

The Mechanics of a Flying Disc

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An Ultimate disc is a wing you can catch. It has no tail, no fuselage, and no static stability whatsoever — by the standards of a fixed-wing aircraft it should tumble within the first few metres. Instead it flies a hundred, because it carries its stabiliser as angular momentum. This treatise works through the mechanics in four movements: the disc as a rigid body, the aerodynamic forces on it, the gyroscopic dance that shapes every throw, and the resulting flight envelope. The canonical sources are Hummel’s flight simulations (Hummel, Sarah Ann, 2003), the Manchester wind-tunnel programme of Potts and Crowther (Potts, Jonathan R. and Crowther, William J., 2002), and Lorenz’s instrumented discs (Lorenz, Ralph D., 2005).¹

the Discraft Ultrastar was certified in 1981 and has been the de facto standard of ultimate ever since

1 The Disc as a Rigid Body

A regulation Ultrastar-class disc has mass $m = 175$ g, diameter $d = 27.3$ cm, overall height 3.2 cm, and a rim that plunges 2.0 cm deep with a 0.7 cm thick lip. Its planform is a circle, so the reference area is

$$A = \frac{\pi d^2}{4} \approx 0.057 \text{ m}^2$$

and the aspect ratio of any disc-wing is fixed at $4/\pi \approx 1.27$ — a stubby wing by any aeronautical standard.

¹The field has an improbable origin: the earliest rigorous study is a 1972 US Navy programme investigating flying-disc delivery of “special ordnance” — self-suspended flares on disc wings (Stilley, Gary D. and Carstens, David L., 1972). The first popular technical account is Schuurmans in *New Scientist* (Schuurmans, Ma, 1990).

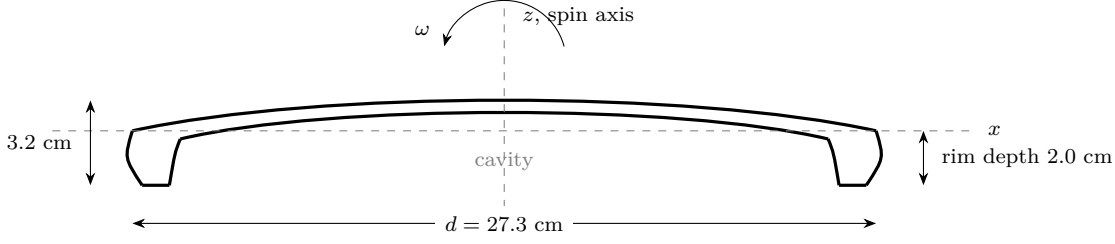


Figure 1: cross-section of a 175 g Ultrastar-class disc: cambered top plate, hollowed underside cavity, and a deep rim that carries most of the mass — raising I_z by 47% over a uniform disc of the same mass and diameter.

Where the mass sits matters more than how much there is. Hummel measured the inertia tensor of an Ultrastar with a trifilar pendulum: $I_z = 2.35 \times 10^{-3} \text{ kg m}^2$ about the spin axis and $I_x = I_y = 1.22 \times 10^{-3} \text{ kg m}^2$ about any diameter (Hummel, Sarah Ann, 2003). A *uniform* disc of the same mass and diameter would have only

$$I_z^{\text{uniform}} = \frac{1}{8}md^2 \approx 1.6 \times 10^{-3} \text{ kg m}^2$$

so the deep rim buys 47% more angular momentum for the same spin — the disc’s first structural advantage over a flat plate. The ratio $I_z/I_x = 1.93$ sits just shy of the value 2 that the perpendicular-axis theorem forces on an ideal lamina, and that near-2 ratio will return below when the disc wobbles.

2 Lift, Drag, and the Reynolds Regime

The air exerts a force that we resolve against the velocity: lift perpendicular, drag parallel,

$$L = \frac{1}{2}\rho v^2 A C_L, \quad D = \frac{1}{2}\rho v^2 A C_D$$

with the dimensionless coefficients depending chiefly on the angle of attack α between the disc plane and the airflow. Across the flyable range the standard models are linear in lift and quadratic in drag:

$$C_L = C_{L0} + C_{L\alpha} \alpha$$

$$C_D = C_{D0} + C_{D\alpha} (\alpha - \alpha_0)^2$$

where $\alpha_0 \approx -4^\circ$ is the angle of both zero lift and minimum drag — negative because the disc is cambered, so it must be pitched slightly nose-down before the lift vanishes. The measured constants (angles in radians):

coefficient	Hummel flight fit	Potts and Crowther tunnel
C_{L0}	0.33	0.20
$C_{L\alpha}$	1.91	2.96
C_{D0}	0.18	0.08
$C_{D\alpha}$	0.69	2.72
C_{M0}	-0.08	-0.02
$C_{M\alpha}$	0.43	0.13

