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WHY DO YOU CALL THEM STORM PETRELS? MECHANICS OF SEA-ANCHOR SOARING

Takeshi SUGIMOTO

Department of Industrial Engineering and Management
Kanagawa University, Yokohama, Kanagawa, JAPAN

ABSTRACT

This study presents a concise mathematical model that accounts for sea-anchor soaring, a special flight technique used by sea birds, in particular storm petrels. Conventional wing theory is used to reveal the mechanics of sea-anchor soaring. The feasibility and existence of an equilibrium are summarized by formulae giving the wind velocity criteria. The stability of the equilibrium is also revealed: among two possible equilibria, the equilibrium at the very slow velocity to water is shown to be stable. Numerical results show the following: sea-anchor soaring is almost always stable; foot-web size regulates the size of a bird using sea-anchor soaring at low velocities to water.

INTRODUCTION

Storm petrels are small sea birds. Like St. Peter, who was described as walking on water, storm petrels are often observed "walking" on the sea surface just before a storm arrives. That is why they are called storm petrels. In reality they soar against the horizontal wind and seek food on the water surface, as they dabble in the water. This is called sea-anchor soaring (Alexander, 1992). The feasibility of this type of soaring was experimentally studied by Withers (1979), but there has been no deeper study of this flight technique since. From the mechanical point of view, however, it is necessary to show the feasibility of the equilibrium, its existence and stability. My study focuses on these points based on conventional wing theory. If the aim of soaring is to save energy during foraging, then this flight technique must be stable. Otherwise a bird would use energy to sustain the required flight conditions. Thus consideration of the stability of the equilibrium is necessary to discuss the storm petrel's strategy.

THEORY

Mathematical model and basic equations

Without loss of generality the relation between air and water can be described by the situation that the wind blows at speed U over still water. If the water has a current, the following analysis holds true by treating U as the relative velocity of an air particle to a water particle.

Figure 1 shows schematically the equilibrium of forces acting on a bird soaring against the horizontal wind with the constant speed U, with webbed feet in the sea at the speed V to water. Note that V is in the same direction as the horizontal wind. The opposite situation is nothing but a variation of take-off, therefore we are not interested in that case. In steady-state soaring the aerodynamic lift L is in equilibrium with the bird's weight W, while the aerodynamic drag D balances with the hydrodynamic resistance R. Hydrodynamic lift may act on feet, but it is usually negligible. In this way a storm petrel can soar without an up-draft (Withers, 1979). We shall disregard the equilibrium of moments, because it is not essential to our discussion on soaring mechanics.

Lift, L, and drag, D, can be written in the following forms:

$$L = \tfrac{1}{2}\rho_a S(U - V)^2 C_L, \tag{1}$$

$$D = \tfrac{1}{2}\rho_a S(U - V)^2 C_D, \tag{2}$$

where ρ_a, S, C_L, and C_D denote the air density, the wing area, the lift coefficient, and the drag coefficient, respectively. According to conventional wing theory, the drag coefficient C_D of a wing can be written in terms of C_L to the second order:

$$C_D = C_{D0} + kC_L^{\,2}, \tag{3}$$

where C_{D0} is C_D at C_L=0; k is a coefficient depending mainly on wing geometry. The second term on the right-hand side of (3) is called induced drag.

On the other hand, the hydrodynamic resistance R is given by

$$R = \tfrac{1}{2}\rho_w AV^2 C_R, \tag{4}$$

where ρ_w, A, and C_R denote the water density, the total web area of two feet, and the resistance coefficient, respectively. In this expression we neglected interaction of two feet. For brevity of manipulation we shall introduce the following non-dimensional quantities:

$$\sigma = (\rho_a SC_{D0})/(\rho_w AC_R), \tag{5}$$

and

$$\kappa = k/C_{D0}\,. \tag{6}$$

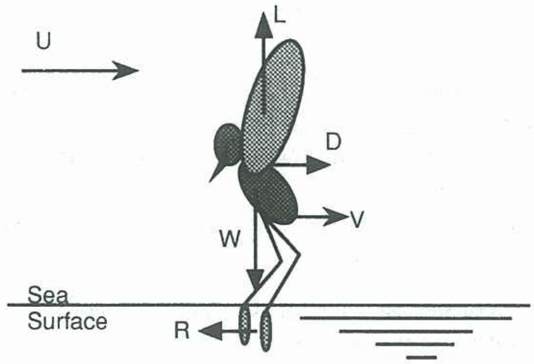

Figure 1 : Schematic diagram of sea-anchor soaring.

