AERODYNAMICS AND TRAJECTORIES OF WINDBORNE DEBRIS
Part 1. Compact Objects

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Introduction

Although testing of building materials for resistance to impact by wind-borne debris has been carried out for many years, in both Australia and the U.S.A., this has apparently been done with little knowledge of the aerodynamics and mechanics of wind-borne debris items. Numerical modeling of the trajectories of generic bluff-body shapes representative of real debris items appears to be the most useful approach to make engineering predictions of missile speeds and trajectories. An essential ingredient of such numerical models is a description of the coefficients of aerodynamic forces (and moments for some objects) with respect to the relative wind vector.

Following the classification of Wills *et al* [1], debris objects can be classified by their aerodynamic behaviour as ‘compact’, ’sheet-type’, or ‘rod-type’. In this paper, the relevant aerodynamic coefficients of spheres and cubes (Figure 1) are discussed, and some comparisons made of calculated trajectories of these compact objects, with experimentally measured ones in wind-tunnel experiments.

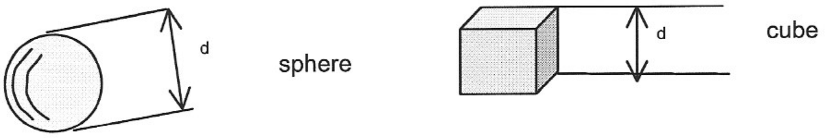

Figure 1. Generic ‘compact’ objects

Aerodynamics of spheres and cubes

Since typical compact windborne debris objects have a characteristic dimension, d, of the order of 10mm (for example roof gravel), compared to scales of atmospheric turbulence of 100 metres, the velocity fluctuations of atmospheric turbulence are clearly quasi-steady with respect to the object, and smooth flow coefficients are appropriate for the calculation of trajectories. However, the effect of small-scale turbulence in wind-tunnel measurements can be quite significant on aerodynamic coefficients of bluff bodies such as spheres and cubes, and may affect the values obtained for force coefficients, or trajectory measurements in wind tunnels.

Drag coefficients for spheres are, like those for the circular cylinder, quite dependent on Reynolds Number (Figure 2); (the coefficients are based on the projected area - $\pi d^2/4$). In the critical Reynolds Number region, where the drag coefficient falls, it may also be dependent on surface roughness.

Assuming missile speeds relative to the air of 10 to 30 m/s, and a diameter of 0.01 m, the Reynolds Number range for a windborne sphere is about 7×10^3 to 2×10^4. For this range of Re, the drag coefficient in smooth flow is in the range of 0.4 to 0.5, and appears to increase slightly with increasing Re over that range (Figure 2, and Reference [2]). The effect of small-scale turbulence is uncertain but is likely to reduce the drag coefficient.

The drag coefficient for a cube, being sharp-edged, should be insensitive to Reynolds Number, but will obviously vary with the angle of pitch and yaw to the flow. It will also be quite sensitive to small-scale turbulence (with scales of the order of the side length, d). ESDU 71016 [3] has conveniently summarized measurements of aerodynamic force coefficients on rectangular blocks, including cubes, up to 1970. However, angles of attack in only one plane are considered (i.e.. either pitch or yaw, but not both together), and it is stated in ESDU 71016 that ".....the user should allow for an uncertainty of ±0.15 on the force coefficients obtained from this Item...".

