THE FLIGHT OF WIND BORNE DEBRIS: AN EXPERIMENTAL, ANALYTICAL, AND NUMERICAL INVESTIGATION. PART II
(EXPERIMENTAL WORK)

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ABSTRACT

This paper describes the instrumentation, wind tunnel testing and experimental results of an investigation into wind-borne sheet-type debris, subjected to a uniform wind profile. This work has enabled an insight into the instantaneous pressure field acting on such objects to be gained during their flight. The work is part of an integrated project which includes the development of a theoretical approach to predict debris flight in three dimensions, in addition to CFD simulations.

KEYWORDS: DEBRIS FLIGHT, WIRELESS INSTRUMENTATION, WIND ENGINEERING

I. Introduction

Previous physical experiments have been undertaken in order to investigate changes in the forces on wind borne debris due to the action of a turbulent uniform wind velocity profile, e.g. Tachikawa (1983, 1988), Richards, et al. (2005) and Lin, et al. (2006). These experiments have all been performed on static or auto-rotating sheet-type specimens in order to infer drag and lift force coefficients as well as autorotation parameters. As a consequence, the previous prediction of flight trajectories computed using existing mathematical models (Tachikawa (1983), Holmes et al. (2006), Baker (2005), and Richards et al. (2008)) have been undertaken using existing data or assumptions based on these data. There is little, if any information relating to the instantaneous pressure field which acts on sheet-type debris either during autorotation or flight. Hence, the accuracy of previous assumptions has not been fully evaluated. The current paper aims to fill this knowledge gap and is concerned with the description of the temporal variations of wind pressures acting on sheet-type debris during motion.
In order to measure the instantaneous pressures acting on an element of sheet-type debris, a specimen of debris, referred to as the ‘test-sheet’ has been implemented with a novel arrangement of pressure transducers and on-board data loggers. This has enabled surface pressure to be measured without the need for the standard tubing systems common in most wind tunnel experiments of this kind. This instrumentation allows data logging to occur during the flight of the projectile, which is then downloaded to a computer after each experiment in order to be processed.

This paper is organized into a number of different sections: section II describes the electronic devices which provided the on-board logging solution and their implementation; section III contains the different cases for testing and support conditions; section IV presents the data recorded in the experiment and pressure coefficients computed based on it; final comments and future developments are discussed in section V.

II. Testing Prototype and On-Board Logging System

Test-sheet

A piece of polystyrene of 1m square, 2.5cm thick, and weighing 2.7 kg, was manufactured and reinforced with a flexible film adhered to its surface in order to resist compression, shear and bending stresses generated during the wind tunnel tests. A maximum stress of 80 kPa was calculated for the extreme fibers of the board, whilst 1.4 kPa was estimated for shear. The resistance of polystyrene to tension and shear respectively ranges between 46 - 60 kPa and about 50 kPa (Gnip et al.2007). The base material takes nearly 50% of the computed tension; nonetheless an adherent film with capacity 4.2 kN/m was thus placed over its surfaces in order to provide additional capacity.

The mass of sheet-debris is important in determining the trajectory of flight when submitted to a wind velocity profile. Using data from Tachikawa (1983) and Baker (2007) an autorotation frequency of 1 Hz and a time of flight of approximately 1 s were predicted for the test-sheet which characteristics result in Tachikawa’s number \( K = \frac{U^2A}{(2mg)} = 2.31 \). It was important to obtain values of these magnitudes to ensure that the data acquired during testing would be meaningful for the later calibration of the analytical model described in Martinez-Vazquez et al. (2009a)

Implementation of Electronic Devices

Twenty four pressure transducers were located on the test-sheet and arranged to cover the regions where peak pressures and suctions would be expected, i.e., along bisecting peripherals, edges and corners. Figure 1 shows the distribution of sensors and data loggers and also the typical position of a sensor within the thickness of the board. The sensors with the polystyrene protection (figure 1b) were fitted into square sections previously cut out from the board and then connected to the nearest data logger, which were positioned along the borders of the specimen in such a way that their mass was uniformly distributed.

