Dynamic Soaring Revisited

Ferdinand (Ferdi) Hendriks

Morgan Hill, CA

Overview

- History
- DS in wind shear
- DS in turbulence
- Conclusions
- Q&A

I premise that if we know anything about mechanics it is certain that a bird without working his wings cannot, either in still air or in a uniform horizontal wind, maintain his level indefinitely. For a short time such maintenance is possible at the expense of an initial relative velocity, but this must soon be exhausted. Whenever therefore a bird pursues his course for some time without working his wings, we must conclude either

(1) That the course is not horizontal

(2) That the wind is not horizontal, or

(3) That the wind is not uniform

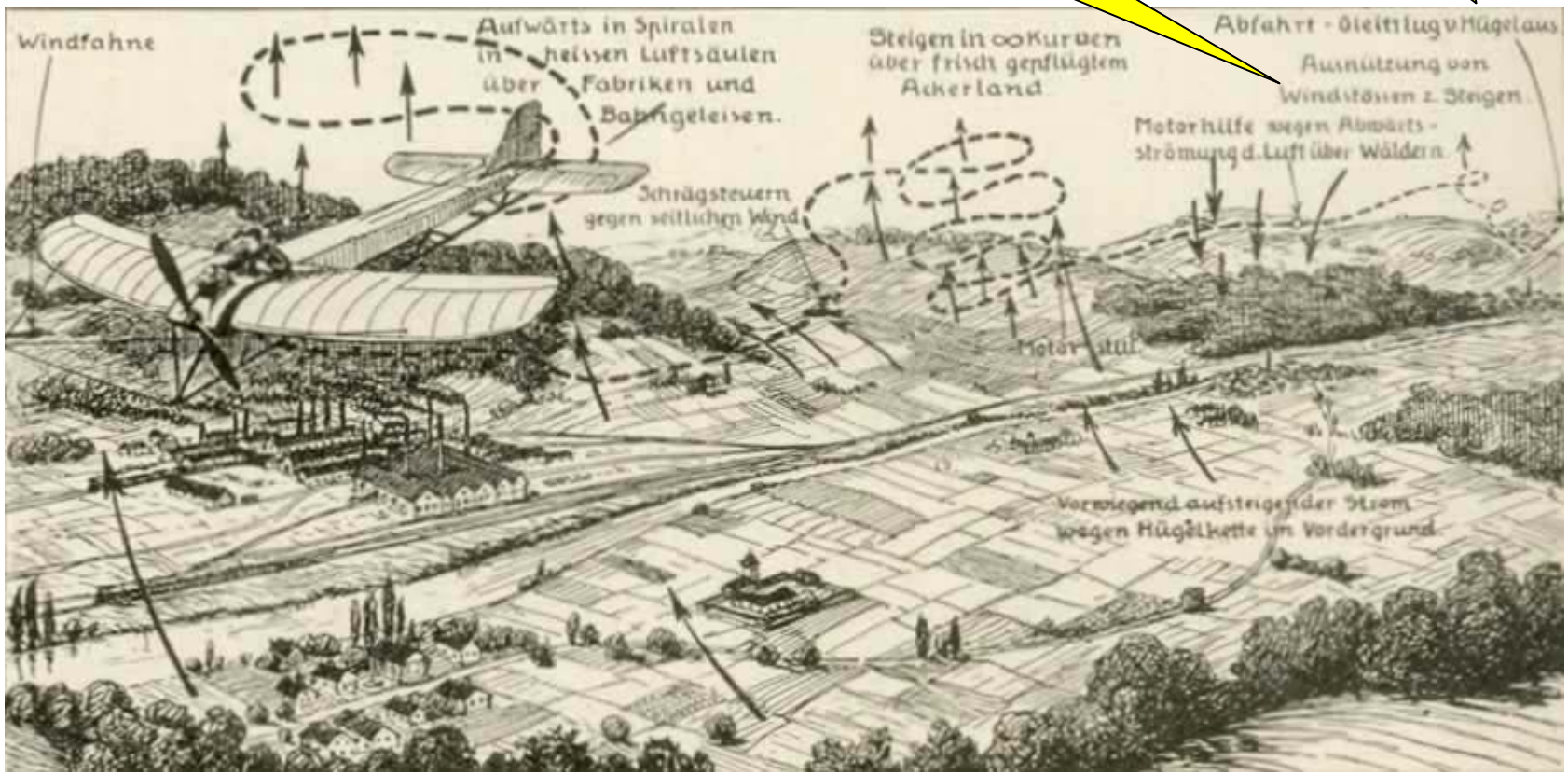
It is probable that the truth is usually represented by (1) or (2); but the question I wish to raise is whether (3) may not sometimes come into operation.