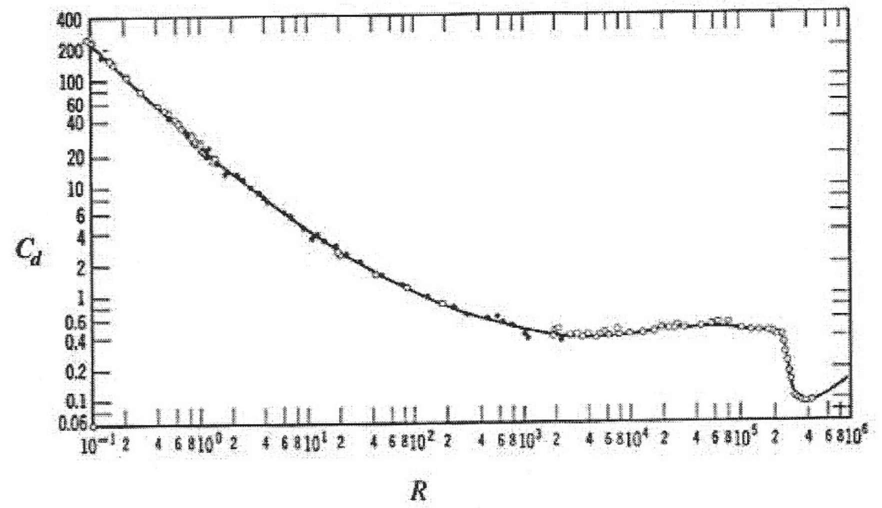

Figure 2. Drag coefficient of a smooth sphere against Reynolds Number (low turbulence flow)

For the above reasons, additional wind-tunnel measurements on cubes, at both Louisana State University and Monash University were carried out. The same size balsa wood cubes (side length 76 mm) were used in both series of tests. In the LSU measurements, the cube was supported on a horizontal threaded rod spanning the width of the wind tunnel (950 mm); in the Monash measurements, the cube was mounted on a sting balance. In both cases, the drag of the exposed supports was subtracted – in the LSU tests this affected every test, in the Monash tests the sting was only exposed at certain larger angles of attack. In both cases the flow had a turbulence intensity of about 1%.

The drag coefficients (based on a reference area of d^2 for all yaw and pitch angles) obtained are shown in Tables I and II. The agreement between the results from both wind tunnels is reasonably good, although the Monash values are lower than those obtained at LSU – this may be because of blockage effects which were higher in the LSU tests.

Table I. Drag coefficients for a cube measured at LSU

	0° pitch	15° pitch	30° pitch	45° pitch
0° yaw	1.00	1.05	1.10	1.16
15° yaw	1.05	1.15	1.23	1.27
30° yaw	1.10	1.23	1.22	1.21
45° yaw	1.16	1.27	1.21	1.21

Table II. Drag coefficients for a cube measured at Monash U.

	0° pitch	15° pitch	30° pitch	45° pitch
0° yaw	0.99	1.06	1.07	1.07
15° yaw	1.06	0.90	1.07	1.15
30° yaw	1.07	1.07	1.17	1.09
45° yaw	1.07	1.15	1.09	1.04

The LSU results also agree well with values given by ESDU 71016 [3] for a cube in smooth flow with various pitch angles with respect to the flow, but with zero yaw (or vice-versa) [4].

Equations of motion

The equations for the horizontal and vertical components of acceleration for a compact object driven by a steady wind speed neglecting any lift forces, are as follows ([4], [5]) :

$$\frac{d^2x}{dt^2} = \frac{\rho_a C_D (U - u_m)\sqrt{\left[(U - u_m)^2 + v_m^2\right]}}{2\rho_m . \ell} = K(U - u_m)\sqrt{\left[(U - u_m)^2 + v_m^2\right]} \qquad (1)$$

$$\frac{d^2z}{dt^2} = \frac{\rho_a C_D (-v_m)\sqrt{\left[(U - u_m)^2 + v_m^2\right]}}{2\rho_m . \ell} - g = K(-v_m)\sqrt{\left[(U - u_m)^2 + v_m^2\right]} - g \qquad (2)$$

where u_m and v_m are the horizontal and vertical components of the missile, or debris object, and U is the wind speed. K is equal to $\rho_a C_D/(2\ \rho_m.d)$ where ρ_a and ρ_m are the densities of air and the missile, respectively.

Equations (1) and (2) can readily be solved numerically on a step-by-step basis to give the velocities and displacements of the wind-borne object as a function of time. This was done for spheres and cubes, taking a constant average value for the drag coefficient, C_D.

