the influence of turbulence intensity on the 3D effect.

EXPERIMENTAL ARRANGEMENT

The experiments were conducted in the $2m \times 1m$ working section of the wind tunnel at Monash University. The homogeneous turbulent flow was achieved using a grid turbulence generator. The turbulence intensities I_u were 4.5% and 11.5%, with the same longitudinal integral scale of 140mm. The turbulence intensity of the flow without the grid was 0.4%, and will be called smooth flow.

The model circular cylinders were aluminium tubes with an outside diameter of 100mm and a length of 800mm above the wind tunnel floor level. The Reynolds number based on the model diameter was 1.1×10^5. The main cylinder, on which the measurements were made, was cantilevered on a steel plate bolted on a massive concrete block underneath the tunnel floor. Strain gauges were mounted near the base of the main cylinder, two full bridges were used to measure alongwind and crosswind base overturning moments. The interfering cylinder was bolted rigidly onto the wind tunnel floor. Figure 1 shows a sketch of the experimental arrangement.

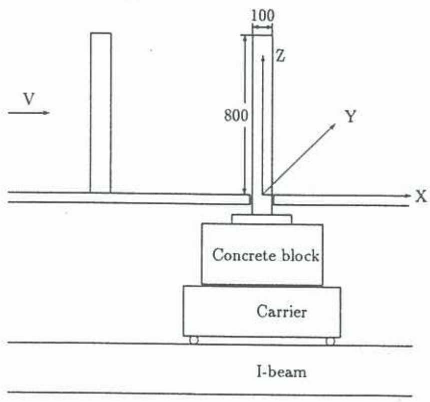

Figure 1: The cylinder set-up in the tunnel.

Time mean and standard deviations of the moments (about the floor level) were measured. The moments about the alongwind axis, m_x, (referred as the crosswind moments in this paper) were caused by the crosswind forces and the moments about the crosswind axis, m_y, were caused by the alongwind forces. The data were digitised at a sampling frequency of 1000Hz and collected by a minicomputer which outputs the average over a buffer of 35000 points.

The natural frequencies of the cylinder were sufficiently higher than the frequency range of interest, that is only moments of aerodynamic origin were measured, with no contribution from resonance response. To eliminate the influence of modal vibrations of the cylinder on the results, both analogue and digital filters were used.

EXPERIMENTAL RESULTS

The data were first reduced into the form of moment coefficients which are defined as:

$$C_{\overline{m}} = \frac{\overline{m}}{\frac{1}{2}\rho {V_\infty}^2 DL^2}; \quad (1)$$

$$C_{\sigma_m} = \frac{\sigma_m}{\frac{1}{2}\rho {V_\infty}^2 DL^2}. \quad (2)$$

where:

$\overline{m}$ is the time mean base moment,
σ_m is the standard deviation of moment,
V_∞ is the free stream velocity,
ρ is density of air,
D is the diameter of the cylinders,
L is the length of the cylinders.

In order to define the interference effect, an interference moment coefficient, $I_{\overline{m}}$, and interference factor, I_{σ_m}, are introduced for the presentation of results. They are defined as follows:

$$I_{\overline{m}} = C_{\overline{m}} - C_{\overline{m}_i}; \quad (3)$$

$$I_{\sigma_m} = C_{\sigma_m}/C_{\sigma_{m_i}}. \quad (4)$$

where $C_{\overline{m}}$ and C_{σ_m} are the mean and standard deviation of moment coefficients on the cylinder suffering interference and the subscript i denotes the results obtained on an isolated cylinder under the same free stream conditions.

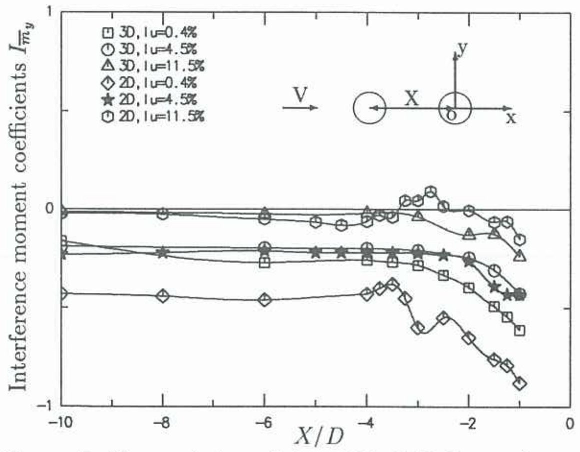

Figure 2: The variation of $I_{\overline{m}_y}$ with X/D for tandem arrangements, $Y/D = 0$.

