

The Decay of Bluff Body Wakes

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ABSTRACT

Vehicles on the road operate in the turbulent flow field resulting from the combined effects of the natural wind and the wakes of other vehicles. While substantial data exists on the properties of the natural wind, much less information is available for the wake properties of road vehicles. The wake information available for road vehicle shapes is mainly restricted to the near wake region, but to understand the vehicle operating environment it is the wake downstream of this region which is of interest. To determine the range of this area of interest requires some knowledge of the decay of the wake properties. From wind tunnel studies using small simple bluff bodies in free stream and in ground proximity the principle wake properties, velocity deficit and peak turbulence intensity have been measured. The maximum velocity deficit is shown to approximately decay with $x^{-2/3}$, where x is the distance downstream, while turbulence intensity decays at a slightly slower rate. A relationship with body drag is established. Ground proximity is shown to significantly modify the velocity distribution in the wake.

INTRODUCTION

The environment in which a road vehicle operates has been the subject of a number of recent studies; see, for example Wordley and Saunders, (1), and Lindener et al., (2). These extensive investigations measured the onset flow field immediately upstream of a vehicle travelling along the road and considered the combined effects of both the natural wind, including its interaction with roadside features, and traffic. They provide an understanding of the limitations of the conventional full scale automotive wind tunnel, which typically have very low turbulence levels, and help define appropriate turbulent flow properties where these can be

introduced, as in the Pininfarina Turbulence Generating System, designed by Cogotti, (3).

The flow conditions produced by traffic are poorly understood. The influence on a vehicle travelling in traffic is experienced through wake interaction when downstream as well as through the local pressure field when overtaking. Of particular interest is the interaction between large and small vehicles as typified by a truck and passenger car, respectively. While the passenger car shapes usually generate lift so that the wake structure is dominated by trailing vortices, the disturbing wakes from trucks are typical of bluff non-lifting bodies, with low transverse velocity components.

The principal wake properties examined here are the mean and turbulent velocity distributions and the primary interest is in their decay rates and also the growth of the wake. Sketches in [Figure 1](#) define the terms. For axisymmetric bodies, as well as two dimensional sections, the mean velocity profile across a significant central part of the wake is closely matched by a cosine curve. The characteristic wake parameter is the velocity deficit, U_D , which is given by $U_D = U_0 - U$, where U_0 is the freestream velocity and U is the local velocity measurement in the wake. The velocity deficit on the wake centre-line is denoted by U_C . The wake size is usually defined in terms of the half widths, which are defined as the distance between the points where the velocity deficit has reduced to half the maximum value. The turbulence intensity distribution shows an off centre peak. In the wake, both the velocity deficit and the turbulence intensity decay with distance aft of the body generating the wake.

Theoretical studies of wakes behind axisymmetric bodies, by Swain (4), Schlichting, (5), for example, show that the velocity deficit decays as $x^{-2/3}$, while the wake width grows as $x^{1/3}$. The velocity deficit is also a function of body drag

represented by $C_D A$, where C_D is the drag coefficient and A is the frontal area.

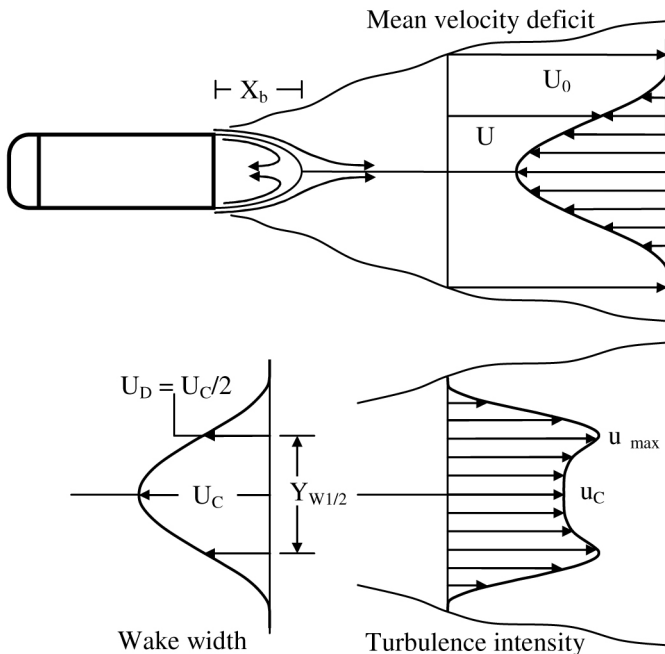


Figure 1. Wake features and definitions.

