Flight Dynamics Measurements on an Instrumented Frisbee

Ralph D Lorenz
Lunar and Planetary Laboratory,
University of Arizona

Corresponding author :

Dr. R. D. Lorenz, M.RAe.S.
Lunar and Planetary Laboratory,
University of Arizona
1629 E. University Blvd
Tucson, AZ 85721
USA

T: +1 520 621 5585
F: +1 520 621 4933
E: rlorenz@lpl.arizona.edu

Submitted 9 November 2003 as a Rapid Communication to Measurement Science and Technology
[Paper was rejected by referees as the lack of angle-of-attack measurements makes it impossible to compare drag coefficients etc with other published data. Therefore if referencing this work, please cite as 'R D Lorenz, Flight Dynamics Measurements on an Instrumented Frisbee, unpublished note, 2003']

Keywords : Frisbee, Disc-Wing, Aerodynamics, Accelerometer

Abstract

In-flight measurements of the accelerations on a recreational flying disc are made with miniaturized accelerometers and a microcontroller data acquisition system using off-the-shelf components. These data are used to determine the aerodynamic performance of the disc, and illustrate several of the complex gyrodynamic aspects of frisbee flight.

1. Introduction and Motivation

The impressive flying characteristics of a spinning disc were discovered rather than invented. Such a disc is commonly termed a Frisbee after a Connecticut baker whose cake tins were the first documented examples of recreational flying discs (the Frisbee designation - a mis-spelling of the baker's name, W. R. Frisbie - is now a registered trademark of Wham-O, Inc.) Despite their familiarity, however, their flight dynamics have not been thoroughly explored.

The broad aerodynamic characteristics are reasonably well-understood (e.g. [1]) and the aerodynamic properties of spinning discs have recently been thoroughly documented in wind tunnel tests [2]. However, wind tunnel tests on somewhat idealized models mounted on force balances under steady-state conditions do not graphically demonstrate the dynamic behaviour of a spinning disc in free flight : this behaviour makes possible the various 'trick throws' in 'Ultimate Frisbee', 'Frisbee Golf' and other sports. Disc-wing flight dynamics are also of interest in non-recreational settings : disc-wings have also been proposed as an architecture for Unmanned Aerial Vehicles (UAVs), e.g [3].

Some of the dynamic characteristics of free-flight can be measured from video records (e.g. [4]). However, this approach is somewhat laborious, and while useful for overall characterization by forward-modelling a trajectory with assumed parameters (e.g. [5]) it suffers significant noise errors in the determination of some point properties, since it relies on differentiating or double-differentiating a series of (usually manually-digitized) positions in order to infer accelerations.

In this paper I report preliminary results from accelerometer measurements made on a disc in flight. Modern commercial-off-the-shelf microcontrollers and accelerometers make it possible to install compact recording instrumentation on a disc or other small vehicles (e.g. [6]) without dramatically changing their weight or flying characteristics. Instantaneous acceleration measurements permit the direct determination of aerodynamic coefficients at various phases in the flight, and present a time-series of data that can be compared with forward models with minimal effort.

2. Equipment and Method

A commercial (175g 'Wham-O Competition Frisbee') disc was obtained. Such discs are available in flying weights of 90g to 175g, the former suitable for maximum-duration flights in light conditions, the latter best for long-distance throws and penetration in windy conditions. The heaviest model was chosen to minimize the relative influence of the instrumentation.

A Parallax Basic Stamp 2 microcontroller (BS2IC) was used to acquire and store data. This ~$50 unit in a 24-pin dual in-line package is easily programmed in a high-level BASIC language, has adequate execution speed in this application, but has a fairly modest current draw of around ~6mA. This latter point is crucial, in that it permitted the use of very small Lithium 'button' cells (model CR2032) as a power source - other, faster, microcontrollers such as the Netmedia X-24 or the BS2SX have too high a current drain unless highly specialized batteries are obtained. The unit recorded the pulse-width modulated signal from a 2-axis accelerometer, an Analog Devices ADXL202, mounted on a small evaluation board. The two accelerometer axes were mounted along and orthogonal to the axis of the disc.