The cylinder coordinate system, as shown in Figures 2 to 4, is fixed on the cylinder on which the measurements were made. Figures 2 to 8 present the variation of $I_{\overline{m}}$ and I_{σ_m} with cylinder spacings for various turbulence intensities I_u. In addition to the 3D results, 2D results for the same flow conditions obtained by Zhang and Melbourne are also presented in those figures.

In Figure 2 and Figure 4, it can be seen that the interference moment coefficients $I_{\overline{m}_y}$ in general are closer to zero for the 3D case than those for the 2D case. This suggests that in the 3D case, the upstream cylinder cannot provide as much shielding for the downstream cylinder as in the 2D case. Moreover, the variations of $I_{\overline{m}_x}$ and $I_{\overline{m}_y}$ with cylinder spacing are more gradual for the 3D case. The characteristics associated with different interference regimes, as demonstrated by Zhang and Melbourne(1991), in the 2D case could hardly be detected in the 3D case, particularly for tandem arranged cylinders. As I_u is increased, the results for most of the arrangements show less difference between the 2D and 3D cases.

As opposed to interference effects on the mean moments, the effect on the standard deviation moments in smooth flow is a lot higher for the 3D case in general. As shown in Figures 5 to 8, $I_{\sigma_{m_x}}$ for the 3D case can be as high as 8, while for the 2D case, it is no more than 3. For the 3D case, the interference is of much greater magnitude than that for the 2D case with respect to the dynamic forces.

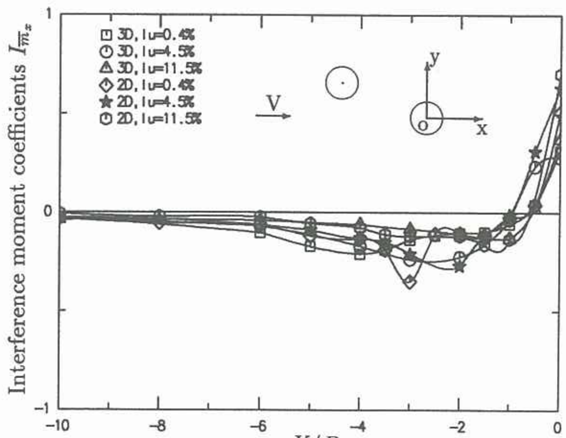

Figure 3: The variation of $I_{\overline{m}_x}$ with X/D for staggered arrangements, $Y/D = 1$.

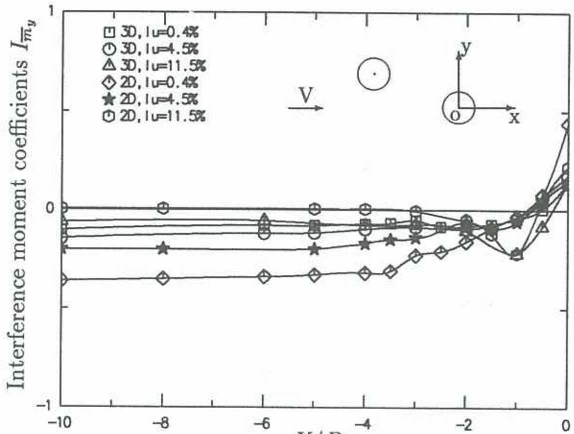

Figure 4: The variation of $I_{\overline{m}_y}$ with X/D for staggered arrangements, $Y/D = 1$.

DISCUSSION

The influence of free ends on flow interference can be rather complicated. As shown in the last section. Whilst the presence of the free ends on the cylinders leads to a reduction in $I_{\overline{m}_y}$, it causes a marked increase in both $I_{\sigma_{m_x}}$ and $I_{\sigma_{m_y}}$. The reduction in $I_{\overline{m}_y}$ for the 3D case may be attributed by the separated flow on top of the upstream cylinder. The separated flow deflects towards the gap between the cylinders. Consequently, for 3D cylinders, more fluid can be entrained from free stream into the gap region. This would cause higher mean pressure in the gap and thus smaller $I_{\overline{m}_y}$.

