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A SIMPLE METHOD TO DETERMINE DRAG COEFFICIENTS IN AQUATIC ANIMALS

By D. BILO and W. NACHTIGALL
Fachbereich Biologie der Universität des Saarlandes,
6600 Saarbrücken, W. Germany

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The drag coefficient $C_D = 2D/(A\rho v^2)$ (D drag, A characteristic area of the object, ρ density of medium, v relative speed between object and medium) is important in determining energetic requirements of a biological or technical 'construction' that is moving in a fluid. A small value indicates low energetic requirements. Before World War II drag coefficients of cares were usually determined by deceleration measurements. We have modified the measuring system and developed a simple method of analysis to determine C_D values without influencing the swimming animal in any way. Gentoo penguins (*Pygoscelis papua*) were filmed during decelerating underwater gliding ('Ausgleiten') without any movements of extremities, parallel to a large underwater window of a penguinarium. From these films distance–time functions were plotted (Fig. 1 *a*). Using distance-differences Δx and time differences Δt between two points, momentary velocity $v = \Delta x/\Delta t$ can be determined. The reciprocal velocity v^{-1} as a function of time t gives a straight line in the case of undisturbed deceleration as explained by the following.

The gliding speed decreases gradually during undisturbed deceleration during which at any given time the force of inertia (F) of the body counterbalances the body drag (D):

$$F(t) = -D(t). \tag{1}$$

According to Newton:

$$F(t) = m\dot{v}(t) \tag{2}$$

(m mass; $\dot{v} = dv/dt$ acceleration; t time).

For greater Reynolds numbers the drag D is (cf. previous C_D definition):

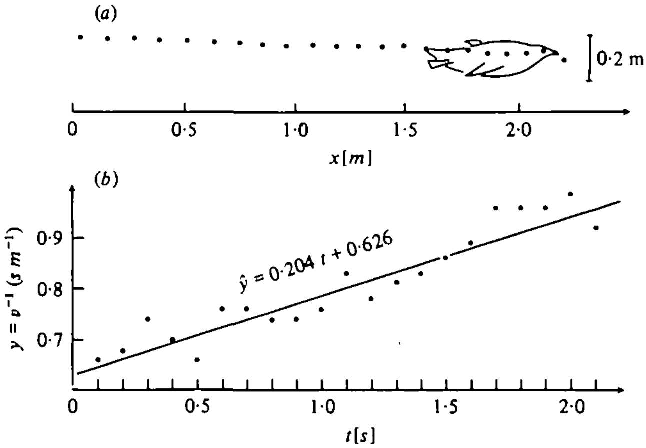
$$D(t) = C_D A \frac{\rho}{2} v^2(t). \tag{3}$$

Equations (2) and (3) combined in (1) give:

$$m\dot{v}(t) = -C_D A \frac{\rho}{2} v^2(t). \tag{4}$$

The method of analysis is as follows. The nonlinear differential equation (4) can be simplified to give:

$$\dot{v}(t) = -cv^2(t) \tag{5}$$



(c)

Frontal area $A_F = 0{\cdot}0200$ m^2

Frontal-area drag coefficient $C_{D_F} = \dfrac{2D}{A_F.\rho.v^2} = 0{\cdot}07$

Total surface area $A_s = 0{\cdot}4488$ m^2

Surface drag coefficient $C_{D_S} = \dfrac{2D}{A_S.\rho.v^2} = 0{\cdot}0044$

Volume $V = 0{\cdot}01581$ m^3

Volume drag coefficient $C_{D_V} = \dfrac{2D}{V^{\frac{2}{3}}.\rho.v^2} = 0{\cdot}031$

Fig. 1. (*a*) Trajectory of the penguin's head during decelerating underwater gliding. *x*, Horizontal distance. (*b*) Reciprocal gliding velocity (v^{-1}) plotted as a funtion of time (t). The regression line is fitted by the method of least squares, assuming a linear relationship. (*c*) Definitions and values of the penguin's drag coefficients. *D*, drag: ρ, density of medium (water); *v*, gliding velocity.

with

$$c = \frac{C_D A \rho}{2m}. \tag{6}$$

The integration of (5) gives:

$$v(t) = \frac{1}{y_0 + ct} \tag{7}$$

with $1/y_0 = v_0$ = speed at time $t = 0$ (initial speed).

Equation (7) can be transformed into the linear equation

$$y(t) = ct + y_0 \tag{8}$$

with $y(t) = 1/v(t)$. The slope c is achieved by linear regression of the data pairs $\{t_i, y_i\}$ (Fig. 1*b*). With known body mass m, area A and density ρ of the medium, the drag coefficient C_D can be calculated from (6) as the dimensionless coefficient

$$C_D = c\frac{2m}{A\rho}. \tag{9}$$

This method enables one to determine whether decelerating underwater gliding is undisturbed and to compensate for errors in measuring and plotting. Therefore this method is superior to the principly sufficient two-point measurement (Clark & Bemis, 1979). It can be used to determine drag coefficients in fish, seals, sea lions, water beetles, etc. Using this method the following drag coefficients were determined for *Pygoscelis papua* and Reynolds numbers around 10^6: frontal-area drag coefficient 0·07, surface drag coefficient 0·0044, volume drag coefficient 0·031 (see Fig. 1*c*). These values indicate that the body drag of the penguin is extraordinarily small, smaller than the body drag of any known technical system at the same Reynolds number, but the boundary layer is still partly turbulent. The technique assumes that the drag coefficients re constant over the range of velocities and Reynolds numbers experienced during deceleration. In the case of underwater gliding penguins this is a very reasonable assumption. Details are given in Nachtigall & Bilo (1980).

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