The microcontroller was programmed to sample the two accelerometer axes, recording each result as an 8-bit number (representing from +2 to -2g) into its on-board EEPROM. The 2K space on the microcontroller permitted about 800 pairs of samples, in addition to the program code. These samples were acquired in about 12.5 seconds, yielding a data acquisition rate of about 65 sample pairs per second.

The microcontroller and accelerometer were attached with silicone adhesive to the underside of the frisbee (see figure 1), with the accelerometer mounted as close as could be determined by eye to the center of the disc. The batteries were similarly mounted close to the other items to minimize any displacement of the center of mass or change in moments of inertia. A small power switch was installed near the rim of the disc, to permit turn-on as the disc was thrown.

The equipment had a mass of about 28g, giving a flying weight of 204g, about 15% higher than the 'clean' frisbee. The total cost of parts was ~$100 and design, assembly and programming time amounted to around 8 hours (further particulars of the construction and the microcontroller code will be made available elsewhere and can be supplied upon request.) More serious weight-reduction efforts, and in particular the exclusive use of surface-mount components, could reduce the instrumentation mass by factor of 2-3, although at the expense of considerable labor.

The instrumentation had a side area of around 3cm^2, although none of it projected below the lip of the disc. Flow disturbance was minimized by fairing the equipment with adhesive tape, to present a smooth profile. Since wind-tunnel tests show that the pressure on the underside of a disc is in fact quite modest and uniform, it is believed that the instrumentation's perturbation to the aerodynamic characteristics is minimal.

The disc was thrown outdoors and the flight characteristics (and ancillary information such as wind speed) were noted. The distance from the throwing position to the impact point was recorded with a tape measure to an accuracy of ~0.3m. After the data acquisition window ended, the microcontroller read the data out at 9600 baud to a serial cable which could be attached to a laptop computer after landing. The data was captured as a text file by a terminal program for off-line analysis.

4. Results - Conventional Level Flight

The record for a typical near-level flight is shown in figure 2. It was expected that the axial accelerometer would present a slowly-decreasing signal to indicate a steady decrease in lift throughout the flight, and that the in-plane ('radial') accelerometer would present a zero-mean decaying sinusoidal signal corresponding to the spin-modulated projection of decreasing drag along the sensing axis.

In fact, while these underlying trends are present, the recorded data was substantially richer, in part due to the kinematics of the rotating disc, and in part due to a small misalignment of the accelerometer.

The spin period can be directly measured from the modulation of the radial accelerometer which is alternately pointed along and against the direction of flight. In the case shown, it is ~6.5 revolutions per second immediately after launch (corresponding to an advance ration of around 0.5) , and decreases to around 5.5 revolutions per second during the ~2.3s of free flight. This is consistent with an e-folding spin decay timescale of ~14s, which compares well with the estimate of 7-60s of [4].

The radial accelerometer signal does not, however, have a zero mean in flight. It was determined by subsequent balance measurements that the accelerometer was in fact installed 4+/-2mm from the axis of the (loaded) disc. The accelerometer therefore experiences a centripetal acceleration of $\omega^2 r$ = 5.8 ms^{-2}=0.59 g, (ω= 6.5*2π, r~0.0035m.)

The axial accelerometer signal presents some complications. The signal is very strongly modulated, with a period of ~ 0.09s. It was noted that the disc visibly 'wobbled' during the first part of the flight, perhaps as a result of non-principal axis rotation introduced during the throw as a result of imbalance in the instrumentation mass distribution. Although this nutation signal in the data deserves future exploration, for the present we consider only the signal with this modulation removed by smoothing.