-- Lord Raleigh, Nature, 27, April 5, 1883, pp534-5

History – Wasserkuppe, Germany 1920's

Launch: Glide from a Hill

Use of wind gusts to rise



Pioneers: Klemperer, Hirth, von Karman and many others; John Montgomery, Langley ("Internal Work of the Wind")

History – Idrac on Thermals

Pierre Idrac "Etudes Experimentales sur le Vol a Voile," 1931

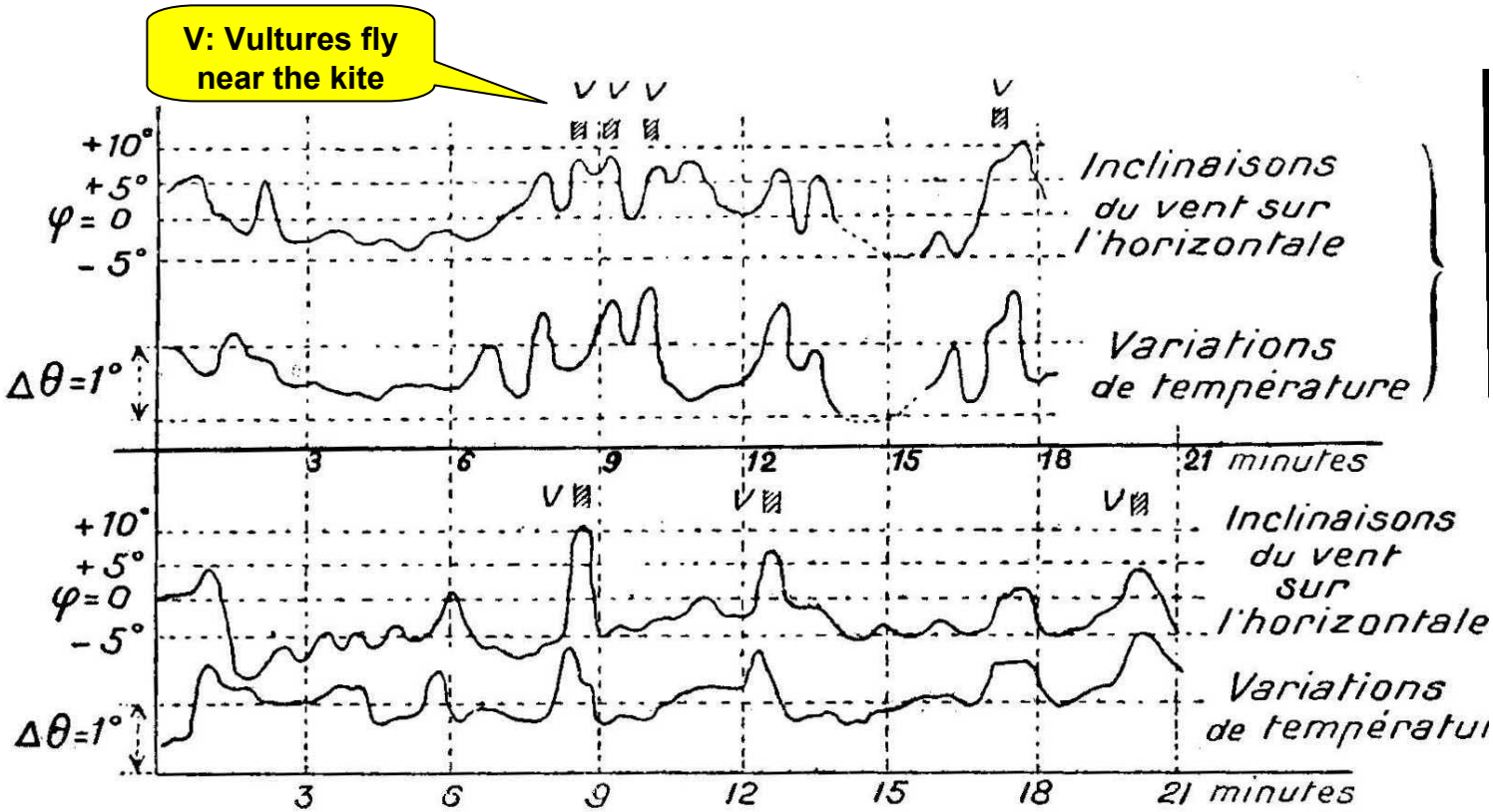
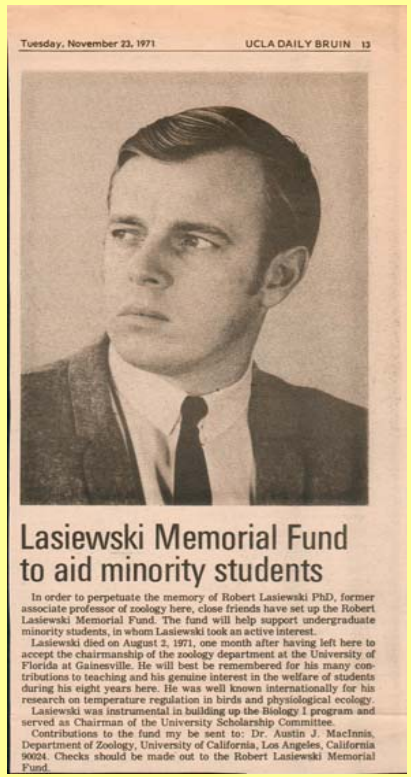


Abb. 30 u. 31. — Diagramme der Neigungswinkel des Windes gegen die Horizontale (Inclinaisons...) und der gleichzeitigen Aenderungen der Temperatur (Variations...) in Abhängigkeit von der Zeit in Minuten. — Die Schraffuren über den Kurven *vv* bedeuten, dass Vögel zu diesem Augenblick in unmittelbarer Nachbarschaft der Apparate fliegen.