Most wake studies for automotive applications involve the very near wake close to the reverse flow 'bubble', or 'dead-water' region, immediately behind the vehicle, and perhaps extending a further body length downstream. The region of interest here extends to the point where flow velocities are within a few percent of the free stream value, but not into the extreme far wake. There is a distinct lack of data for flows in this region.

One exception is a moving model experiment conducted by Baker et al, (6). Wake measurements were obtained for a model lorry propelled past a fixed probe. Data, of necessity, was obtained outside the model envelope, but in the far wake region the velocity decay with time, measured above the model, had an exponent between -0.6 and -0.7 . Beside the model, however, the decay exponent was much less, generally between -0.1 and -0.3 .

There is substantial data on the far wakes behind axisymmetric bluff bodies, such as a circular disc. For example, Johansson and George, (7), show that wake similarity is achieved after approximately 30 diameters downstream. The velocity deficit and wake growth data match the theoretical predictions but a virtual origin for the wake is required.

Much less wake data exists for three dimensional bodies. Rectangular flat plates of varying aspect ratio have been investigated by Fail et al, (8), and Kuo and Baldwin, (9),

studied the wakes of two elliptical plates. An interesting feature of three dimensional wakes is the deformation which occurs downstream, as identified by Verna, (10). For a rectangular or elliptical section body the near wake major axis aligns with the major axis of the body, but within a few body diameters the wake rotates through 90° so that the wake major axis aligns with the body minor axis. For a square section body the wake appears to rotate through 45° , while for a triangular section body an apparent rotation of 180° occurs.

EXPERIMENTAL INVESTIGATION

WIND TUNNEL

The data presented here was obtained by the author during the early 1970's while conducting research for his PhD, (11). The wind tunnel used in these experiments was the T3 Low Speed closed return tunnel in the Department of Aeronautics at The City University (London). This wind tunnel has an octagonal working section, 1.14m wide by 0.93m high and 1.53m long. Ground simulation was provided by a full span fixed ground board mounted 0.2m above the tunnel floor. Circulation control around the ground plane was provided by a variable flap on the underside of the ground board, which was adjusted to balance pressures readings above and below the ground board, just aft of the leading edge. The nominal test speed was 30m/s, giving a Reynolds No, Re , of $2.0 \times 10^6/m$. Flow uniformity obtained in the empty wind tunnel over the region of the model and wake was within 0.5%, while the turbulence intensity was less than 0.6%. The boundary layer thickness was measured over the ground surface. The growth was found to be similar to that expected for a zero pressure gradient boundary layer, varying from 0.017m at 0.25m aft of the ground board leading edge to 0.029m at 1.5m. The boundary layer profile was close to a $1/7$ th power law so the displacement thickness was approximately $1/8$ th of the overall thickness.

SIMPLE BODIES

The simple bodies used in this experiment were rectangular blocks with a rounded leading edge as shown in Figure 2. The overall body dimensions are given in Table 1. Each basic block was 0.3m long and 0.1m high. Three model spans were used; 0.1, 0.2 and 0.3m, although only the two smaller span cases are shown in Figure 2. The leading edge extended to model length to 0.325m and included a radius of 0.025m on the horizontal edges. The vertical leading edges were left sharp. For force measurements of drag and lift the blocks were mounted to an overhead 3-component balance, which allowed the pitch angle to be varied. For the wake measurements reported here the bodies were always mounted at zero incidence. Based on the area above the ground board the solid blockage varied from 1.33% for Block 1N to 4% for Block 3N.

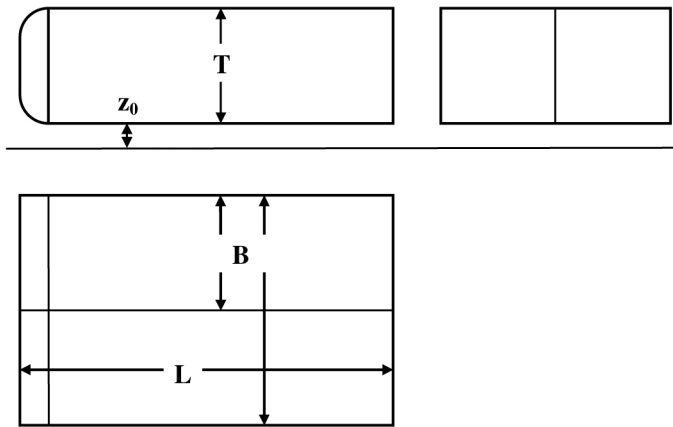


Figure 2. Bluff body models.