A portion of the flight, between 1.0 and 1.7s, has rather stationary characteristics, with a radial acceleration amplitude of 0.055g and an axial acceleration of ~0.85g - this corresponds to a slight downward acceleration, with lift compensating for all but 15% of the weight. The axial and radial acceleration components must be resolved by trigonometrical transformation into the lift and drag forces : specifically, at an angle of attack α , the amplitude of the radial acceleration corresponds to (D$\cos\alpha$ + L$\sin\alpha$)/m where D and L are drag and lift forces respectively along and orthogonal to the direction of flight and m is the disc mass of 0.215 kg ; the axial acceleration is (L$\cos\alpha$ - D$\sin\alpha$)/m. Assuming an angle of attack of 15-20^o (consistent with estimates 'by eye' during the flight, and video measurements in [4]), this yields a lift:drag ratio ("L/D")of 2.3-2.95. By comparison, wind tunnel tests [2] indicate L/D of 2.0-2.5 and video records

[4] give 2.2-2.4. Note, incidentally, that while the models tested by [2] are substantially representative of the commercial disc used in these experiments and those of [4], they appear not to have the topside ridges to prompt 'turbulation' and thus prolonged attachment of the boundary layer, which may be significant at high angles of attack.

Note that while the spin-modulation on the radial accelerometer falls off rapidly, indicating crudely that the drag force declines sharply with time as would be expected for a slowing disc, the fact that the mean axial accelerometer signal remains constant at close to -1g would suggest that the lift remained substantially constant. Clearly, this picture is not consistent with an invariant lift:drag ratio. What is happening is that the angle of attack is increasing (as observed in several flights recorded by [4]) so that the decreasing airspeed is compensated for by increasing lift coefficient – the spin modulation on the radial accelerometer becomes dominated by the lift vector than by the drag. This increase in angle of attack is essentially a gravity turn – drag reduces the forward velocity, and gravity (which exceeds lift) gives the frisbee a downward motion – hence the disc falls through the air ever-steeper.

To recover aerodynamic coefficients from these data requires that the angle of attack and the airspeed be known. Without ancillary data, these quantities can only be estimated, and this process can be most self-consistently done with a forward numerical model. However, we can demonstrate consistency of the flight data with published values. As a lower bound on the launch speed, the disc covered 24m in 2.4s - an average ground speed of 10 m/s. Taking into account the wind, the average airspeed was 8.5 m/s : it was known from observation that the disc slowed approximately to a halt before landing, and thus the launch speed was approximately double this. The amplitude of the radial deceleration immediately after the throw is -0.85g and decays roughly as exp(-t/0.6s) – the actual drag (taking into account the angle of attack projection) may have been up to ~20% higher. The drag coefficient we deduce at launch is $C_d=2D/\rho SV^2$: at the 800m altitude of the flight site, atmospheric density ρ is 1.1 kgm^{-3} ; the disc reference area S is 0.057 m^2 and thus we find for D~2 N, V~17 ms^{-2}, C_d~0.22 – quite consistent with [2,4] for ~15^o angle of attack.

5. Results - Hammer Throw

A very different behaviour is shown in figure 3, the record from a 'hammer' throw. This is a high overarm throw, with the spin axis of the disc approximately horizontal. It is widely used in Ultimate Frisbee as a forward pass when a conventional fore- or backhand throw is blocked by an opposing player immediately in front of the thrower. After flying up and forwards some distance (apparently near-ballistically), the disc turns over and becomes horizontal but inverted, and then falls near-vertically in this inverted attitude to the ground.

This behaviour is captured in the accelerometer record. It can be first noted that there is a very soon a positive 'downward' axial acceleration on the disc - i.e. a negative lift. The disc is therefore (although the thrower is probably unaware of it, the throw being a substantially unconscious action) being thrown into a negative angle of attack.

At low or negative angle of attack, there is a nose-down pitching moment (see also [2]), which causes the angular momentum vector of the spinning disc to precess anticlockwise (as seen from the thrower) - i.e. the disc rolls onto its back. The velocity vector, initially perhaps 45^o to the horizontal, steadily tilts downwards towards the horizontal under the action of gravity. This change in flight-path angle causes an increase in (negative) angle of attack.