History – Applied Math/Zoology project

UCLA, 1971



Tuesday, November 23, 1971 UCLA DAILY BRUIN 13

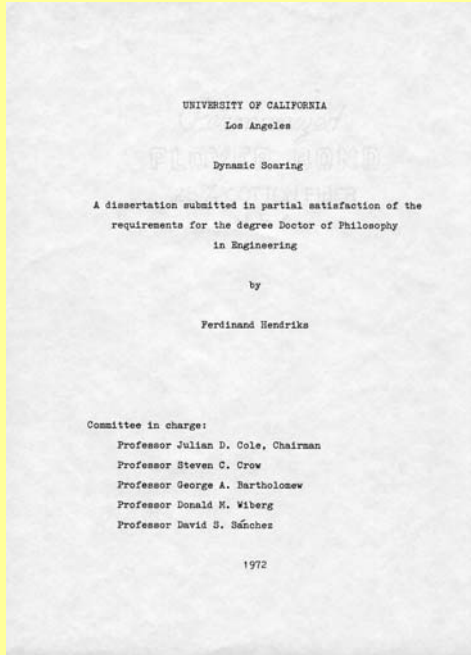
Lasiewski Memorial Fund to aid minority students

In order to perpetuate the memory of Robert Lasiewski PhD, former associate professor of zoology here, close friends have set up the Robert Lasiewski Memorial Fund. The fund will help support undergraduate minority students, in whom Lasiewski took an active interest.

Lasiewski died on August 2, 1971, one month after having left here to accept the chairmanship of the zoology department at the University of Florida at Gainesville. He will best be remembered for his many contributions to teaching and his genuine interest in the welfare of students during his eight years here. He was well known internationally for his research on temperature regulation in birds and physiological ecology.

Lasiewski was instrumental in building up the Biology I program and served as Chairman of the University Scholarship Committee.

Contributions to the fund my be sent to: Dr. Austin J. MacInnis, Department of Zoology, University of California, Los Angeles, California 90024. Checks should be made out to the Robert Lasiewski Memorial Fund.



UNIVERSITY OF CALIFORNIA
Los Angeles

Dynamic Soaring

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy in Engineering

by

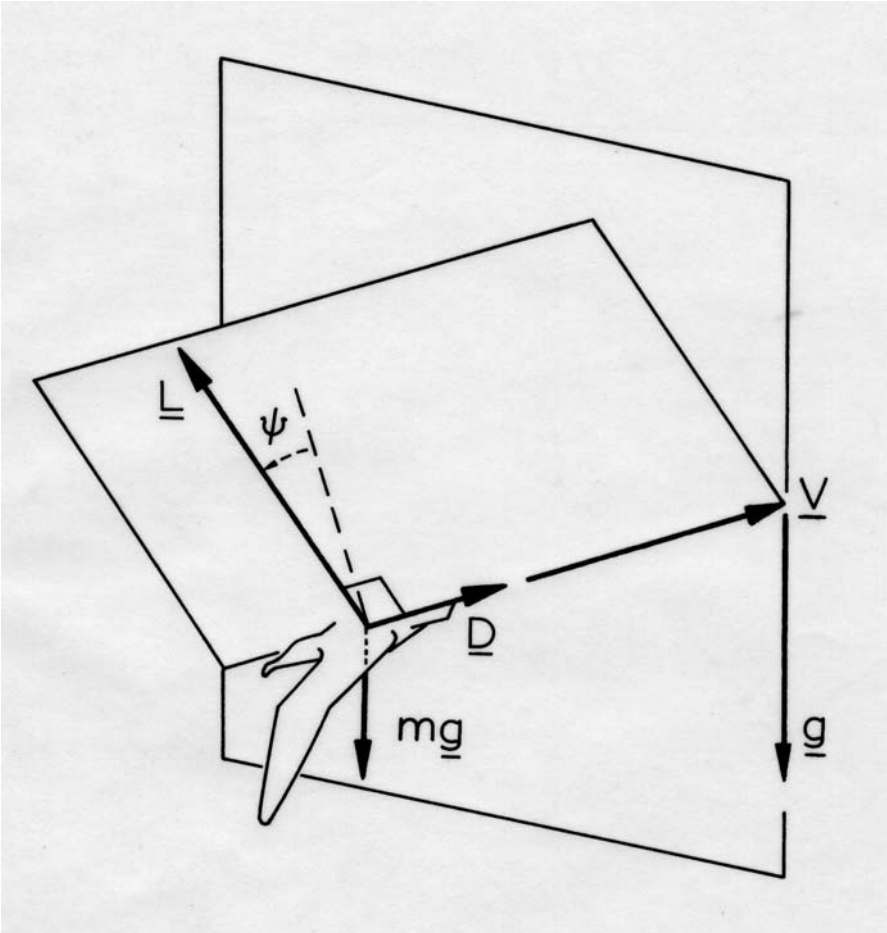
Ferdinand Hendriks

Committee in charge:
Professor Julian D. Cole, Chairman
Professor Steven C. Crow
Professor George A. Bartholomew
Professor Donald M. Wiberg
Professor David S. Sánchez

