In this case, the boundary conditions [Eqs. (9) and (10)] will also fail and they must be calculated on the surface of the wing. The expansion of the pressure coefficient will be divergent and Eqs. (11) and (12) will fail; hence, its original expression must be used.

When we deal with a rolling wing,[2] we can choose a set of axes fixed to and rolling with the wing. The nondimensional variable x axis coincides with the axis of roll. If the conditions

$$K\sigma/\mu = \mathcal{O}(1) \text{ or } \mathcal{O}(\delta) \tag{19}$$

$$\mu^2 < \sigma^2 \tag{20}$$

are satisfied, the additional term due to the Coriolis acceleration in the second-order equation is only

$$-2KM^2 y\phi_{0xy}$$

where the dimensionless parameter σ is a measure of the lateral extent of the boundaries and μ is a measure of the vertical extent of this neighborhood. The pressure coefficients include two more linear terms

$$-2(Kz\phi_{0y} - Ky\phi_{0z}) \qquad \text{for Eq. (11)}$$

$$-2(Kz\phi_{1y} - Ky\phi_{1z}) \qquad \text{for Eq. (12)}$$

If the condition

$$\mu^2 \ll \sigma^2 \tag{21}$$

is satisfied, besides Eqs. (1-6), the second term on the left side of Eq. (7) can be neglected. This flow is a local two-dimensional one.

In addition to the above, there are many simpler cases, for example, when $K \ll \mathcal{O}(1)$, which are explained in detail in Ref. 3. In general, the second-order approximation will not be uniformly valid in the neighborhood of the wing edges and the Mach cone emanating from the vortex of the wing. But this difficulty can be circumvented by the PLK method.[1] The validity of the second-order theory beyond the variable range described here is very interesting for engineering calculations. Hence, this theory should be used with caution outside of this range until sufficient test data are available to indicate what range of parameters mentioned above should be used for any particular body.

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Wake Periodicity in Subsonic Bluff-Body Flows

J.L.F. Porteiro
University of South Florida, Tampa, Florida

Introduction

A SIGNIFICANT part of the total drag experienced by bluff bodies is generated by the low pressures existing in the near wake. This drag component is known as base drag and is strongly dependent on the fore- and afterbody geometry. This note reports an experimental study of the influence of the boundary-layer thickness and base mass transfer on the time-dependent, near-wake pressure and velocity fields of an axisymmetric blunt-based cylinder in subsonic flow. Both of these parameters are known to have a significant influence on the base pressure.[1-3]

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*Associate Professor, Chemical and Mechanical Engineering Department.

Experimental Apparatus and Technique

This investigation was conducted in the Rutgers axisymmetric near-wake tunnel (RANT II). This is the same facility used by Porteiro et al.[4] in their studies of the influence of mass transfer on the wake of a blunt-based body. The present work is a continuation of that study. The tunnel is an open-jet facility designed and constructed for interference-free studies of turbulent, subsonic, axisymmetric near-wakes behind a 1.9 cm diam cylindrical model. The model support sting is hollow, allowing the transfer of mass to and from the boundary layer and base region. Boundary-layer blowing and suction is carried out through a porous metal sleeve of 1.9 cm o.d. extending from the model support sting to a distance 3 diam upstream of the model base. Base mass transfer takes place through a porous metal plate 1.9 cm in diameter and 0.159 cm thick. Pressure regulators were used to stabilize the bleed air pressure and flow meters were used for metering the airflow.

Boundary-layer velocity measurements were made at a location 3 diam upstream of the base with a miniature total pressure probe and a Statham ± 3.45 kPa·g transducer. The probe location was zeroed by electrical continuity and its position could be determined within 0.025 mm in 152.4 mm of total travel. Total pressure measurements were taken at 27 radial locations chosen to provide detailed information on the velocity profile. Reference static pressure measurements were also taken at an axial location 3 diam upstream of the base. Base pressure was measured with a static pressure tap located at the center of the base of the model. An alcohol micromanometer providing readings to 0.05 mm of water was used for these measurements.

The fluctuating component of the base pressure was measured with a Kulite XCS-093-5 pressure transducer with a natural frequency of 70 kHz. The transducer dc output was analyzed with a Hewlett-Packard 3490A wave analyzer up to a frequency of 62 kHz.

Near-wake velocity studies were made with a constant-temperature hot-wire anemometer. An analysis of the frequency spectrum of the hot-wire signal was carried out at the stagnation point, in the far wake, and in the shear layer at points located in the vicinity of the base and at a halfway point in the near wake.

This investigation was carried out with a nominal Mach number of 0.11. The corresponding Reynolds number was 2.57×10^6/m. The nominal stagnation pressure was 102 kPa abs and the value of the stagnation temperature 280 ± 10 K. The approaching boundary layers were turbulent.

Experimental Results and Discussion

The fluctuating component of the near-wake velocity was studied by analyzing the frequency spectrum of the hot-wire signal up to a frequency of 62 kHz.

When the hot wire was placed in the shear layer very close to the base, analysis of the frequency showed no peaks in the signal amplitude for any combination of boundary-layer thickness and base mass transfer, except those involving moderate suction rates. Moderate suction rates produced a slight but noticeable increase in the signal amplitude at a frequency corresponding to a Strouhal number of 0.19. Altering the boundary-layer thickness brought about changes in the frequency of the amplitude maximum.