It is interesting to observe the increase then decrease of the radial accelerometer amplitude. The initial increase is due to increasing lift and drag as the rolling disc encounters progressively higher (negative) angles of attack. The radial acceleration then decreases because the angle of attack is so high that the vector sum of lift and drag has a zero component along the radial direction (i.e. the radial components of lift and drag cancel out). Specifically, the radial accelerometer will read zero at an angle of attack arctan $(L/D)^{-1}$, i.e. typically $\alpha \sim 25^o$. This condition is passed, with angle of attack still increasing, such that now the (negative) lift component in the radial direction dominates the signal.

In this condition, the disc rapidly slows, reaching an approximate halt in mid-air, and thus the radial signal decreases. Depending on the angle of attack when it slows, it either slides backwards or to one side, or falls approximately vertically. This latter condition is evident in figure 3 - the axial accelerometer reads approximately -0.8g, suggesting a vertical descent near terminal velocity in an inverted attitude. The non-zero drag measured by the radial accelerometer indicates a residual angle of attack, either due to a slight non-verticality of the spin axis, or some sideways velocity component.

6. Conclusions and Future Work

This work has demonstrated a proof of concept : useful flight data on frisbee dynamics can be obtained with onboard instrumentation at rather modest effort and expense. These data can be analyzed by hand to yield estimates of aerodynamic coefficients that compare well with previous work. Furthermore, the data can be readily assimilated into or compared with numerical simulations of flight where forward modeling can be used to determine aerodynamic coefficients.

Additional ancillary information (e.g. independent launch speed measurement by a radar 'speed gun', or a simple video record) would improve the accuracy of the dynamics reconstruction by imposing additional constraints : this is particularly important for deriving aerodynamic coefficients. Use of a larger-range accelerometer (a +/-10g range should be adequate) could provide a launch speed constraint, and would permit exploration of the biomechanics of the throw [7]. In addition to the purely research aspects of these experiments, their intrinsic appeal may make them useful in teaching applications. It may be noted that the problem of determining aerodynamic properties from these measurements is exactly analogous to that of determining the density profile of a planetary atmosphere from accelerometer measurements on an entry probe (e.g. [8]) where spin-stabilization can introduce complications similar to those encountered here.

Other frisbee sensors might also provide useful data - for example, a pressure sensor to measure the suction distribution on the disc during flight or optical sensors to measure the attitude motions directly via the position of the sun. Conceivably, a frisbee instrumented much as the one here might also make an inexpensive platform for boundary layer meteorological or small-scale geomagnetic surveys.

Acknowledgements

Jessica Dooley is thanked for assistance with these experiments.

References

[1] Bloomfield, L. A., The Flight of the Frisbee, Scientific American, p.132 April 1999

[2] Potts, J.R. and W.J. Crowther, Frisbee Aerodynamics, AIAA-2002-3150, 20th AIAA Applied Aerodynamics Conference and Exhibit, 24-26 June 2002, St. Louis, Missouri.

[3] Potts, J. Stabilising the Spin, Unmanned Vehicles, p.36, August 2001

[4] Hummel, S. and M. Hubbard, Identification of Frisbee Aerodynamic Coefficients using Flight Data, 4th International Conference on the Engineering of Sport, Kyoto, Japan, September 2002. (available at)

[5] Hubbard, M. and S. Hummel, Simulation of Frisbee Flight, 5th Conference on Mathematics and Computers in Sport, G. Cohen, Editor, University of Technology, Sydney, New South Wales, Australia, 14-16 June 2000

[6] Lorenz, R. D. and J. M. Dooley, A Miniature Probe-Parachute Dynamics Testbed, in Proceedings of the Workshop on Planetary Entry and Descent Trajectory Reconstruction and Science, Lisbon, Portugal October 2003 (in press as ESA SP-418, European Space Agency, Noordwjik, the Netherlands)

[7] Hummel, S. and Hubbard, M. A Musculoskeletal Model for the Backhand Frisbee Throw, 8th International Symposium on Computer Simulation in Biomechanics, Politecnico di Milano, Milan, Italy, July 2001.

