cylinders, the rms pressure obtained a highest level just beyond the critical spacing.

2 The spanwise correlation length of the pressure fluctuations at the 90 deg generator of the upstream cylinder increased in a steplike manner through the critical spacing to the level found for a single cylinder.

3 The rms lift and drag were much larger for the downstream cylinder than for the upstream cylinder up to the spacing of 7 diameters. At the spacing of 10 diameters, they were different from those for a single cylinder by only a small amount.

4 For the upstream cylinder, the rms lift was extremely small for the spacings less than critical whereas it was approximately equal to that for a single cylinder beyond the critical spacing.

5 For the downstream cylinder, the rms lift was strongly dependent on the spacing and amounted to as high as 2.8 times the value found for a single cylinder at the spacing of 4 diameters.

6 The rms drag for both cylinders was only weakly dependent on the spacing.

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DISCUSSION

M. M. Zdravkovich[1]

The authors are to be complimented for systematic and comprehensive measurements of fluctuating pressure around two circular cylinders in tandem arrangement at $R_e = 1.57 \times 10^5$. They stated that the cylinder surface was not polished so some minor effect of surface roughness might be expected. An early precritical regime might be inferred from a rather low spanwise correlation coefficient of 1.8 behind the single cylinder at the same Reynolds number (Fig. 4*a*). The precritical regime could also be inferred from the value of pressure drag coefficient for the single cylinder. It will be helpful if the authors could provide the value of drag coefficient (either uncorrected or corrected for the blockage effect).

Another important issue is the possible existence of the laminar separation bubble(s) on the downstream cylinder. The bubble usually formed a kink beyond $Cp_{\min}$ on the mean pressure curve for the single cylinder. The kinks were absent on the second adverse pressure gradient parts of all Cp curves in Fig. 2(*b*).

The reattaching shear layers separated from the upstream cylinder were fully turbulent before they impinged on the downstream cylinder and it was unlikely that the relaminarization took place before separation at 110°. Oil film visualization was carried out at $R_e = 5 \times 10^5$ by Okajima [5] and the trace of the separation bubbles was found only on the upstream cylinder. It might be expected that either a single or both separation bubbles were obliterated on the downstream cylinder by the turbulence produced by the upstream cylinder. Similar obliteration of separation bubbles was found on the single cylinder submerged in turbulent free stream.

The most interesting and intriguing finding was the variation of two $C'_{p_{\max}}$ in Fig. 3(*b*) with the spacing between the cylinders. The first peak which was caused by the reattachment of turbulent shear layers was less than the second one produced by the separation for $1/d = 2$ and 3. However, for $1/d = 4$ when the vortex shedding was established behind the upstream cylinder the "reattachment" peak was the dominating one. It will be revealing if the authors could provide separately the contribution of periodic and turbulent fluctuations for each $C'_{p_{\max}}$ shown in Fig. 3(*b*).

An unexpected significant increase in the spanwise correlation length behind the downstream cylinder at $1/d = 2$ indicated strong and well correlated vortex shedding behind the downstream cylinder. This was confirmed by the high C'_L in Fig. 6 for $1/d = 2$. Similar increase in $C'_{p_{\max}}$ was found by Igarashi [3] at $R_e = 3.5 \times 10^4$ with the absolute maximum of $C'_{p_{\max}}$ at $1/d = 2.35$. However, for both $1/d = 2$ and 3 the reattachment peak was greater than the separation peak and also the overall fluctuations were greater for spacing $1/d = 3$ than for $1/d = 2$. These differences were presumably caused by different Reynolds numbers i.e., medium subcritical and precritical regimes. The authors comments on this peculiar nature of $C'_{p_{\max}}$ peaks will be most valuable.

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Authors' Closure

We would like to thank Dr. Zdravkovich for his valuable comments.

As the discusser suggests, the flow around the single cylinder was in the precritical regime. The uncorrected time-mean drag coefficient C_D was 1.06. If this is corrected for the wind-tunnel blockage by Allen and Vincenti's [10] formula, we obtain $C_D = 0.93$. This value of the drag coefficient suggests that the flow was in the precritical regime.