We shall also define non-dimensional velocities by using the parameter μ:

$$u = U/\sqrt{\mu}\,, \tag{7}$$

and

$$v = V/\sqrt{\mu}\,, \tag{8}$$

where

$$\mu = W/\left(\tfrac{1}{2}\rho_a S\right). \tag{9}$$

Then the equilibrium of vertical forces, $L = W$, is written in the form:

$$(u-v)^2 C_L = 1\,. \tag{10}$$

Solving the equation above with respect to C_L, we obtain

$$C_L = (u-v)^{-2}\,. \tag{11}$$

This equation directly links the flight velocity u-v with the lift coefficient C_L. It should be noted that the use of (11) corresponds to considering the equilibrium of vertical forces.

Now we shall define the non-dimensional forms of the resistance and drag:

$$\tilde{R} = R/\left(\tfrac{1}{2}\rho_a \mu S C_{D0}\right) = v^2/\sigma\,, \tag{12}$$

and

$$\tilde{D} = D/\left(\tfrac{1}{2}\rho_a \mu S C_{D0}\right) = (u-v)^2\left(1+\kappa C_L{}^2\right). \tag{13}$$

Eliminating C_L from (13) by use of (11), we have

$$\tilde{D} = (u-v)^2 + \kappa(u-v)^{-2}\,. \tag{14}$$

Equating (12) with (14), we have the final equation to solve in search of the equilibrium.

Feasibility of sea-anchor soaring

Firstly we shall consider the wind condition that sustains a bird aloft. In equation (10) C_L has an upper limit, *i.e.*, the maximum lift coefficient $C_{L\max}$, which is usually the value of C_L at aerodynamic stall. This $C_{L\max}$ is insensitive to the ground effect (*e.g.*, Tani, 1937), a phenomenon known to enhance the aerodynamic efficiency of wings in the proximity of ground or water-surface. Substituting $C_{L\max}$ into (10) and solving with respect to the minimum flight velocity, say designated by $(u\text{-}v)_{\min}$, we obtain

$$(u-v)_{\min} = 1/\sqrt{C_{L\max}}\,. \tag{15}$$

Eliminating u-v from the right-hand side of (14) by use of the equation above, we have

$$\tilde{D} = \left(\kappa C_{L\max}{}^2 + 1\right)/C_{L\max}\,. \tag{16}$$

The equilibrium of horizontal forces is fulfilled, when the right-hand side of (12) is equal to the right-hand side of the equation above:

$$v^2/\sigma = \left(\kappa C_{L\max}{}^2 + 1\right)/C_{L\max}\,. \tag{17}$$

Hence we have

$$v = \sqrt{\sigma\left(\kappa C_{L\max}{}^2 + 1\right)/C_{L\max}}\,. \tag{18}$$

Substituting the equation above into (15), we finally obtain u_f, the minimum wind velocity to sustain a bird aloft:

$$u_f = \left[1+\sqrt{\sigma\left(\kappa C_{L\max}{}^2+1\right)}\right]/\sqrt{C_{L\max}}\,. \tag{19}$$

To summarize, a bird can soar in a wind with a speed greater than or equal to u_f.

Existence of sea-anchor soaring

Next we shall consider the existence of an equilibrium. In (12) and (14) σ, u, and κ are given constants or parameters. The velocity v is obviously smaller than the wind speed u. Equation (12) shows that the resistance assumes a parabola in terms of v and independent of u. On the other hand, the first term on the right-hand side of (14) is a parabola in terms of u-v, while the second term diverges as v approaches u. Hence there are only three possibilities in the relations between the resistance and drag curves: the two curves have no intersection; the two curves have one point in common; the two curves cross each other at two points. An intersection of two curves corresponds to an equilibrium between drag and resistance.

Let u_e be the wind velocity giving one and only common point to two curves. Figure 2 shows typical three cases plotted against v: if $u < u_e$, there is no equilibrium; if $u = u_e$, there is only one equilibrium; if $u > u_e$, then there are two equilibria. In the last case, $u > u_e$, one can easily recognize the intersection at larger v, but not the other which is located in the close vicinity to the origin, because the resistance is zero and the drag is equal to $u^2 + \kappa u^{-2}$ at v=0. Therefore the existence of an equilibrium is assured if u is greater than or equal to u_e.