1972

Attempts to demonstrate DS with an RC glider over flat terrain …

DS in shear – modelling the glider



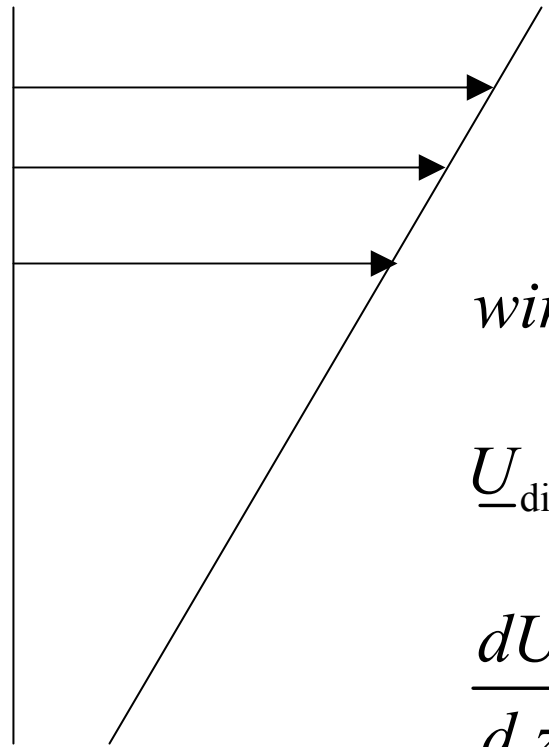
$$L = c_L \frac{1}{2} \rho V^2 S$$

$$D = c_D \frac{1}{2} \rho V^2 S$$

$$c_D = c_{D_0} + k\, c_L^{\ 2}$$

$$control \;\; \psi(t), \;\; \alpha(t)$$
$$mass \;\; m, wing \;\; area \;\; S$$

DS in shear – modelling the wind



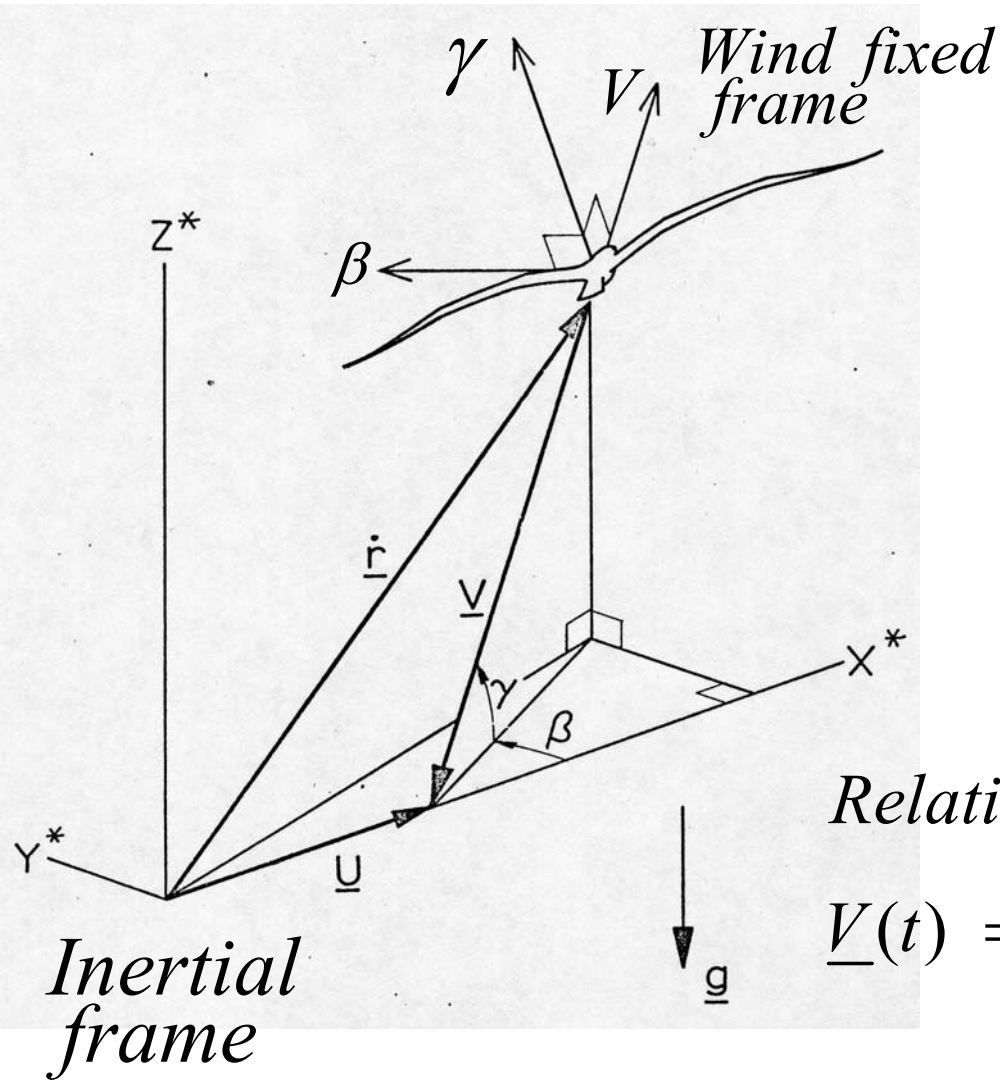
$$air\ density\ \rho$$

$$wind\ velocity\ vector$$

$$\underline{U}_{\dim} = \left\{ \left(\frac{dU_{\dim}}{d\,z^*} \right) z^*,\ 0,\ 0 \right\},$$

$$\frac{dU_{\dim}}{d\,z^*} = const \geq 0$$

DS in shear – "Wind-fixed" axes



$$Relative\,(apparent)\,wind:$$

$$\underline{V}(t) = \left\{ \underline{U}(\underline{x}^*) \right\}_{\underline{x}^* = \underline{r}(t)} - \dot{r}(t)$$