[8] Withers, P., Towner, M. C., Hathi, B. and Zarnecki, J. C. Analysis of entry accelerometer data: A case study of Mars Pathfinder, Planetary and Space Science, 51, 541-561, 2003

Figures

Figure 1. View of the underside of the frisbee, 27.5cm across. The microcontroller board and accelerometer are flanked by the two button cells. Wire leads to a switch near the rim of the frisbee permit activation at the moment of launch. Clear adhesive tape fairs the equipment to minimize aerodynamic perturbations.

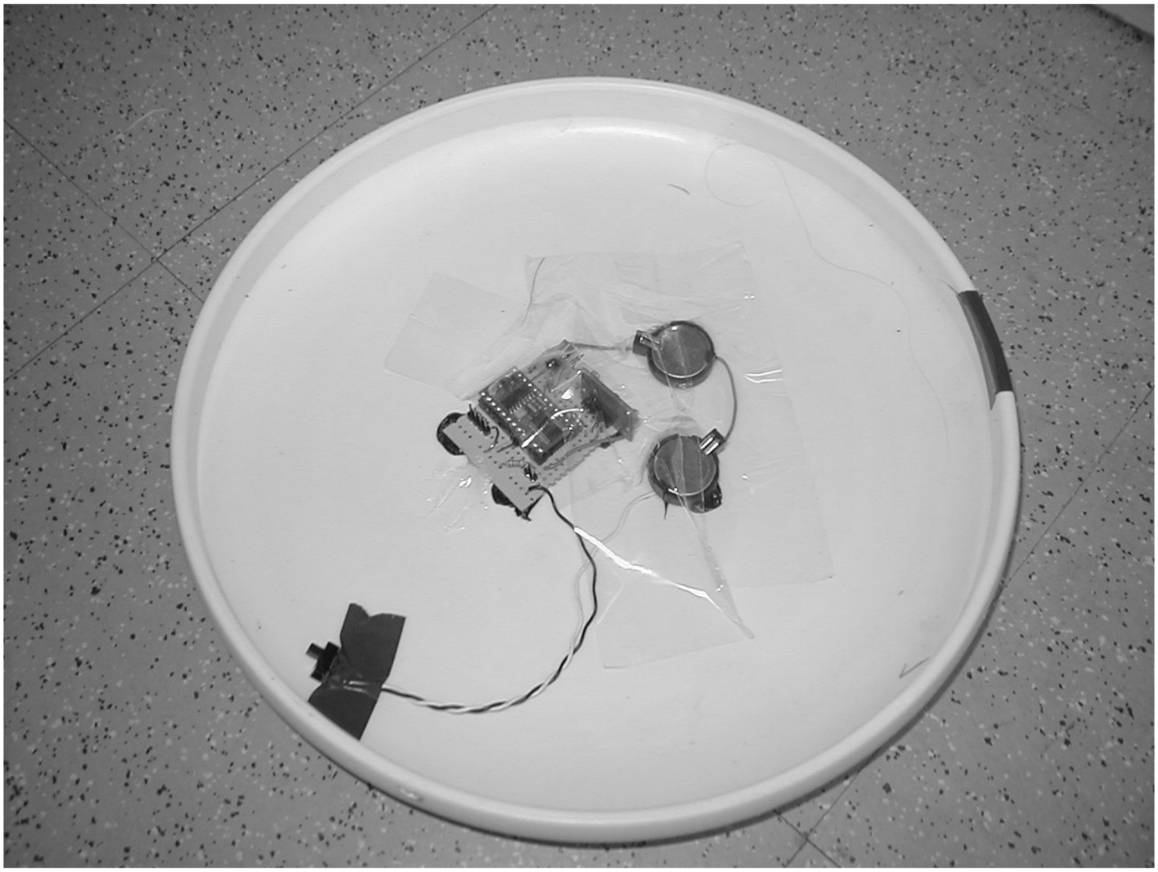

Figure 2. Accelerometer records for a level flight about 24m long. Thin solid curve with crosses is the radial accelerometer. Dashed curve with diamonds is axial accelerometer, with a 16-point running mean indicated by the thick solid line. Although the entire record can be fit with a dynamic model, parameters can be conveniently extracted in the section of steady conditions between 1.2 and 1.7 seconds.