Analyses were also carried out at the location in the shear layer having the maximum level of turbulence ($X \cong 0.5D$) at the stagnation point and on the far-wake centerline at an axial location 4.25 diam downstream of the base. At the first two locations, the amplitude v the frequency plots revealed a clearly defined peak for all combinations of a boundary-layer thickness and near-wake mass transfer rates, except those involving high base bleed rates. Typically, plots of the hot-wire frequency spectrum were similar to those obtained by Calvert[2] in his investigation of the flow behind a 60 deg cone.

Both the boundary-layer thickness and the base mass transfer were found to alter the frequency of the peak. The amplitude of the peak seemed to depend only on the base mass transfer rate. The amplitude was a maximum at high suction rates; it decreased as the suction decreased, becoming even smaller with low and moderate values of the base bleed. It disappeared completely at relatively high bleed rates.

The analysis of the hot-wire signal in the far wake yielded similar results, but the amplitude of the maximum was considerably smaller.

A detailed study of the influence of the boundary-layer thickness and the base mass transfer on the frequency spectrum was carried out with the hot wire located at the stagnation point.

The hot wire signal was analyzed using a 10 Hz bandwidth and a sampling rate of 1 cps. The resulting wave analyzer plots showed excellent frequency resolution, allowing the determination of the peak frequency within 2 or 3 cps. The repeatability of the spectrum was excellent. The values obtained for the peak frequency were for most cases within the accuracy of its determination, i.e., 3 cps.

The influence of base mass transfer on the peak frequency is shown in Fig. 1. The mass transfer rate is expressed in terms of the mass transfer parameter Γ, which is a ratio of the mass bled through the porous base to the equivalent mass flow that would pass through the base area at the freestream conditions. The frequency is expressed in terms of the Strouhal number based on the base diameter, freestream velocity, and central frequency of the peak.

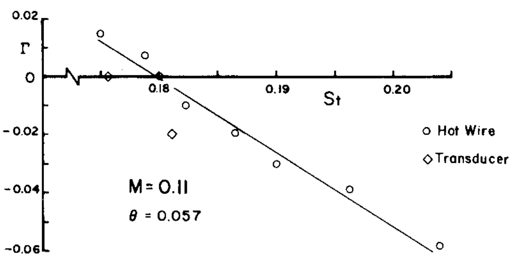

Fig. 1 Influence of base mass transfer on wake Strouhal number.

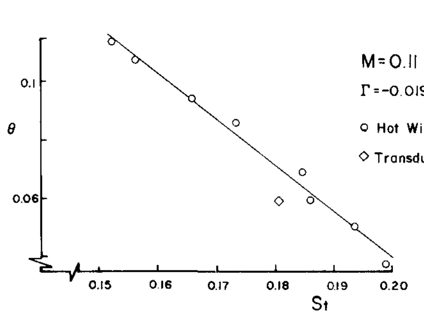

Fig. 2 Boundary-layer thickness vs Strouhal number.

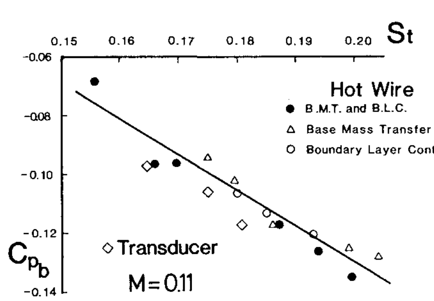

Fig. 3 Interrelationship of base pressure and Strouhal number.

Strouhal numbers increased with suction and decreased with base bleed in a linear way. This behavior is completely different to the one observed by Bearman[5] and Wood[6] in two-dimensional flows.

As shown in Fig. 2, a linear decrease of the Strouhal number was found as the dimensionless momentum thickness of the boundary layer, defined as the ratio of the momentum thickness to base radius, was increased. No significant variation in the amplitude of the signal at the peak frequencies was found as the boundary-layer thickness was changed.

Figure 3 shows the relationship between base pressure and Strouhal number. Despite some scatter in the data points, the dependence seems to be reasonably linear. This result is especially remarkable in view of the fact that the data points were obtained by using boundary-layer control and near-wake mass transfer both independently and in combination. A detailed analysis of the influence of near-wake mass transfer and boundary layer blowing and suction on base pressure for this particular flowfield may be found in Ref. 4.

The fluctuating component of the base pressure was similarly studied. The output of a Kulite pressure transducer located in the center of the base was anaylzed using the procedure described for the hot-wire signal analysis.

The frequency spectrum did not exhibit a sharp, well-defined peak similar to the one found in the hot-wire signal spectrum. Evidence of periodicity was found, however, as a region where signal amplitude reached levels about twice as high as those of neighboring frequencies. The central frequency of the region was determined and the results proved to be repeatable for different runs within 3%. This region of maximum amplitude behaved in every way like the peak in the hot-wire spectrum. Increases in the boundary-layer thickness and base bleed brought about decreases in the Strouhal number. Similarly, suction increased both the Strouhal number and the amplitude of the signal. A comparison between transducer and hot-wire results is shown Fig. 1-3.

Strouhal numbers obtained using the transducer were found to agree within 6% with those obtained using the hot wire when such comparisons were possible. Base bleed and suction significantly altered the amplitude of base pressure oscillations over the whole frequency spectrum. High base bleed rates reduced the base pressure oscillations to 1% of the value of the time-averaged base pressure. When no bleed or suction was used, the oscillations rose to a level of 5% for the region of maximum amplitude and 2.5% for the rest. Base suction greatly increased the magnitude of the oscillations. Moderate suction rates increased the values to 7% and 5%, respectively; at high suction rates, the values of the oscillating pressure were about 10% of those of the time-averaged pressure.

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