The tunnel values come from a disc on a sting; the flight fits absorb everything a real wobbling throw does that a rig cannot (Potts, Jonathan R. and Crowther, William J., 2002, Hummel, Sarah Ann, 2003). The flow regime is set by the Reynolds number

$$\text{Re} = \frac{\rho v d}{\mu} \approx 2.6 \times 10^5$$

the two columns disagree by factors of two to four — identification from real flights and clean tunnel measurements bracket the truth

at a typical 14 m/s throw, and Potts and Crowther found the force coefficients essentially independent of both Reynolds number (over $1.0\text{--}3.8 \times 10^5$) and spin rate — the disc's lift is not a Magnus effect; spin matters gyroscopically, not aerodynamically.

What the flow actually does is richer than either textbook story about lift. Smoke and surface-pressure visualisation shows the boundary layer separating off the leading rim into a **separation bubble** that reattaches along an arc of constant radius; underneath, the cavity flow separates at the front lip and reattaches near the centre; and the wake rolls up into a pair of **trailing vortices** shed from two symmetric points on the trailing rim, driving a strong downwash (Potts, Jonathan R. and Crowther, William J., 2002). Nakamura and Fukamachi saw the same streamwise vortex pair even at zero incidence — camber alone generates downwash, hence lift, on a disc that is not even spinning (Nakamura, Yuichi and Fukamachi, Nobuyuki, 1991). Hummel's caution is worth repeating: Bernoulli arguments are qualitative decoration here; the honest accounting is momentum flux — the disc throws air downward, and the reaction is lift (Hummel, Sarah Ann, 2003).

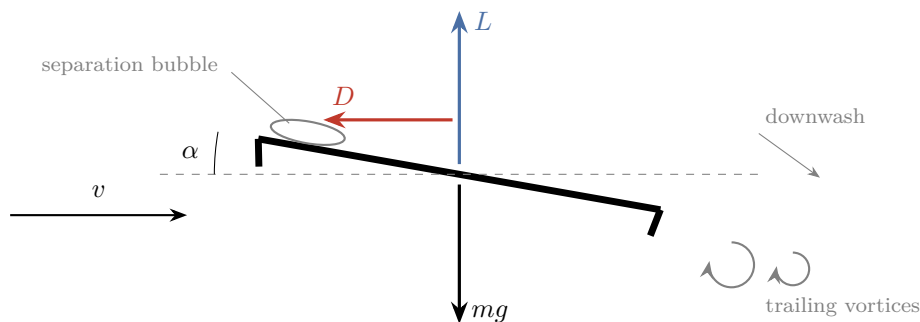


Figure 2: a disc at angle of attack α : lift perpendicular to the oncoming flow, drag along it, weight down. the boundary layer separates off the leading rim into a bubble and reattaches; the wake rolls up into a trailing vortex pair with strong downwash.

3 Pitch, Precession, and the Shape of a Throw

The force system does not act at the centre of mass. Its net effect includes a pitching moment, modelled linearly as

$$C_M = C_{M0} + C_{M\alpha} \alpha$$

and this coefficient carries the whole plot of a frisbee's flight. The centre of pressure sits *behind* the centre of mass at low angles of attack (nose-down moment), crosses it at a trim angle of roughly 9° , and moves ahead of it beyond (nose-up moment) (Potts, Jonathan R. and Crowther, William J., 2002). Since $C_{M\alpha} > 0$, the disc is **statically unstable in pitch**: a fixed-wing aircraft with this polar would depart immediately. Spin is the cure. The disc's angular momentum $H = I_z \omega$ points along the spin axis, and Euler's equation makes the axis respond to torque by precessing rather than tipping:

a frisbee is an unstable wing flown by a gyroscope

$$\frac{d\mathbf{H}}{dt} = \mathbf{M} \implies \Omega = \frac{M}{I_z \omega}$$

The response is rotated a quarter-turn of spin phase from the stimulus: a *pitching* moment produces a *rolling* precession. Run the numbers for a right-hand backhand (spin clockwise seen from above) at $v = 14$ m/s, $\omega = 50$ rad/s, $\alpha = 5^\circ$: the Hummel-fit moment $M \approx -0.078$ N m precesses the disc at about 0.7 rad/s of bank — to the **right**. This is the “turn” every player knows: early in the flight, when the disc is fast and α sits below trim, the nose-down moment banks it right. As drag bleeds speed, the disc settles, α climbs through trim, the moment changes sign, and the same gyroscope banks it **left**: the “fade”. The S-shaped path of a flat, hard backhand is a pitching-moment polarity plot drawn in the air (Hummel, Sarah Ann, 2003, Kamaruddin, Noorfazreena M. and Potts, Jonathan R. and Crowther, William J., 2018).