DS in shear – inertial eqns of motion

$$Inertial\ \ frame:$$

$$m\ \underline{\ddot{r}}(t) = \underline{L} + \underline{D} + m\,\underline{g}$$

$$l_c = 2m/\rho S \qquad characteristic\ \ speed$$

$$V_c = \sqrt{g\,l_c} \qquad characteristic\ \ speed$$

$$t_c = \sqrt{\frac{l_c}{g}} \qquad characteristic\ \ time$$

DS in shear – "wind-fixed" eqns of motion; linear shear

wind fixed equations
made non – dimensional using V_c and t_c

DS rule

drag

$$\dot{V} = -V\frac{dU}{dz}\boxed{\sin\gamma\cos\gamma\cos\beta} - c_D V^2 - \sin\gamma$$

gravity

$$V\dot{\gamma} = V\frac{dU}{dz}\sin^2\gamma\cos\beta + c_L V^2\cos\psi - \cos\gamma$$

$$(V\cos\gamma)\dot{\beta} = V\frac{dU}{dz}\sin\gamma\sin\beta + c_L V^2\sin\psi$$

$$\dot{x} = V\cos\gamma\cos\beta + U$$

$$\dot{y} = V\cos\gamma\sin\beta$$

$$\dot{z} = V\sin\gamma$$

DS in shear – Energy eqn

Indicated air speed

Altitude

$$\frac{d}{dt}\left(V^2/2 + z\right) = -V^2 \frac{dU}{dz} \sin 2\gamma \cos\beta - c_D V^3$$

Rate of change of total relative energy

Rate of relative

Energy gain or loss

Rate of dissipation

DS in shear – Necessary Cond'n to stay aloft

From the energy equation, we want the rate of change of the total energy to be greater or equal to zero, thus

$$-V^2 \frac{dU}{dz} \sin 2\gamma \cos \beta - c_D V^3 \geq 0$$

$$\frac{dU}{dz} \geq c_D V$$

In dimensional terms:

$$\left(\frac{dU}{dz}\right)_{\dim} \geq g \sqrt{\left(\frac{c_D{}^2}{c_L}\right)\left(\frac{2\rho}{W/S}\right)}$$

Wandering albatross:

$$W/S = 150\ N/m^2$$

$$c_L = 1 \quad c_D = .1$$

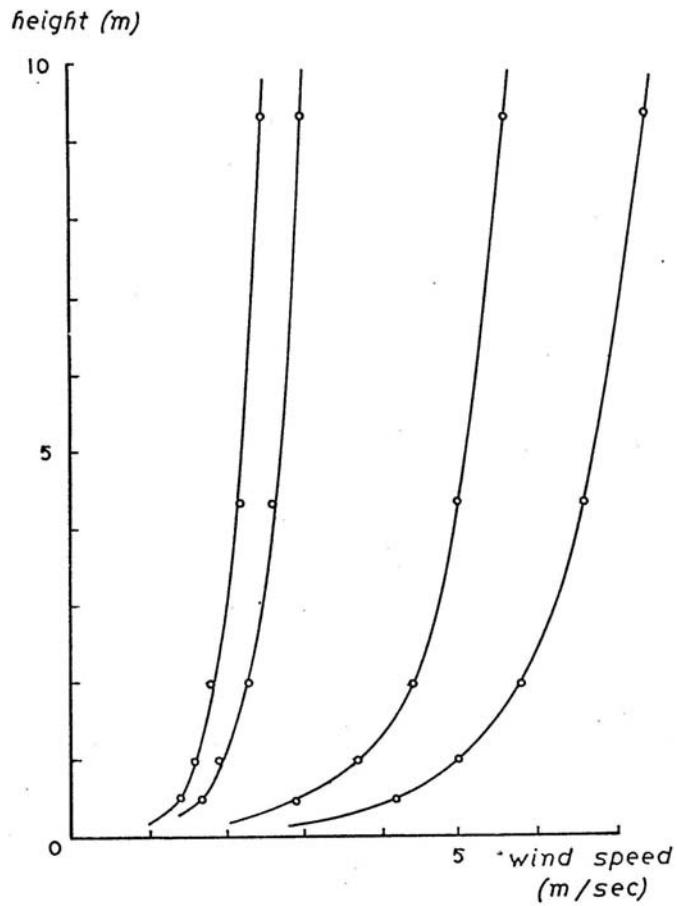
$$g = 9.81\ m/sec^2$$

$$\rho = 1.25\ kg/m^3$$

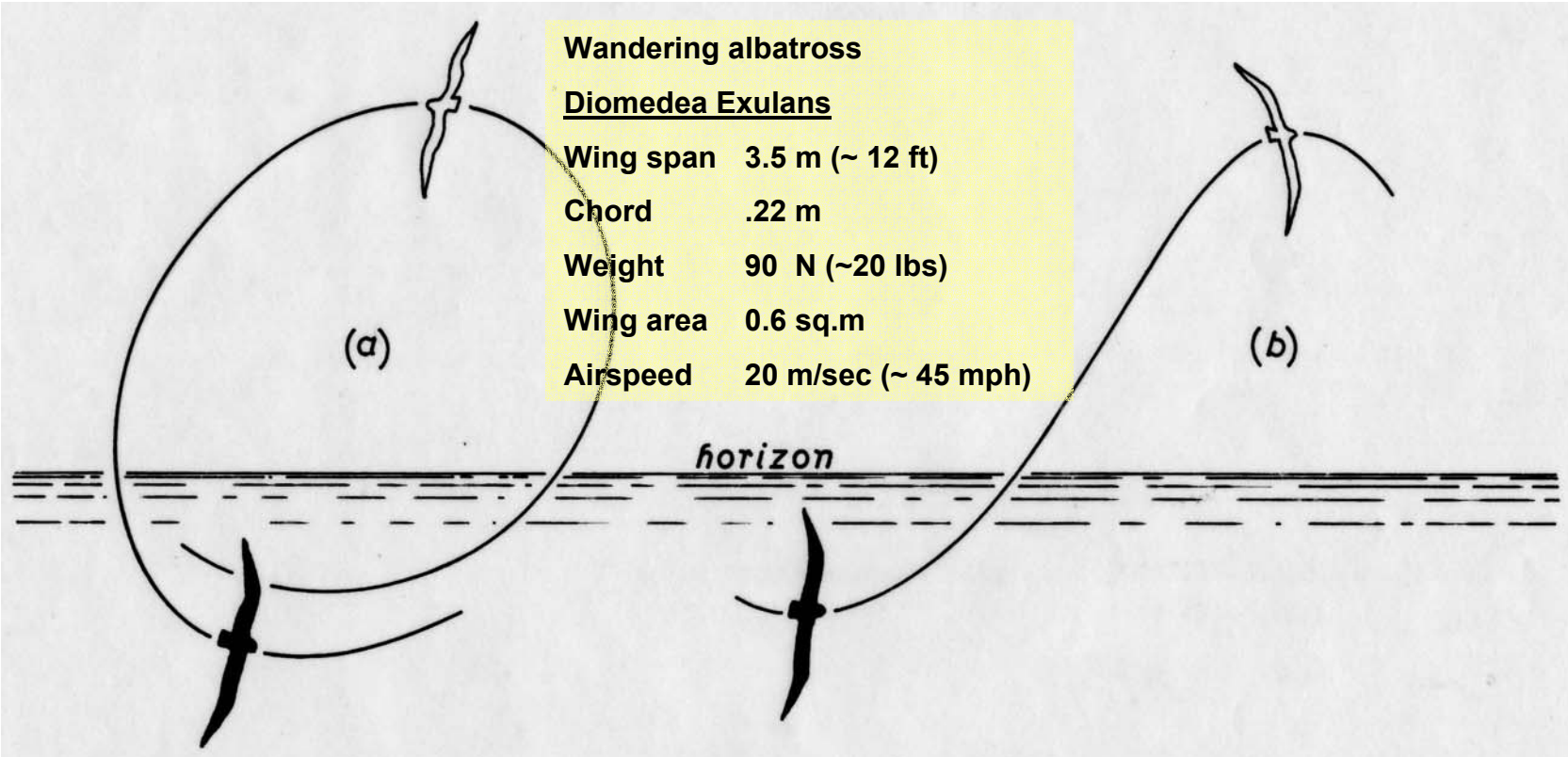
$$(dU/dz) \geq .108\ sec^{-1}$$

High wing loading and laminar flow airfoils are favored.
Vertical wind shears exceeding .1 sec-1 are common.**

DS in shear – wind profiles over land



DS in shear – trajectories observed by Idrac



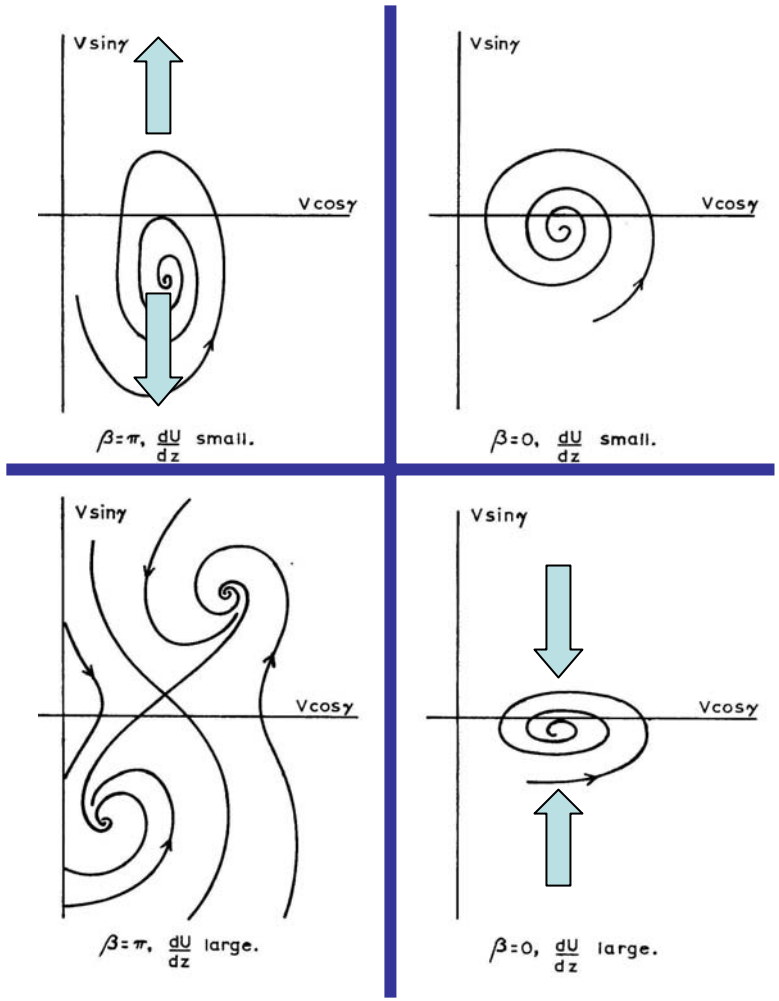
Wandering albatross

<u>Diomedea Exulans</u>

Wing span	**3.5 m (~ 12 ft)**
Chord	**.22 m**
Weight	**90 N (~20 lbs)**
Wing area	**0.6 sq.m**
Airspeed	**20 m/sec (~ 45 mph)**