We shall calculate the critical wind speed u_e. Since the resistance and drag curves have the equilibrium point and the tangent there in common, the following equations must hold:

$$v^2/\sigma = (u-v)^2 + \kappa(u-v)^{-2}\,, \tag{20}$$

$$v/\sigma = -(u-v) + \kappa(u-v)^{-3}\,. \tag{21}$$

The subtraction of $(u_e - v)$ multiplied by (21) from (20) yields

$$v^2 - \frac{(1-4\sigma)u_e}{2(1-\sigma)}v - \frac{2\sigma u_e{}^2}{2(1-\sigma)} = 0\,. \tag{22}$$

Solving (22) with respect to v in $(0, u_e)$, we have the equilibrium velocity:

$$v = \frac{1-4\sigma+\sqrt{1+8\sigma}}{4(1-\sigma)}u_e\,. \tag{23}$$

On the other hand the addition of $(u_e - v)$ multiplied by (21) to (20) yields

$$u_e v (u_e - v)^2 = 2\sigma\kappa\,. \tag{24}$$

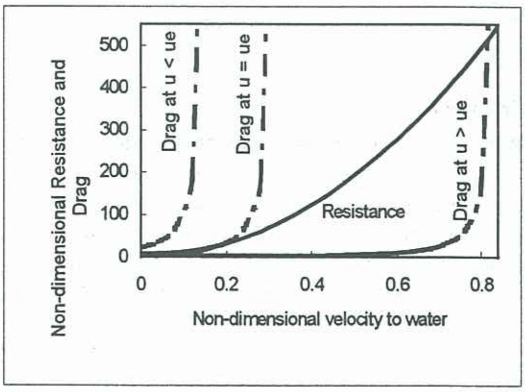

Figure 2 : Typical relations between drag and resistance.

Substituting the equilibrium velocity (23) into (24), we have the nonlinear equation for u_e:

$$\frac{\left(1-4\sigma+\sqrt{1+8\sigma}\right)\left(3-\sqrt{1+8\sigma}\right)^2}{64(1-\sigma)^3}u_e^{\,4} = 2\sigma\kappa \, . \qquad (25)$$

This equation can be solved analytically with respect to u_e:

$$u_e = \left[\frac{128\sigma(1-\sigma)^3\kappa}{\left(1-4\sigma+\sqrt{1+8\sigma}\right)\left(3-\sqrt{1+8\sigma}\right)^2}\right]^{1/4} . \qquad (26)$$

To summarize, a bird can attain equilibrium flight if the wind velocity is greater than or equal to u_e.

Stability of sea-anchor soaring

In order to make sure of the feasibility of an equilibrium, we must examine the static stability of the equilibrium, *i.e.*, whether there is a restoring force against any disturbances. Figure 3 describes how the restoring force would be generated. Suppose a petrel, soaring on the equilibrium condition $D=R$, is disturbed and the velocity to the sea v becomes slower or faster.

First we consider the case of the slower v. As v becomes slower, the bird moves behind the equilibrium position as shown on the left portion of Fig.3. Therefore in the slower v situation the bird is pulled back to the equilibrium, if $D'>R'$.

The other is the case of the faster v. As v becomes faster, the bird takes on the equilibrium position as shown on the right portion of Fig.3. Therefore in the faster v situation the bird is pulled back to the equilibrium, if $D''<R''$.

The inset at the top of Fig.3 shows the possible relation between D and R against V, which corresponds the situation discussed above.

Returning to Fig.2, we shall look for the stable equilibrium. By comparing the inset in Fig.3 with curves at $u = u_e$ on Fig.2, it is obvious that the equilibrium at $u = u_e$ is not stable. When $u > u_e$, the intersection at larger v does not meet the above requirements for return to equilibrium, either. Only the equilibrium in the close vicinity to the origin meets the requirements, and therefore it is stable. This equilibrium is quite preferable to a petrel: v is very slow, and hence it can soar almost stationary to water; slower v also implies larger $u - v$, and hence aerodynamic lift can easily sustain the weight.

The discussion of this subsection reveals that petrels can soar stably at very small v, when $u > u_e$.

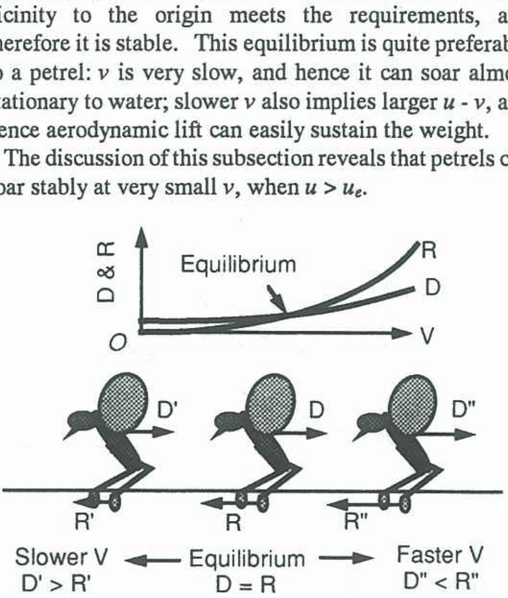

Figure 3 : Stability of sea-anchor soaring.