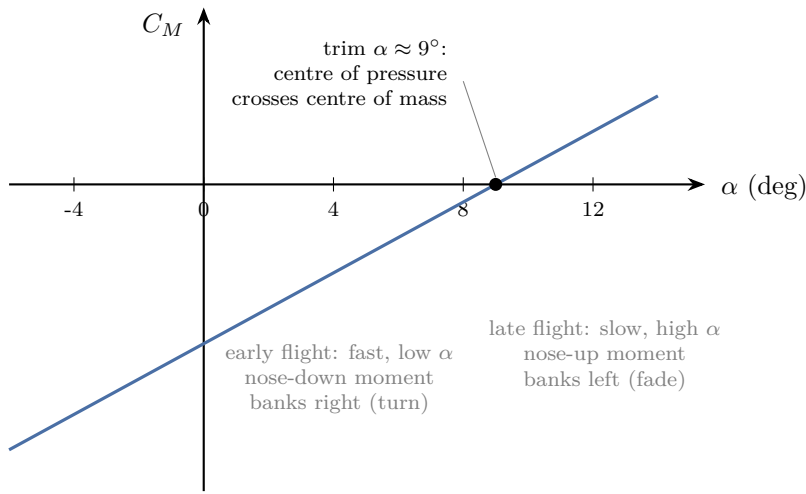


Figure 3: the pitching moment changes sign at the trim angle near 9° : below it the nose-down moment precesses a clockwise-spinning disc into right bank (turn), above it the nose-up moment banks it left (fade).

Two smaller torques finish the rotational story. Aerodynamic friction spins the disc down so slowly (Lorenz measured roughly 15% of spin lost over a full flight) that ω is effectively conserved (Lorenz, Ralph D., 2005). And a badly released disc *wobbles*: torque-free precession of a nearly-flat body runs at

$$\omega_{\text{wobble}} = \frac{I_z}{I_x} \omega \approx 1.93 \omega$$

— Feynman’s wobbling cafeteria plate gave exactly 2ω for an ideal lamina; the rim-heavy Ultrastar falls just short.

the wobble is damped aerodynamically within the first second — the damping derivatives are small but they only need to kill a small motion

4 The Equations of Motion and the Envelope

Assemble the translational dynamics,

$$m \frac{d\mathbf{v}}{dt} = \mathbf{L} + \mathbf{D} + m\mathbf{g}$$

couple them to the moment equations above, and you have the 6-degree-of-freedom

simulations of Hummel and of Crowther and Potts (Crowther, William J. and Potts, Jonathan R., 2007). The inputs are startlingly modest. Hummel’s motion-capture of real backhands measured release speeds of 12.7 ± 0.9 m/s and spins of 46.5 ± 3.7 rad/s — about 7.4 revolutions per second, a kinetic investment of some 17 joules of which only 2.5 J is rotation. The dimensionless spin is the advance ratio

the spin is energetically almost free, yet it is the part doing the stabilising

$$\text{AdvR} = \frac{r\omega}{v} \approx 0.5$$

— the rim moves at about half the flight speed. For unaccelerated level flight the lift must carry the weight, which sets the speed scale

$$v_{\text{level}} = \sqrt{\frac{2mg}{\rho AC_L}}$$

— about 16 m/s at $\alpha = 0$, dropping to 9 m/s at trim. Once the thrust of the throw is spent the disc settles onto a steady glide at angle γ given by

$$\tan \gamma = \frac{C_D}{C_L}$$

which at trim gives a glide ratio just under 3 — Lorenz’s instrumented flights bracket it at 2.3–2.95 (Lorenz, Ralph D., 2005). The envelope in practice: simulated fixed-effort launches carry a frisbee about 48 m where a golf driver goes 63 m and a flat plate collapses at 35 m (Kamaruddin, Noorfazreena M. and Potts, Jonathan R. and Crowther, William J., 2018); a huck hangs 3–4 seconds; and the maximum-time-aloft record — the pure-glide corner of the envelope — stands at 16.72 seconds, set by Don Cain in 1984.²

