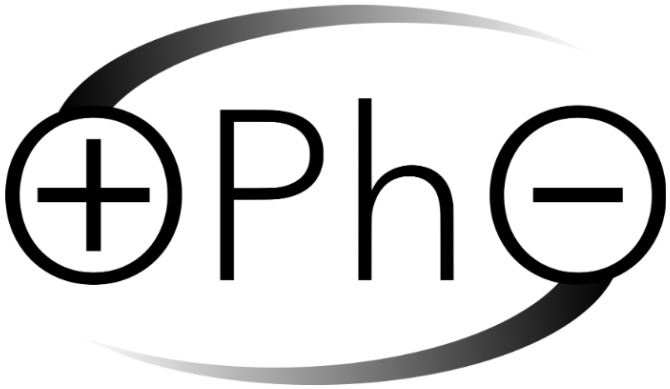
2025 Online Physics Olympiad: Invitational Contest



Part II Solutions

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Experimental Question [15 marks] — Solution

Ball Knowledge [15 marks]

No official solution was published, and the organisers' `magnus` executable was not available to us. This solution is worked on data from the HaslaLab simulator (web and Python versions), which uses the same model with hidden values chosen by HaslaLab. Like the organisers' program it adds random errors of the stated size to v_0, θ_0 and ω_0, and writes the camera's points (x, y) rounded to 1 cm.

Equations of motion. With $\vec{u} = (\dot{x} - v_w,\ \dot{y})$ the velocity of the ball relative to the air (the wind blows along x),

$$\begin{aligned} \ddot{x} &= -k|\vec{u}|u_x - \frac{Kr\omega}{m}u_y, \\ \ddot{y} &= -k|\vec{u}|u_y + \frac{Kr\omega}{m}u_x - g, \qquad k = \frac{\rho C_d A}{2m}, \\ \dot{\omega} &= -B\omega|\vec{u}|, \end{aligned} \tag{1}$$

with $A = \pi r^2 = 0.0380$ m², $m = 0.430$ kg and $C_d = 0.47$. The file holds no times, only the order of the points, so the n-th point is at $t_n = n/r_c$. The last point is the landing point, not a frame, and is left out of the fits.

1. Camera frame rate r_c [0.8 pt]

For a fast, flat kick ($v_0 = 40$ m/s, $\theta_0 = 10°$, $\omega_0 = 0$) the displacement over the first frame is almost v_0/r_c. Extrapolating the first two displacements s_1, s_2 to $t = 0$, $s_0 \approx \frac{3}{2}s_1 - \frac{1}{2}s_2$, removes the effect of drag, and

$$r_c = \frac{v_0}{s_0}. \tag{2}$$

Twenty kicks give a mean of 24.02 Hz with a scatter of 0.32 Hz per kick (as expected from the $0.5/40 = 1.3\%$ uncertainty of v_0), so $r_c = 24.0 \pm 0.1$ Hz. Frame rates are whole numbers, so we take $\boxed{r_c = 24\ \text{Hz}}$ from here on.

2. No spin: wind speed v_w [2 pts], air density ρ [2.6 pts], gravity g [2.6 pts]

With $\omega_0 = 0$ the spin stays zero, the Magnus terms in (1) vanish and the only unknowns are v_w, ρ and g. Nine kicks, $v_0 \in \{15, 25, 35\}$ m/s and $\theta_0 \in \{30°, 50°, 70°\}$, were fitted together by least squares. Because the actual launch speed and angle differ from the inputs, each kick also gets its own free v_0 and θ_0 (three common parameters plus two per kick). The rms residual is 6–8 mm, as expected from the 1 cm rounding and the camera noise.