Comparison of experimental and numerical trajectories

Experimental measurements were made of trajectories of a variety of spheres and cubes in a wind tunnel at Texas Tech University. Various small wooden spheres (d=25, 50 and 76 mm) and cubes (d=25 mm)were released at known wind speeds from a height of 350 mm in the wind tunnel, and their trajectories up to impact with the wind-tunnel floor were monitored using a high-speed digital movie camera, and compared with calculated trajectories. The details of the experimental approach are described by Wang and Letchford [6].

Figure 3(a) and (b) show comparisons of the calculated and measured horizontal displacements, at impact with the wind-tunnel floor, for spheres and cubes respectively.

The drag coefficients used for the calculations of the trajectories were 0.40 and 0.835 for spheres and cubes respectively. These are lower values by about 20% than the expected values in smooth flow for spheres and cubes, averaged over Reynolds Number and angle of attack, respectively. This reduction is made for the effect of small-scale turbulence of 7-10% in the wind tunnel over the trajectory path of the objects (ESDU 71016 actually recommends a reduction of 28% for rectangular prisms).

The cubes travel considerably further than the spheres due to their higher drag coefficients. The lower displacements of the spheres makes the errors in their measurement greater and probably explains the greater scatter and lower correlation compared with the cubes. The agreement between the calculated and measured displacements in Figure 3 is reasonable, although the calculated values overestimate the measured trajectories. The drag coefficients may be even lower than those assumed, and there may be a significant wake downstream of the release platform, which wasn't accounted for in the calculations. In the case of the cubes, neglect of the small lift forces may also have had some effect on the calculations.

Conclusions

The aerodynamic drag forces on spheres and cubes, as representative of 'compact' wind-borne objects have been discussed. The drag coefficient for a sphere depends weakly on the Reynolds Number, and that for a cube depends on the angle of pitch and yaw with respect to the relative wind vector.

Comparisons of horizontal trajectories, of both spheres and cubes, calculated from the equations of motion considering onlty drag forces agree quite well with measurements in a wind tunnel, although the horizontal displacements are slightly overestimated.

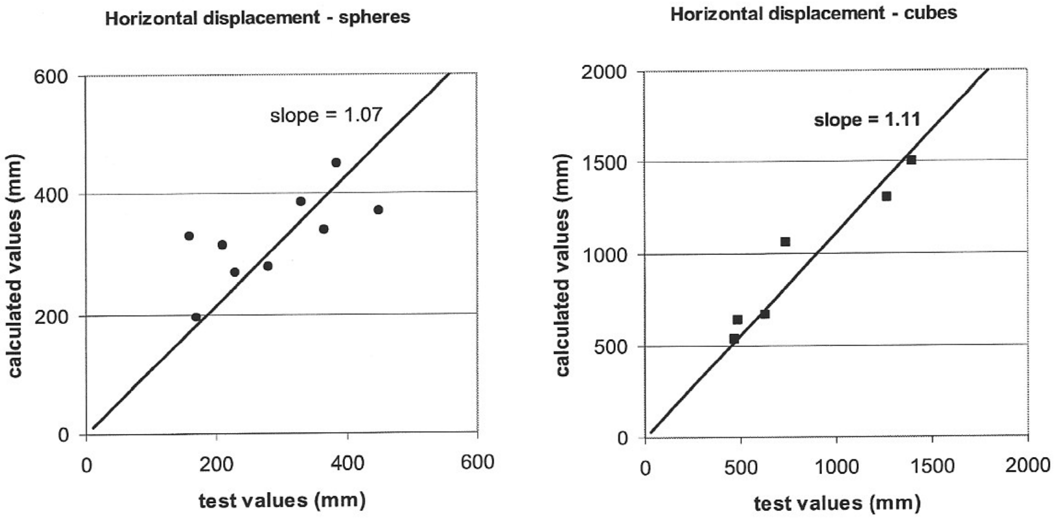

Figure 3. Calculated and measured horizontal displacements of (a) spheres and (b) cubes

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