To better understand the mechanism of causing the large $I_{\sigma_{mx}}$ and $I_{\sigma_{my}}$ on the 3D cylinders, power spectra of fluctuating moments and velocity in the wake of the downstream cylinder are presented in Figures 9 to 11. Measurements on a single cylinder are also provided. The spectra of velocity fluctuations behind the cylinder were obtained at three different heights above the floor level and the values of Z/L were indicated in Figure 11.

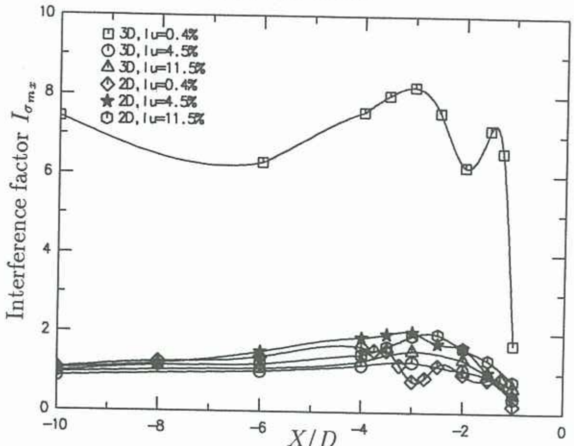

Figure 5: The variation of $I_{\sigma_{mx}}$ with X/D for tandem arrangements, $Y/D = 0$.

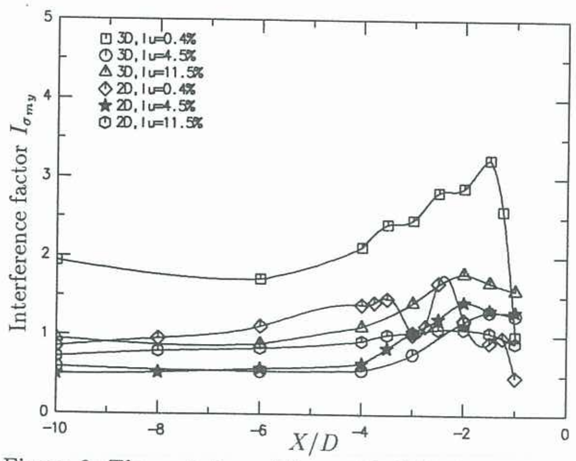

Figure 6: The variation of $I_{\sigma_{my}}$ with X/D for tandem arrangements, $Y/D = 0$.

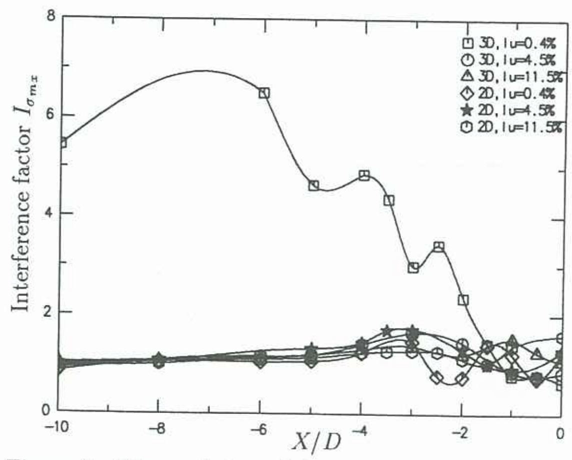

Figure 7: The variation of $I_{\sigma_{mx}}$ with X/D for staggered arrangements, $Y/D = 1$.