Selection of Electronic Devices

The electronic devices for the experiment were selected to be compatible in terms of the input / output voltage, and working pressure range. Differential pressure transducers manufactured by Sensortechonics, with output voltage within the range 0.25 - 4.5 V, pressure range 0 - 2.5 mbar, and resolution of 12 bit, were selected. The test-sheet was submitted to wind velocities within the range \( U = 5 - 10 \) m/s, from this values a peak pressure of 60 Pa was expected, using a pressure coefficient \( C_P = 1 \). This value was suitable for the range of
pressure accepted by the sensor and also for the resolution which represented $4 \times 10^{-4}$ times the predicted peak pressure. In the case of the data logger, a portable card manufactured by Omni instruments was considered suitable to work in combination with the sensors. One data logger supports 4 sensors, has an input signal range of 0 - 5 Vdc and it provides a resolution of 8 - 12 bits with a maximum sampling frequency of 200 Hz.

![Distribution of Sensors](image_url)

**Figure 1.** Distribution of Sensors and Data Loggers.

### III. Wind Tunnel Tests

#### Wind Tunnel Facilities

The experiments were carried out at The University of Auckland, New Zealand. In this facility the stream of wind goes through a 3.5 m square nozzle towards an open area for testing with a turntable on the floor. A range of wind speeds were selected: $U = 5, 10$ m/s for static testing and $U = 5, 7.5$ and 10 m/s for autorotation. The test duration was approximately 36 minutes for static testing using a sampling frequency of 10 Hz which allowed accommodating several runs in a session; around 2 min were required for autorotational tests, using a sampling frequency of 200 Hz. The sampling frequency was chosen in order to provide data at every 0.1 s in static runs and at about every 10˚ for autorotation.

#### Supporting System

Two metallic frames of height 1.5 m were built to support the test-sheet. The test-sheet was fit into an aluminum frame connected to the lateral stands through metallic pins. A mechanism for static and autorotation tests was implemented which consisted of two parallel plates connected through bearings and bolted in place every 15˚. This arrangement allowed the plate to adopt the static positions by varying the pitch angle whilst yaw angle variation was given by rotating the base platform. The plate was allowed to autorotate by releasing the parallel plates at the bearings. This supporting system caused some disturbance on pressure measurements taken on the lower half of the board, mainly due to the blockage produce by the vertical stands. Inaccuracies caused on the collected data by this effect were corrected during analysis.
Cases for Testing

The wind tunnel tests were divided into two categories: static (test-sheet restricted from translation and rotation) and autorotation (only rotation around the horizontal axis was permitted). Axis $y-y'$ has been represented in figure 1. Rotation of the board around $y - y'$, fixed in a general coordinate system, defines yaw angle; pitch angle represents rotation around a horizontal axis – zero pitch and yaw corresponds to the flow normal to the larger face of the plate. The initial condition for static testing, e.g. linear and angular velocities, were set to zero, the initial angle of incident wind (wind acting on the board at an angle given by the combination pitch and yaw) was varied from 0° - 90° in increments of 15° with an additional run per velocity level at 37.5°, where the stall region was detected. For autorotation tests the board was released at an angle of 15° clockwise direction with regard to a horizontal plane.

IV. Collected Data and Analysis Results

A set of approximately 200 runs were carried out which included static and autorotation tests. Data was post-processed through a series of programs prepared in C++. The analysis of the data enabled static and autorotation force coefficients to be obtained. Static force coefficients were corrected to eliminate blockage effects caused by the presence of the stands whilst auto-rotational data had to be aligned due to a time delay detected in some of the data loggers employed. The computed static normal coefficients $C_N = F_N / (\rho U^2 A/2)$ – where $F$ is the total force and $A$ the area of the board, are presented in figures 3, 4 for $U = 5, 10 \text{m/s}$. Figure 3 shows this coefficient for wind velocities $U = 5, 10 \text{m/s}$. The stall region appears within the interval 25° - 45° pitch angle, after which curves settle to values around 1.0 and 1.1, for $U = 5$ and $U = 10 \text{ m/s}$, respectively. The computed force coefficients show higher values for the testing wind velocity $U = 5 \text{ m/s}$ than for $U = 10 \text{ m/s}$. The pressure registered across the centre of the board (sensor #13 in figure 1) for $U = 5 \text{ m/s}$ with zero pitch and yaw
was 22% higher than the dynamic pressure registered at the Pitot-static tube located at the entrance of the tunnel and 7% higher for \( U = 10 \, \text{m/s} \) at the same position. The Reynolds number, defined as \( R_e = \frac{\rho UL}{\mu} \) where \( \mu \) represents dynamic viscosity is \( R_e = 3.34 \times 10^5 \), \( R_e = 6.69 \times 10^5 \) for \( U = 5, \, 10 \, \text{m/s} \), respectively. The differences observed in figure 3 might be the result of higher turbulence in the approaching flow when increasing the wind velocity.

\[ R_e = \frac{\rho UL}{\mu} \]

Figure 3. Static force coefficients for \( \text{yaw} = 0^\circ, \, U = 5, \, 10 \, \text{m/s} \).