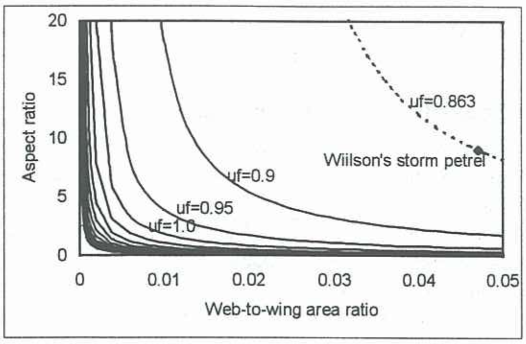

Figure 4 : Contour plot of u_f in $(A/S, AR)$ plane.

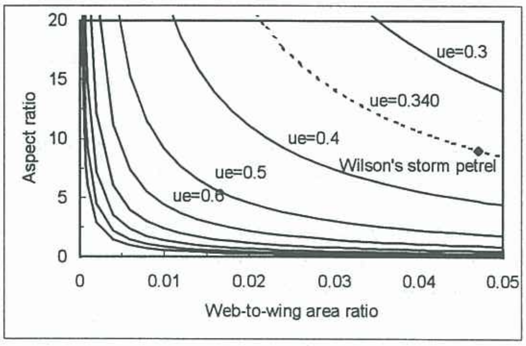

Figure 5 : Contour plot of u_e in $(A/S, AR)$ plane.

NUMERICAL RESULTS AND DISCUSSION

Assumptions on parameters

I assumed the following values: ρ_a=1.25[kg/m^3], ρ_w=1025[kg/m^3], C_R=1.0, C_{D0}=0.05, and $C_{L\max}$=1.5. Induced drag in ground effect is estimated by the formula (Laitone 1989, Rayner 1991):

$$k = \frac{1-2/\pi+(8\delta/\pi)^2}{e\pi AR\left[1+(8\delta/\pi)^2\right]}, \qquad (27)$$

where δ, e, and AR denote respectively a ratio of the flight altitude to the semi-span, Oswald's wing efficiency, and the aspect ratio of the wing, *i.e.*, the full-span squared and divided by the wing area. The value of δ was assumed to be unity. The wing efficiency e takes the value between around 0.7 of the worst-shape wing and unity for the best wing. We call eAR the effective aspect ratio.

Substituting these values into (5), (6), and (9) we obtain the relations among σ, κ, μ, A/S, eAR, and W/S.

Wind speed criteria on sea-anchor soaring

Substituting assumed parameters into (19) and (26), we can relate u_f and u_e with A/S and AR.

Figures 4 and 5 show, respectively, velocity contours of u_f and u_e in the parameter space $(A/S, AR)$ with $e = 1$. Sea birds have AR values ranging from around 5 to 20, so u_f is almost always larger than u_e. This means stability of sea-anchor soaring is almost always assured, if the wind speed is greater than u_f. With different e values, situations are similar.

Figure 4 also shows that at a given AR, a bird with smaller A/S needs stronger winds to achieve sea-anchor soaring. Storm petrels have well developed webs and moderate wing area, therefore their A/S values are the largest among sea birds.

Scale effects to wind speed criteria

All the preceding arguments have been made on non-dimensional values. In this subsection we shall discuss the scale effects. Among parameters, only W/S has dimension, *i.e.*, $[N/m^2]$. Using (7), (8), and assumed parameters, we will regain velocities with the right dimension. We shall also compare and discuss performances of two extreme examples, *i.e.*, the Wilson's storm petrel (*Oceanites oceanicus*) and the Wandering albatross (*Diomedea exulans*). We shall use the relevant data, taken from Withers (1979) and Azuma (1992) and shown in Table 1.

The accurate estimate of U_f for the Wilson's storm petrel with e=1 is $4.79[m/s]$. Even if we assume the Wandering albatross's A/S is as large as the Wilson's storm petrel's, we obtain a very large value for the albatross with e=1: U_f=$4.79[m/s]$.

According to the Beaufort wind scale, wind as fast as 12.5 to $13.1[m/s]$ would induce water waves as high as $6[m]$! Therefore larger sea birds like albatrosses are incapable of sea-anchor soaring because too strong a wind is required in rough sea waves. In reality albatrosses are not observed to sea-anchor soar.