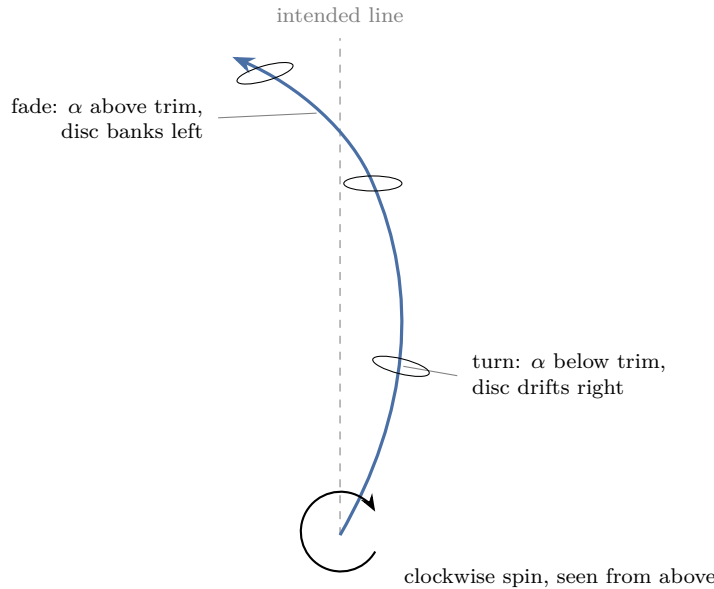


Figure 4: plan view of a flat right-hand backhand: clockwise spin from above, an early rightward turn while α sits below trim, and a leftward fade as the disc slows — the S-curve is the pitching moment made visible.

²The outright flying-disc distance record — 338 m by David Wiggins Jr. in 2016 — was set with a 154 g golf disc in a howling tailwind, not an Ultrastar; ultimate-weight discs top out around 100 m (Lissaman, Peter B. S. and Hubbard, Mont, 2010).

5 Why a Disc and Not a Plate

Three mechanisms separate a frisbee from the dinner plate it superficially resembles (Kamaruddin, Noorfazreena M. and Potts, Jonathan R. and Crowther, William J., 2018).

1. **The rim as flywheel.** The 47% inertia surplus over a uniform disc directly slows every precession rate: for a given aerodynamic moment, $\Omega \propto 1/I_z\omega$.
2. **A tamed pitching moment.** The aerodynamic centre of a Frisbee-shaped disc sits at $x_{ac}/d = 0.03$ versus 0.21 for a thin flat plate, and its moment gradient is roughly 0.001 per degree against 0.009 — an order of magnitude less torque for the gyroscope to fight. The hollowed cavity does the work: at low α , flow separating off the cavity's front lip loads the rear lip and cancels most of the nose-down moment, shifting the trim point from 0° (flat plate) to a usable 9° .
3. **A tripped boundary layer.** The moulded concentric rings on the Ultra-star's crown trip the boundary layer turbulent, and the energised layer resists separation — though Hummel notes their real significance is debatable.

6 On the Field

Everything a thrower does is a boundary condition on the dynamics above. An *inside-out* or *outside-in* flight is release bank superimposed on the intrinsic S-curve; a flat pull is a bid to spend the whole turn-fade cycle symmetrically and buy hang time; extra spin on a windy day is an increase in $I_z\omega$ to stiffen the disc against gusty moments. The upside-down throws — hammer and scoober — fly with inverted camber, so lift is weak and there is no stable trim at all: the disc precesses continuously through its roll rather than settling, which is why every hammer traces a helix and lands the same way up. The tactical layer built on top of these mechanics lives in [ultimate frisbee tactics](#) and [cutting patterns](#); what the rules permit the disc to do is codified in the [WFDF rules 2025–28](#).

the hammer never settles: an inverted disc has no trim to find, so it rolls through the whole flight

7 see also

- [ultimate frisbee tactics](#) — what teams do with a disc that curves on demand
- [ultimate frisbee cutting patterns](#) — moving to where the S-curve ends
- [WFDF rules 2025–2028](#) — the constraint set
- Lorenz's *Spinning Flight* (Lorenz, Ralph D., 2006) — frisbees alongside boomerangs, samaras, and skipping stones

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