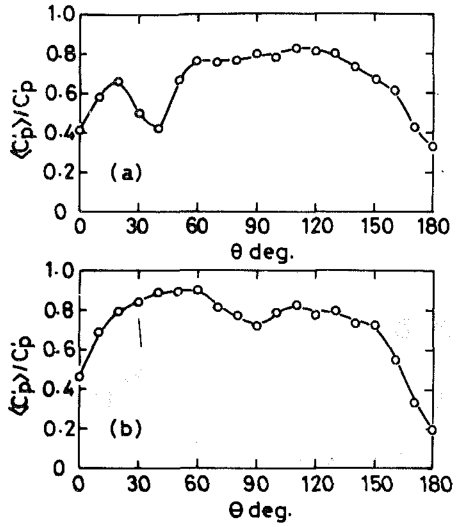

Fig. 7 Circumferential distribution of the r.m.s. periodic pressure fluctuation divided by C_p' at the same position for (a) $l/d=2$ and (b) $l/d=4$. The uncertainty in the ordinate is ±0.05 and that in the abscissa is ±0.2 deg.

The time-mean pressure profiles for the downstream cylinder showed no kink in the tested range of l/d. The authors agree to the discusser in that the separation bubbles were obliterated by the turbulence produced by the upstream cylinder.

With regard to Fig. 3(*b*), Dr. Zdravkovich expresses his concern about the changes in the relative magnitude of the reattachment and separation peaks of C_p' with l/d. In this connection, he suggests to provide separately the contribution of periodic and turbulent fluctuations for each peak shown in Fig. 3(*b*). Figure 7 presents the circumferential distribution of the r.m.s. periodic pressure fluctuation $<C_p'>$ divided by C_p', i.e., the overall r.m.s. pressure fluctuation at the same position, for $l/d=2$ and 4 (Sakata and Kiya [11]). The experimental condition was the same to the present one. At both reattachment and separation peaks, the r.m.s. periodic fluctuation is seen to be roughly 80 percent of the overall r.m.s. value.

The last point raised by the discusser concerns with the differences in the reattachment and separation peaks of C_p' between the present results and those of Igarashi [12]. As Dr. Zdravkovich suggests, these differences were possibly caused by the different flow regimes. At present the authors have no clear idea about this feature. It should be noted that in this experiment the reattachment peak was always greater than the separation peak in the range $l/d=4-10$, as shown in Fig. 8.

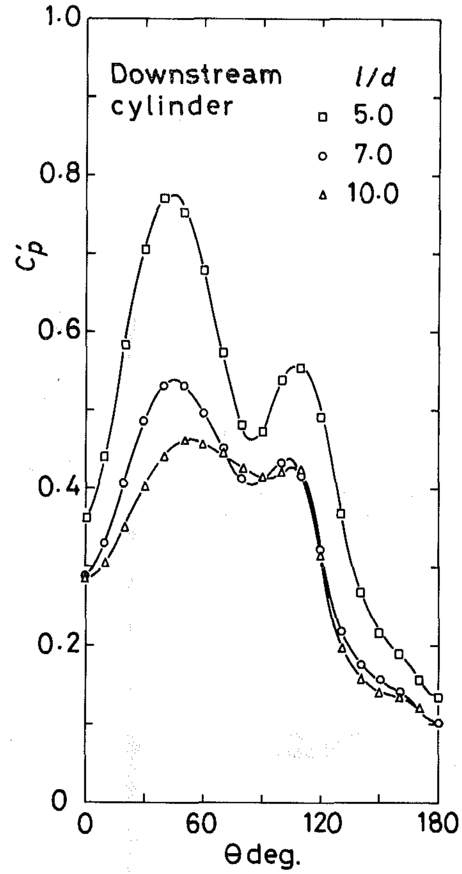

Fig. 8 R.m.s. pressure distribution for the downstream cylinder at $l/d=5$, 7, and 10. The uncertainty in the ordinate is ±0.01 and that in the abscissa is ±0.2 deg.

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