AERODYNAMICS AND TRAJECTORIES OF WINDBORNE DEBRIS.
Part 2. Sheet Objects

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Introduction

Wills *et al* [1], classified wind-borne debris objects by their aerodynamic behaviour as 'compact', 'sheet-type', or 'rod-type'. The companion paper to the present one [2] discusses the aerodynamic coefficients and trajectories of compact objects. In this paper (Part 2), the normal aerodynamic force coefficients and centres of pressure of square flat plates, representing sheet-type objects (Figure 1), are discussed. In the real world, these can represent roof tiles, shingles or steel roof or wall sheeting. The dimensions of such objects are characterized by two dimensions – the breadth, ℓ, and the thickness, t.

Comparisons are then made of calculated trajectories of flat plates, with experimentally measured ones in wind-tunnel experiments.

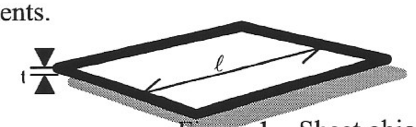

Figure 1. Sheet objects

Aerodynamics of flat plates

Hoerner [3] gives the *normal* force coefficient on a square flat plate at various angles of attack. This can be represented to a good approximation by the function shown in Figure 2. C_N is based on the planform area, ℓ^2. Some additional measurements of C_N at Monash University are also shown in Figure 2; these agree quite well with the assumed function, although further measurements in the angle of attack range from 30 to 40 degrees would be useful to better define that region where 'stall' occurs.

The lift and drag forces due to normal pressures on the plate can then be obtained from the resolution of the normal force into components normal and parallel to the wind direction. The pitching moment acting about the centroid of the plate is obtained by multiplying the normal force by the distance of the centre of pressure from the centroid, c. A tentative model of the distance of the centre of pressure, as a fraction of the side dimension of the plate, ℓ, is shown in Figure 3.

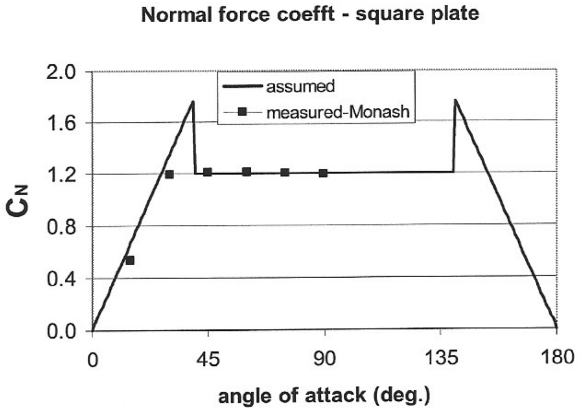

Figure 2. Simplified model for the normal force acting on an inclined flat plate

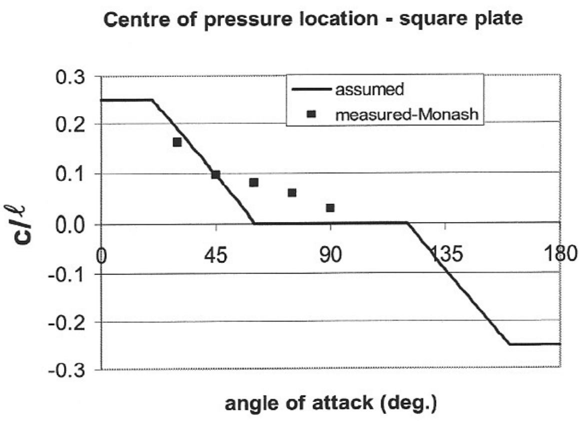

Figure 2. Simplified model for centre of pressure position on an inclined flat plate

For angles of attack between 0 and 20 degrees, the centre of pressure is assumed to be at the quarter chord point ($c/\ell = 0.25$). (c/ℓ) is then assumed to vary linearly between 0.25 and zero, as the angle of attack varies between 20 and 60 degrees. Between 60 and 90 degrees, the centre of pressure is assumed to be at the centre of the plate. Unfortunately, it is difficult to get high accuracy in measurements of centres of pressure; however some measurements from Monash University are shown on Figure 3. These agree reasonably well with the assumed model, although, unsurprisingly, the sharp 'corners' in the assumed model are not seen in the measurements.

Equations of motion

To calculate the trajectories of flat plates, the lift force and pitching moment induced by the relative wind and the rotational motion of the plate are significant,and should be included.

Figure 3 shows that the apparent angle of attack of the wind, relative to a plate that is rotating as well as moving horizontally and vertically, is equal to ($\beta+\theta$), where β is the angle of attack of the relative wind induced by the vertical motion of the plate, with respect to the horizontal, and θ is angle of rotation of the plane of the plate with respect to the horizontal.

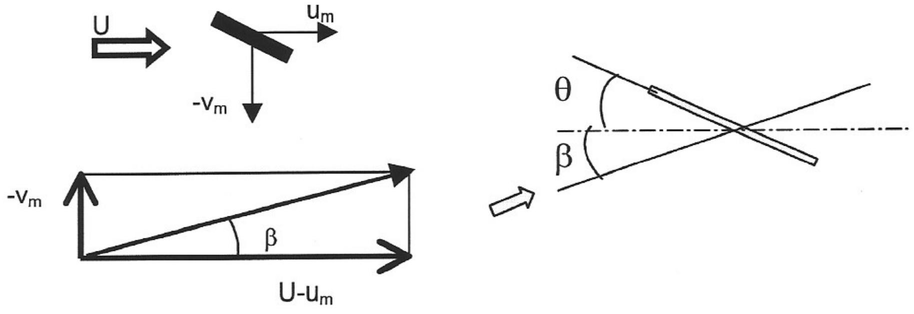

Figure 3. Relative angle of attack for a translatimg and rotating plate

The following equations then describe the horizontal, vertical and angular accelerations of the plate:

$$\frac{d^2x}{dt^2} = \frac{\rho_a (C_D \cos\beta - C_L \sin\beta)\left[(U-u_m)^2 + v_m^2\right]}{2\rho_m . t} \qquad (1)$$

$$\frac{d^2z}{dt^2} = \frac{\rho_a (C_D \sin\beta + C_L \cos\beta)\left[(U-u_m)^2 + v_m{}^2\right]}{2\rho_m . t} \tag{2}$$

$$\frac{d^2\theta}{dt^2} = \frac{\rho_a C_M A\,\ell\left[(U-u_m)^2 + v_m{}^2\right]}{2I} \tag{3}$$

where t is the plate thickness, A is the plan area (ℓ^2), and I is the mass moment of inertia.

These equations can be solved numerically for the x and y and θ displacements. The force and moment coefficients, C_D, C_L, C_M are all functions of the relative angle of attack, (β+θ), and must be adjusted at every time step.

Comparison of experimental and numerical trajectories

Tachikawa [4] measured in a wind tunnel the trajectories of square flat plates released at various initial angles of attack. Calculations were made of these trajectories, using Equations (1) to (3) and the model of aerodynamic coefficients given previously. An example of one of these comparisons is given in Figure 4. In this case, the initial angle of attack of the plate is 15°. The agreement between the measurements of Tachikawa and the calculations is good for all three displacements.

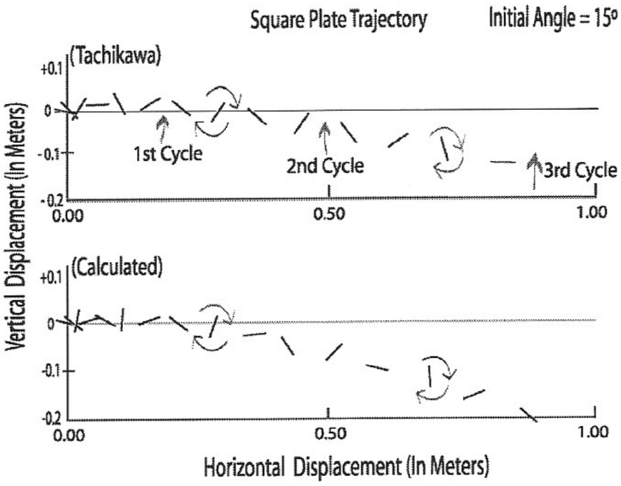

Figure 4. Experimental and numerically calculated displacements for a square plate (measured trajectory by Tachikawa [4] above; calculated trajectory below)

Several different square 'sheets' of varying materials, sizes and masses were 'flown' in the wind tunnel at Texas Tech University, their trajectories monitored using a high-speed digital movie camera and compared with the calculated trajectories, with the latter being obtained using the equations given in the previous section. The methodology for the measurements is described more fully by Wang and Letchford [5].

Figure 5(a) and (b) show comparisons of resultant velocities, and horizontal and vertical displacements, for one case of a small square balsawood sheet, at an initial angle of 45 degrees in a wind speed of 10.8 m/s. In this case, the agreement between the calculated and measured trajectories, up to the time when the sheets hit the wind-tunnel floor, is good.

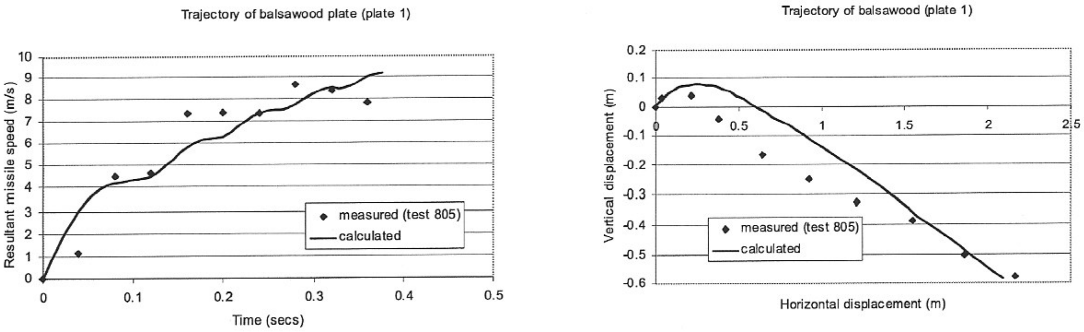

Figure 5. Experimental (Texas Tech University) and numerically calculated trajectories for a square plate. (a) Resultant plate velocity versus time. (b) Vertical versus horizontal displacements.

Tachikawa [4] showed that the vertical displacements and angular rotations of sheet objects are quite sensitive to the initial angle of attack at the start of their flight. At low initial positive angles of attack, the rotational moments are large, and many cycles of rotation occur during a typical flight. At angles of attack near 90 degrees, little or no rotation occurs, but the downward vertical displacements are larger. At negative initial angles of attack, reverse rotation can occur during the initial stages of flight.

Conclusions

The aerodynamic forces and centres of pressure on an inclined square flat plate are discussed. This shape is representative of 'sheet-type' wind-borne debris as defined by Wills *et al* [1]. Calculated trajectories of a plate in a vertical plane in a steady wind speed have been made, including the variation in angle of attack induced by the vertical translation and rotation of the plate. Although the model of normal aerodynamic force coefficient and centre of pressure position is simplified, generally very good agreement has been obtained between the calculated trajectories and measurements in wind tunnels.

References

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Acknowledgements

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