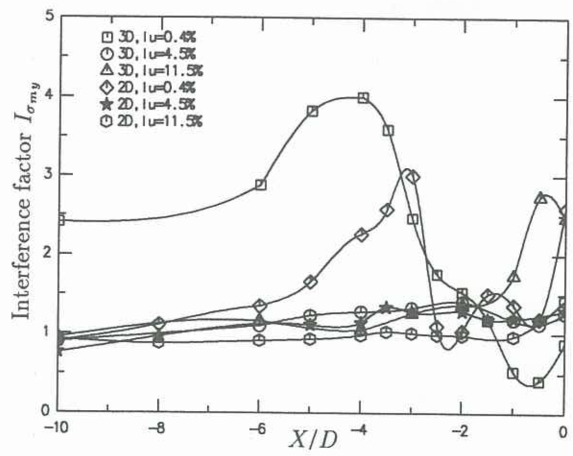

Figure 8: The variation of $I_{\sigma_{my}}$ with X/D for staggered arrangements, $Y/D = 1$.

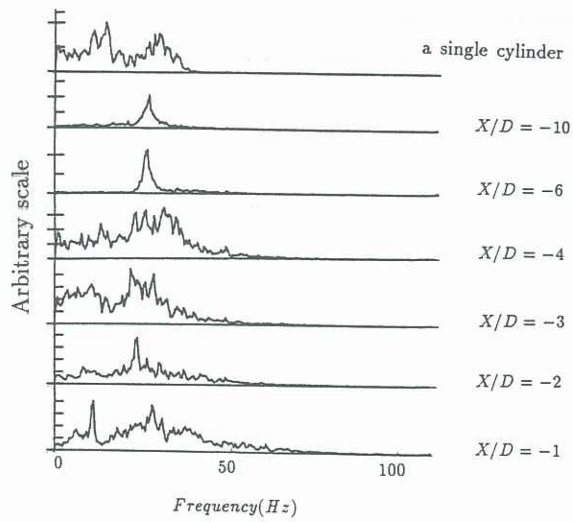

Figure 9: Power spectra of crosswind fluctuating moments for $I_u = 0.4\%$ and $Y/D = 0$.

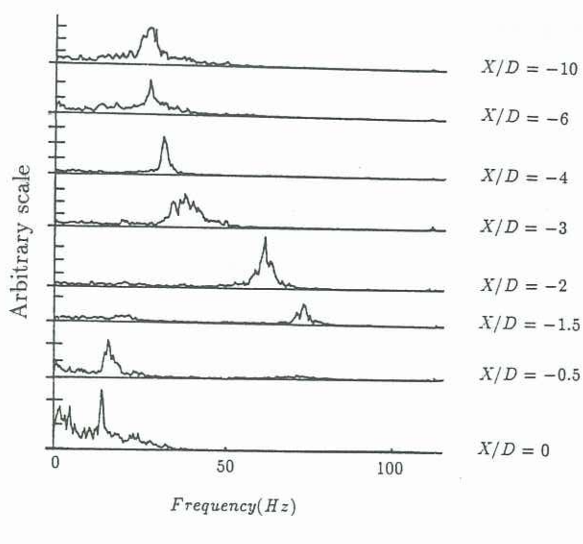

Figure 10: Power spectra of crosswind fluctuating moments for $I_u = 0.4\%$ and $Y/D = 1$.

It can be seen that at the spacing of $X/D = -10$, the spectra for the fluctuating moment $I_{\sigma_{mx}}$ are narrow banded for both tandem and staggered arrangements as opposed to the broad banded spectrum observed on a single cylinder. A comparison between the wake spectra for a single cylinder and those at $X/D = -6$, as shown in Figure 11, indicates that the region of regular vortex shedding along the span of the cylinder expands significantly due to the influence of the upstream cylinder. This contributes to the change in the moment spectra as mentioned above. On the other hand, the influence of the upstream cylinder on the fluctuating forces of the downstream cylinder at large cylinder spacings is a lot less for the 2D case as shown by the work of Zhang and Melbourne. Consequently, $I_{\sigma_{mx}}$ and $I_{\sigma_{my}}$ are a lot higher for the 3D case.