DS in shear – phaseplane portraits

plots of the relative wind vector V

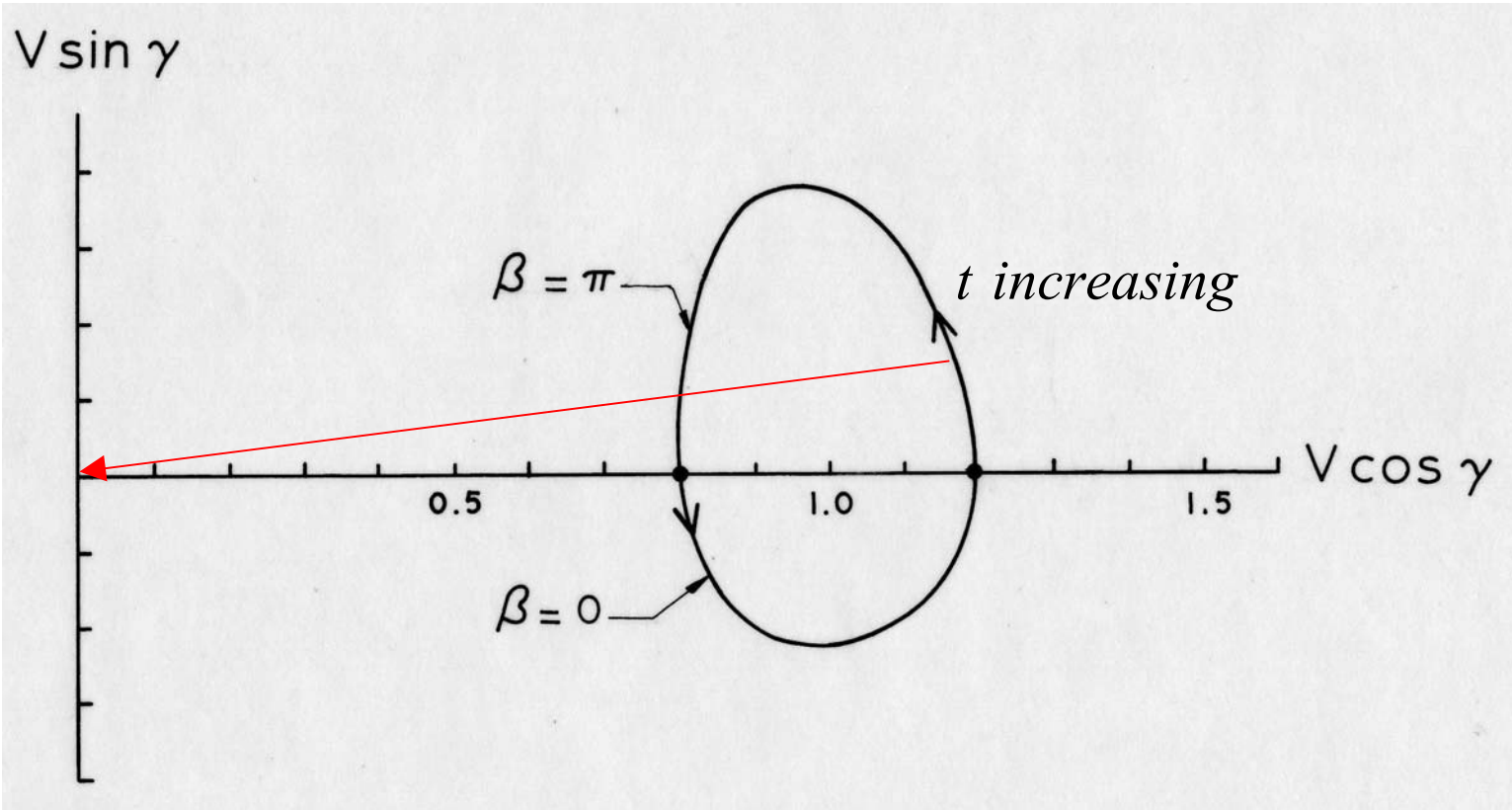


$$\beta = 0 \quad \textit{with the wind}$$

$$\beta = \pi \quad \textit{into the wind}$$

The phugoid oscillation
Is “pulled” by the wind
shear.

