waves ahead of the cylinder axis at $\Lambda = 60$ deg. This is almost certainly outside of the separated shear layer at a position above boundary layer separation. Bloor also detected waves outside of the separated layer.

The entire sequence of the development of transition waves and subsequent turbulence is elaborately outlined by Bloor, and we find the same qualitative behavior when the cylinder is yawed. Typical oscilloscope traces are noted in Fig. 9. These data are downstream of the first appearance of transition waves, and the transition wave is superimposed on the lower frequency vortex shedding wave. The transition wave frequency was measured by storing a 10 to 100 millisec waveform in an oscilloscope and simply counting the wave cycles over a known time interval. At $\Lambda = 0$ this was generally satisfactory and it gave results of frequency versus Reynolds number consistent with Bloor's data, as noted in Fig. 10. The variation in the data obtained at any Reynolds number is large and the frequency measurement is subject to significant variation, especially at the lower frequencies, as noted by the bars about the data points in Fig. 10. The data at $\Lambda = 0$ degrees do follow the established result for separated shear layers that transition wave frequency is proportional to $U^{3/2}$ where U is the characteristic velocity. The free-stream velocity is taken to be characteristic of the problem of the unyawed cylinder.

We found it even more difficult to measure transition wave frequency on the yawed cylinder than on the unyawed cylinder. The transition to turbulence is occurring more rapidly when the cylinder is yawed and this transition destroys the periodicity, which characterizes transition waves, thus making it difficult to count cycles over extended duration of time. The data on transition wave frequency presented in Fig. 10 for the yawed cylinder ($\Lambda = 30$ deg) involve a large uncertainty even at the higher frequencies. Thus we present the data only as an indication of a trend and do not draw a firm conclusion on its behavior. We do not expect the characteristic velocity for transition in the near wake of a yawed cylinder to be U_n, which would follow from the Independence Principle. The data on turbulent fluctuations indicate that the spanwise component, w, as well as the crossflow component, u, of velocity contributes to the generation of turbulence. It is to be expected then that the characteristic velocity for a yawed cylinder would be greater than U_n, and it follows that f_t would be greater than the frequency of the unyawed cylinder at the same Re_n. We investigated the possibility that U is the characteristic velocity for all cylinders, regardless of yaw angle; however, this choice of velocity does not make the yawed cylinder data of Fig. 10 consistent with those of the unyawed cylinder. It is also noted that frequency data from the yawed cylinder is not proportional to the $^3/_2$ power of U_n or U, but rather to about the 1.3 power of these velocities.

Summary and Conclusions

In summary, the following phenomena have been observed to be dependent on Reynolds number (Re_n) and cylinder yaw for Reynolds numbers of 2000 to 10,000.

1 The transition from laminar to turbulent motion in the separated region is promoted as the cylinder is yawed. The onset of shear or transition waves in the separated region moves closer to the cylinder and at a yaw angle of 60 deg appears to have reached the boundary layer.

2 The physical manifestations of transition are promoted by the action of yawing the cylinder at constant Re_n. Thus we observed that the base pressure coefficient decreased causing an increase in the pressure drag coefficient, and the size of the region of backflow (defined by the zero velocity line) decreased.

3 The turbulence generation occurs, as expected, in the region of high shear or velocity gradient, it is quite nonisotropic, and biased in the direction of the resultant flow velocity.

4 The vortex shedding frequency obeys the Independence Principle; however, the rising level of turbulence that is promoted by cylinder yaw causes the energy associated with the shedding frequency to be much less dominant than in the unyawed configuration.

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DISCUSSION

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The paper's contributions are twofold:

(*a*) The measurement in its near wake region downstream of a yawed circular cylinder for the much desired information such as base pressure distribution, effects of Reynolds number to base pressure, drag, wake boundary, position of onset of transition and the shedding frequency.

(*b*) Its conclusion based upon these experimental findings. The authors are to be congratulated that by this investigation it is now shown that the wake region base pressure decreases due to transition, confirming also its validity by measuring the increased drag. The conclusion that the Independance Principle is not applicable for base pressure and position of transition is to be noted.

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