As the longitudinal spacing is reduced to below 6 diameters, the spectra for the tandem arrangement become very broad banded as shown in Figure 9. This is different from the 2D case where the downstream cylinder always experiences narrow banded excitations. It is conjectured that for the 3D case, as the spacing is reduced, the buffeting caused by the separated flow from the top of the upstream cylinder on the downstream cylinder becomes more significant, and consequently the regular vortex shedding along the span of the downstream cylinder is disrupted. This is demonstrated in Figure 11 which shows the disappearance of the narrow banded character in the wake spectra as $|X/D|$ is reduced to 5. The fluctuating moments σ_{mx} and σ_{my} on the downstream cylinder keep increasing due to the buffeting, in spite of the disruption of the vortex shedding. The buffeting effect becomes less evident when the downstream cylinder is not directly behind the upstream cylinder. This can be seen from the results of staggered arrangement as shown in Figure 10, the variation of spectra is very similar to that for the 2D case.

The free end effect on flow interference is strongly dependent on free stream turbulence intensity. In general, the difference between the 2D and 3D interference cases becomes much smaller as I_u is increased except for the region near $X/D = 0$ and $Y/D = 1$ where large differences can still be observed in turbulent flow. This is demonstrated in Figures 2 to 8.

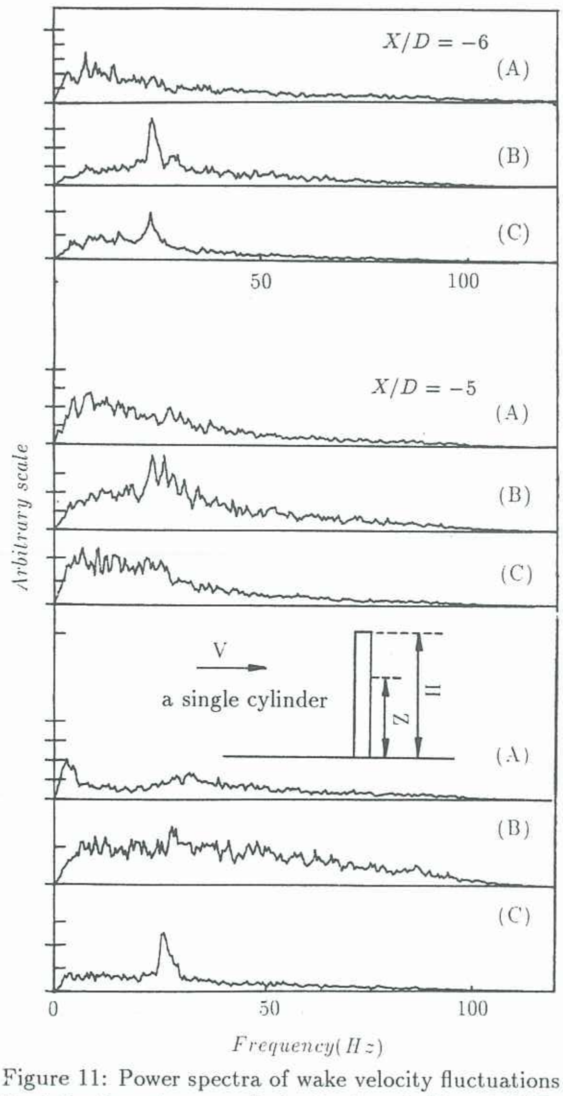

Figure 11: Power spectra of wake velocity fluctuations behind the downstream cylinder for $I_u = 0.4\%$ and $Y/D = 0$. A: Z/L=0.95; B: Z/L=0.70; C: Z/L=0.30.

CONCLUSION

The presence of the free ends of two interfering cylinders can have marked effects on flow interference. In smooth flow, large interference factors of fluctuating moments, $I_{\sigma_{mx}}$ and $I_{\sigma_{my}}$, can be observed for both tandem and staggered arrangements. The presence of an upstream cylinder for the 3D case, can lead to a large expansion in the region along the span of the downstream cylinder, where vortex shedding takes place. For tandem arrangements, as $|X/D|$ is reduced to below 6, the buffeting of the separated flow from the free end of the upstream cylinder becomes more significant than the buffeting of the vortices shed along the span of the upstream cylinder, and is the main source of excitation for the downstream cylinder. By comparison, this buffeting effect is not significant for the staggered arrangements.

In turbulent flow, the influence of free ends on flow interference is reduced significantly in general, except for the cases in which the interfering cylinder is positioned near $X/D = 0$ and $Y/D = 1$.

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