Calculations with $e = 0.7$ estimate about a 10% increase in every velocity, but the overall trend is quite similar to the results above.

Species Names	S $[m^2]$	AR	W/S $[N/m^2]$	A $[m^2]$	Ref.
Wilson's storm petrel	0.017	9	19.3	0.008	Withers
Wandering albatross	0.667	18	147	?	Azuma

Table 1: Morphometrics of two sea-bird species.

Scale effects to the velocity to water

The next consideration is on velocity to water V. This can be estimated from (16) multiplied by the square root of μ. By assuming $e = 1$, we obtain $V = 0.256[m/s]$ for Wilson's storm petrel. Due to this very low velocity to water, they can easily "walk" back to something they drift past on the sea surface, immediately after they find it.

We shall assume the existence of an upper bound for V, partly because too large a V is inconvenient for a bird to watch the sea surface, and partly because too large a V requires too high a walking speed to floating items. Compared to other sea birds, storm petrels have rather long legs for their body size, every sea bird can walk at $0.25[m/s]$ or so. If we require $V < 0.25[m/s]$, then we obtain the inequality with respect to A/S:

$$\frac{A}{S} \geq 1.04\times10^{-3}\left(\frac{W}{S}\right)\left[13.1(eAR)^{-1}+1\right]. \qquad (28)$$

Figure 6 shows the contour plot of A/S, that satisfies the equality of (28), in the parameter space (W/S, AR). Since even a storm petrel's A/S is 0.0471, larger sea birds need huge webs: for example a Wandering albatross must have a pair of webs about $40[cm]$ diameter! If we adopt 0.05 as the maximum value for A/S, birds with W/S larger than about $30[N/m^2]$ cannot make use of sea-anchor soaring at $V = 0.25[m/s]$.

CONCLUSION

Based on conventional wing theory I have analyzed the sea-anchor soaring, and found

(1) the feasibility and existence of an equilibrium are summarized by formulae giving two kinds of lower bounds to the wind speed, *i.e.*, u_f and u_e;
(2) a stable equilibrium exists at the very low velocity to water, V, only when the wind speed is greater than u_f;
(3) u_f is much greater than u_e for most sea birds, and hence sea-anchor soaring is possible with the wind speed greater than u_f;
(4) the sample calculation shows that the Wilson's storm petrel can sea-anchor soar at $V = 0.256[m/s]$ in the wind with $U = 4.79[m/s]$ under the best conditions;
(5) larger sea-birds like albatrosses need strong winds to soar, but such strong winds make the sea very rough and prevent soaring;
(6) W/S of a bird that can make use of sea-anchor soaring is limited up to around $30[N/m^2]$ due to the upper bound of foot-web size, $A/S = 0.05$, and the upper bound for the velocity to water, $V = 0.25$ $[m/s]$.

REFERENCES

ALEXANDER, R.M. "Exploring Biomechanics", New York: W.H. Freeman & Co., New York, USA, 1992.

AZUMA, A. "The Biokinetics of Flying and Swimming", Springer-Verlag, Tokyo, Japan 1992

LAITONE, E.V. "Comment on 'Drag Reduction Factor Due To Ground Effect'", *J. Aircraft*, **27**, 96, 1989.

RAYNER, J.,M.V. "On the aerodynamics of animal flight in ground effect", *Trans. Roy. Soc. Lond., Ser.B*, **334**, 119-128, 1991.

TANI, I. "The Effect of Ground upon the Aerodynamic Characteristics of a Wing", *J. Soc. Aero. Sci. Nippon*, **4**, 659-674, 1937 (in Japanese).

WITHERS, P.C. "Aerodynamics and Hydrodynamics of the 'Hovering' Flight of Wilson's Storm Petrel", *J. exp. Biol.*, **80**, 83-91, 1979.

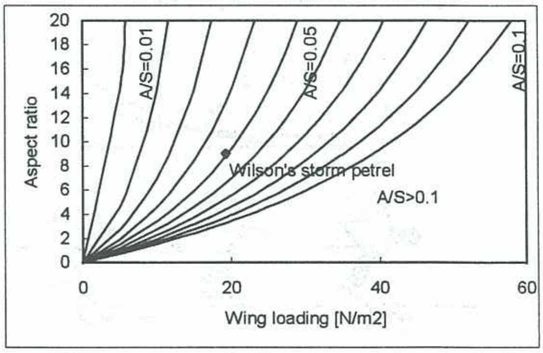

Figure 6 : Contour plot of A/S in (W/S, AR) plane in case of V=0.25 $[m/s]$.