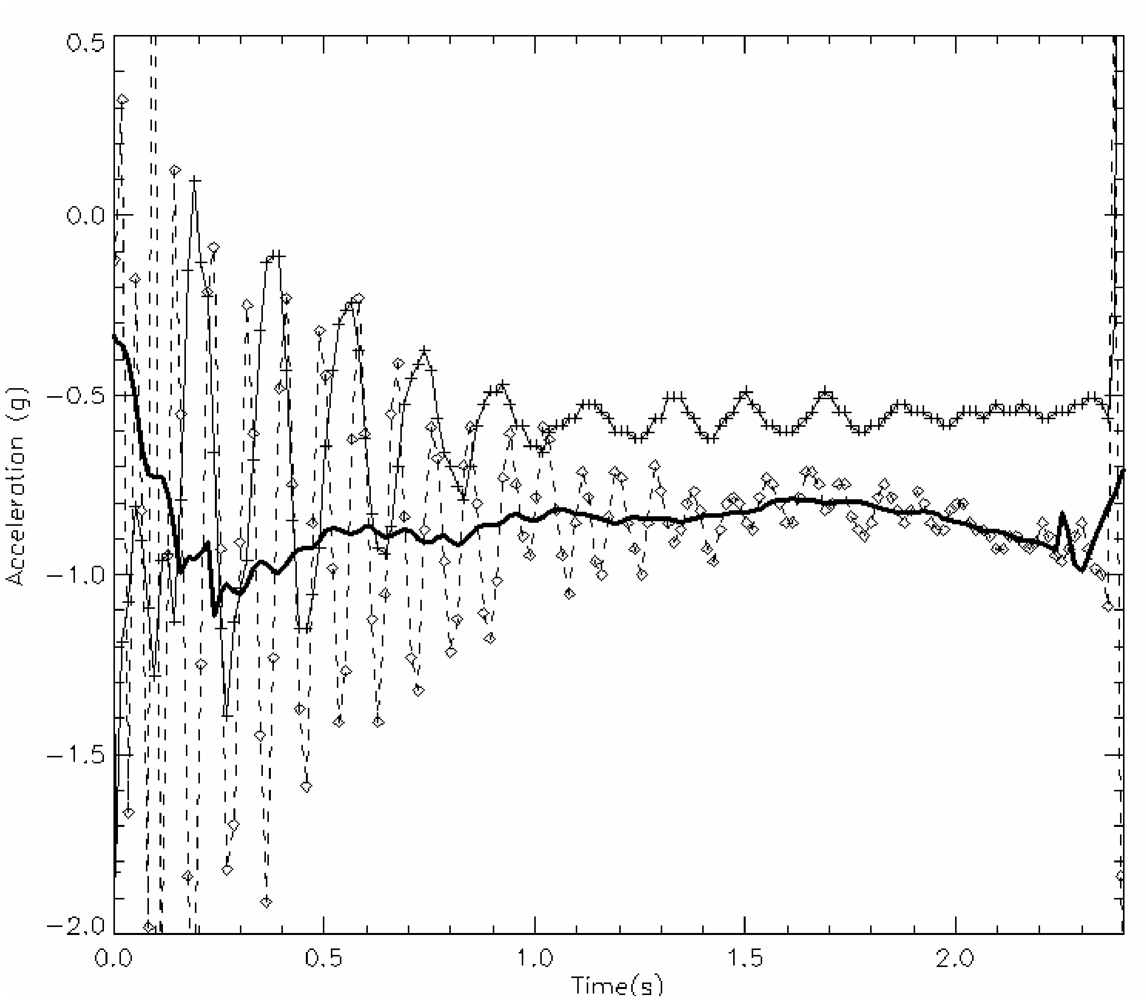

Figure 3. Accelerometer records for a 'hammer' throw, with curves as before. The disc ascended to around 10m altitude, rolling onto its back and increasing in angle of attack before falling near-vertically. Note that the radial acceleration amplitude falls to zero around 0.9s.