The models were mounted to an overhead 3-component mechanical balance via twin vertical struts connected by a horizontal bar through the centre of the model. Pitch control of the model was obtained using a small diameter vertical strut connected to a pivot on the base centerline, immediately behind the model trailing edge. No yaw data was obtained for these models.

Table 1. Bluff body model dimensions, (m).

Block	L	T	B
1N	0.325	0.10	0.10
2N	0.325	0.10	0.20
3N	0.325	0.10	0.30

INSTRUMENTATION

The wake flow measurements reported here were obtained using a hot wire anemometer. The single wire was always aligned parallel to the ground and normal to the free stream direction. The output voltage from the wire was linearised and the mean, E , and rms, e , signals represent flow velocities given by:

$$E = k_1(U^2 + W^2)^{0.5} \quad (1)$$

$$e = k_1(u^2 + k_2 v^2 + w^2)^{0.5} \quad (2)$$

where U , V , W and u , v , w are the mean and turbulent flow velocity components, respectively, in the x , y , z directions. The value of k_2 is approximately 0.2, (12). To avoid confusion the results are plotted as output voltages and not approximated flow velocities. While E represents the longitudinal mean velocity, U , with only small error in most cases, no similar simplification is possible for the rms signal as the turbulence intensity components are of the same order of magnitude. Far downstream, where the turbulence might be considered isotropic, e/E is very approximately $1.5u/U$.

RESULTS

An example of the hot-wire anemometer data obtained downstream of a bluff body in free stream is shown in [Figure 3](#). The model in this case was block 2N, with base aspect ratio, (model width/ height) of 2.0. Similar wake profile data is given in (11) for the other basic bodies in free stream and for a range of ground clearances. In [Figures 3\(a\)](#) and [3\(b\)](#), anemometer data is obtained in the vertical plane on the model centerline for the mean and turbulence velocity components respectively, while in [Figures 3\(c\)](#) and [3\(d\)](#) the data is obtained for the horizontal plane on the line of symmetry.

The vertical velocity distribution follows, approximately, a cosine curve, (13). The origin, $z=0$, is at the centre of the body. A reasonable degree of similarity is observed for all flow profiles measured downstream of the reverse flow region and for all three bodies if the plots are normalised with respect to the maximum velocity deficit and to the wake half width. The turbulence velocity profile demonstrates an off-centre peak which initially results from the shear layer emanating from the separation edges on the base of the body. In this downstream region the peak occurs just inboard of the wake half width and moves progressively outwards.

The horizontal velocity profile for this body, Block 2N, shows a distortion from the cosine curve, which is much more pronounced in the higher aspect ratio body (block 3N) and is not apparent in the square section body, (block 1N). This 'step' in the profile is in the region of the local turbulence intensity peak. The turbulence velocity profile shows peaks which occur inboard of the body side edges and initially move inboard before reversing direction. The peaks are less pronounced than in the case of the vertical profile. The body of square cross section, block 1N, generated a wake with smaller velocity deficit at comparable downstream distances.

The development of the wake size, as defined by the half widths, is shown in [Figure 4](#). It can be seen that the wake growth varies considerably between the square and rectangular bodies. For the square section body, block 1N, the wake width increases slowly downstream of the reverse flow region at the model base. In the vertical plane, as denoted by the open symbols, the rectangular body wakes grow much more rapidly just downstream of this region and the growth increases with base aspect ratio, but in the horizontal plane, denoted by the solid symbols, the wakes contract. In the case of block 2N, with a base aspect ratio of 2.0, the wake height becomes greater than the width at less than four base heights downstream. For block 3N, with a higher base aspect ratio, this crossover does not occur until six base heights downstream. Both cases demonstrate the wake deformation identified by Verna, (10), where the major axis of the wake becomes aligned with the minor axis of the body. The area of