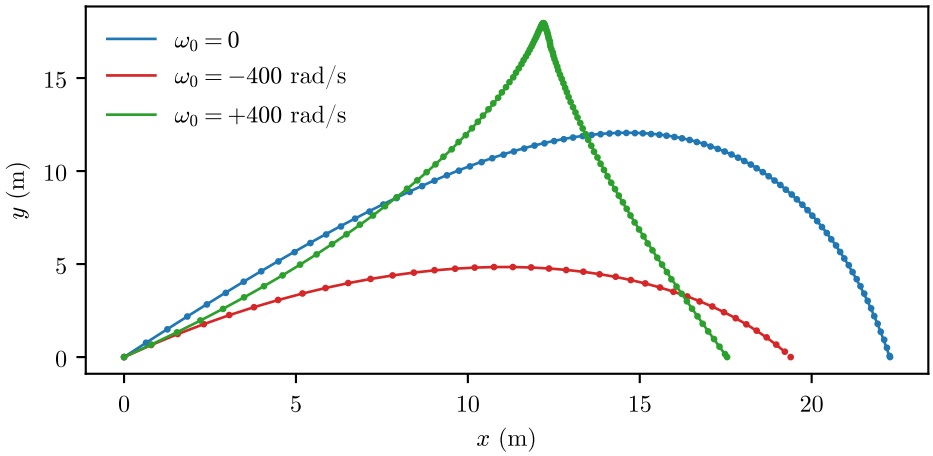
The three are separable because drag depends on the relative velocity: the wind acts differently on a long flat kick and on a steep one (a steep kick is pushed sideways near the top), ρ sets a deceleration that grows with speed, and g a downward acceleration that does not. Repeating the whole procedure five times with fresh kicks gives (mean and standard deviation)

$$v_w = -2.601 \pm 0.004\ \text{m/s}, \qquad \rho = 1.620 \pm 0.001\ \text{kg/m}^3, \qquad g = 7.346 \pm 0.002\ \text{m/s}^2. \tag{3}$$

$v_w < 0$: the wind blows at 2.60 m/s towards $-x$, against the kicks.

3. Spin: Magnus coefficient K [3 pts], inertial coefficient B [4 pts]

With v_w, ρ and g fixed, six spinning kicks were fitted: $\omega_0 = \pm 250$, ± 400 rad/s at $v_0 = 25$ m/s, $\theta_0 = 40°$, and $\omega_0 = \pm 400$ rad/s at $v_0 = 35$ m/s, $\theta_0 = 30°$. Each kick has free v_0, θ_0 and ω_0, but ω_0 carries the stated prior of ± 1 rad/s about the input. This matters: at launch the Magnus force depends only on the product $K\omega_0$, so the known ω_0 is what sets the scale of K. B, on the other hand, is fixed by how the curving of the path fades during the flight as the spin decays, $\omega = \omega_0 \exp(-B \int |\vec{u}|\, dt)$, which is why large spins and long flights help.



The figure shows typical fits (points: simulator data, lines: fitted model). Underspin ($\omega_0 = +400$ rad/s) makes the ball climb steeply; topspin ($\omega_0 = -400$ rad/s) keeps it low. Five repetitions give

$$K = (6.206 \pm 0.004) \times 10^{-3}\ \text{kg/m}, \qquad B = (1.154 \pm 0.003) \times 10^{-2}\ \text{m}^{-1}, \tag{4}$$

the units following from $F = Kr\omega v$ and $\dot{\omega} = -B\omega v$.

Results

Quantity	Measured	Simulator's hidden value
wind speed v_w	-2.601 ± 0.004 m/s	-2.6 m/s
air density ρ	1.620 ± 0.001 kg/m^3	1.62 kg/m^3
gravitational acceleration g	7.346 ± 0.002 m/s^2	7.35 m/s^2
frame rate r_c	24 Hz	24 Hz
Magnus coefficient K	$(6.206 \pm 0.004) \times 10^{-3}$ kg/m	6.2×10^{-3} kg/m
inertial coefficient B	$(1.154 \pm 0.003) \times 10^{-2}$ m^{-1}	1.15×10^{-2} m^{-1}

Every value agrees with the hidden one within two standard deviations.

Solution Needs (suggested by HaslaLab).

- v_w: [1 pt] drag written with the relative velocity, [1 pt] value within ± 0.1 m/s.
- ρ and g, each: [1.6 pts] fitting method with the launch errors as free parameters, [1 pt] value within $\pm 2\%$.
- r_c: [0.4 pt] time scale fixed by the known v_0, [0.4 pt] 24 Hz.
- K: [2 pts] scale of $K\omega_0$ fixed by the known ω_0, [1 pt] value within $\pm 3\%$.
- B: [2.5 pts] decay of the spin fitted from the changing curvature, [1.5 pts] value within $\pm 5\%$.