Figure 4 presents the computed normal coefficients for \( U = 10 \, \text{m/s} \). It includes all tested yaw positions which are plotted against pitch angle. The tall region is observed in all these curves at slightly different positions within the interval 30° - 45°. Data presented in these plots has been corrected to eliminate blockage effects caused by the vertical stands at the bearings.

\[ C_n \]

Figure 4. Normal force coefficients all pitch and yaw angles, \( U = 10 \, \text{m/s} \).

Every autorotation test lasted about 107 seconds, but only the last 30 s were considered for analysis in order to guarantee that the stream of wind in the tunnel was fully developed. Figure 5 below presents the normal pressure coefficient logged at the four sensors at the corners: #1, #5, #20, and #24, plus sensor #13 located at the centre of the board as represented in figure 1.
Figure 5. Time series of normal force coefficients at four sensors on the board, $U = 7.5$ m/s.

Figure 6 below show a comparison between normal force coefficients determined through static and autorotation tests for $U = 5, 10$ m/s. The measured autorotational forces are generally higher, except for the stall region which suggests that the flow mechanisms involved in the definition of static forces change when the plate has an additional degree of freedom. According to this, further differences would be expected for a plate rotating in three dimensions.

Drag and lift coefficients are defined as the normalised component of the autorotational normal force coefficient with regard to global the axis $X$ (along wind direction) and axis $Y$ (perpendicular to $X$) respectively, this is $C_D = F_{Nx} / (\rho U^2 A/2)$, $C_L = F_{Ny} / (\rho U^2 A/2)$. Moment coefficient is defined as $C_M = T / (\rho U^2 L^2/2)$ – where $T$ is the acting torque and $L$ a characteristic length. The derived drag, lift and moment coefficients based on autorotation experiments are presented in Figures 7 - 9 for the three testing velocities: $U = 5, 7.5, 10$ m/s. Data shown in these figures has been derived from time series as presented in figure 5. However, since rotation speed is not constant throughout a cycle, an approximated function to define the moment coefficient was considered for the solution of the equation of movement that approximates the rotational movement of the test-sheet to real measurements. Once the approximated variation of angular velocity was determined, data collected in time domain could be analysed and then represented in angular units – a description of this method can be found in Martinez-Vazquez, et al. (2009b).
A detailed analysis of this data suggests that peak values of normal pressure are possibly the result of shedding vortex locked-in the frequency of rotation of the board - see Martinez-Vazquez, et al. (2009b). The distribution of moment coefficient presented in figure 8 generates a sustained torque that allows the plate to rotate steadily. Previous analysis on elliptic cylinders have been used to determine moment coefficients based on a pseudo-static
approach, i.e. using normal forces and inferring the position of the centre of pressures from static tests, see for example Lugt (1983), however the pseudo-static moment coefficients do not match with the present experimental measurements.

V. Final Comments and Future Developments

The experiments presented in this paper were focused on the measurement of normal pressures from which drag, lift, and moment coefficients have been inferred. The experimental setting adopted consisted of a light weight polystyrene board implemented with portable data loggers and pressure sensors. This solution was selected instead of the traditional tubing system to allow direct measurement of surface pressure during the autorotating motion of the plate. The data collected shows a stall region in the mid-range of angle of attack with a well defined plateau for the curve of normal force coefficient outside that region. Autorotation experiments reveal the nonlinear mechanism that induces sustained torque. This mechanism has been described by others authors in quasi-static terms, although from those approaches no sustained autorotation can be predicted. At the moment of submission of this paper, no free flight tests have been considered. However when these experiments take place, additional measuring equipment e.g. accelerometers and gyros will be fitted to the test-sheet. Data collected from the present and future tests will serve to calibrate existing models for the prediction of the trajectory of debris flight when making available the instantaneous variation of pressures on objects driven by wind.

References


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