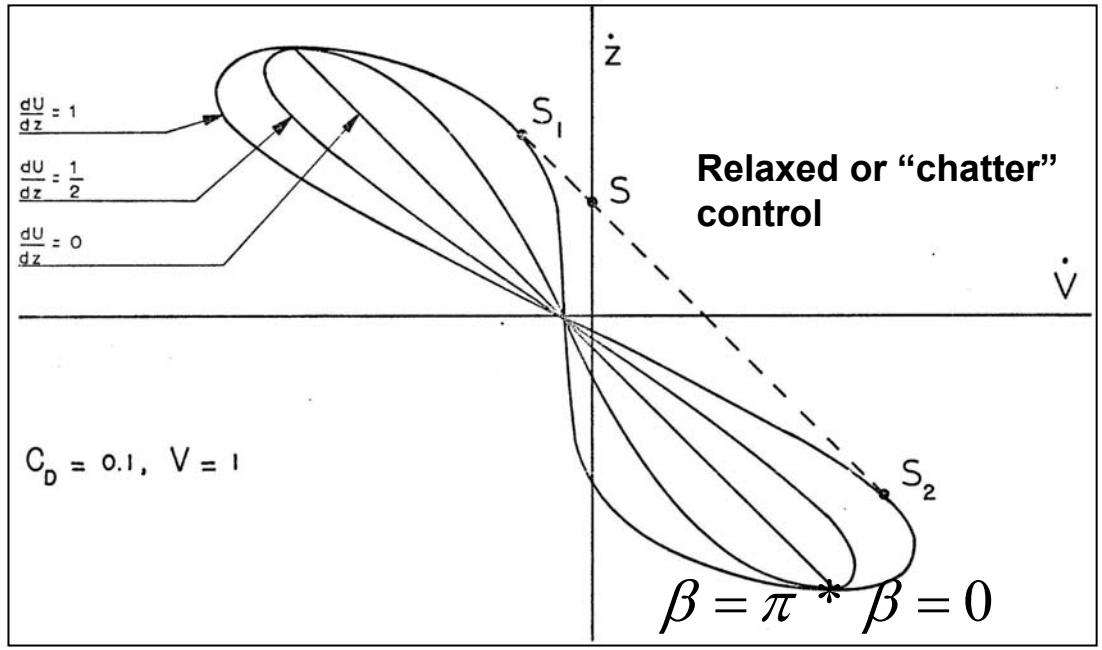
DS in shear – piecing phaseplanes together, drag = 0



DS in shear – Contensou's approach

Assumptions:

- $\beta = 0 \; or \; \pi \quad (+,-sign)$
- **eliminate** γ
- **V = const**



$$\dot{V} = -c_D V^2 \mp \frac{dU}{dz} \dot{z} \sqrt{1 - \left(\frac{\dot{z}}{V}\right)^2} - \frac{\dot{z}}{V}$$

Recall first Eqn. of motion

DS in shear – Perturbation approach

$$\psi = const, \quad \frac{dU}{dz} = O(1)$$

$$V(t) = V_0(t) + \varepsilon V_1(t) + \ldots$$

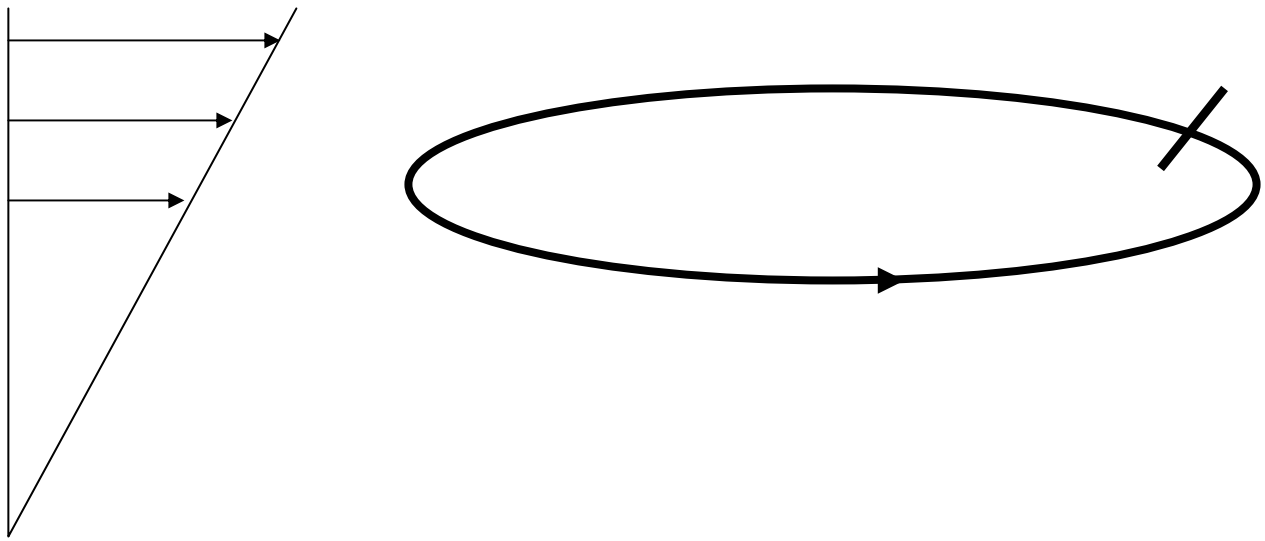
$$\gamma(t) = \qquad \varepsilon \gamma_1(t) + \ldots$$

$$\beta(t) = \beta_0(t) + \varepsilon \beta_1(t) + \ldots$$

$$c_L = c_{L_0}(t) + \varepsilon c_{L_1}(t) + \ldots$$

$$c_D = \qquad \varepsilon c_D$$

DS in shear – O(1) motion (zero drag)



To first order, the motion is a horizontal circle, flown at constant speed V_0
Corresponding to some bank angle ψ

DS in shear – Mathieu eqn.

At O(ε) we obtain

$$\ddot{\gamma}_1 + \left(\frac{2}{V_0^{\,2}} + \frac{2}{V_0} \frac{dU}{dz} \cos \omega_0 t \right) \gamma_1 = -2 c_D + \frac{\dot{c}_{L_1}}{c_{L_0} V_0}$$

"pumping term"

control

Seek a non-sinking solution despite the term $-2 c_D$ on r.h.s.

DS in shear – Bank rule

The control $c_{L_1}(t)$ *that achieves the goal is*

$$c_{L_1}(t) = -\frac{1}{2}\sqrt{6}\; c_D \sin 2\omega_0(t)$$

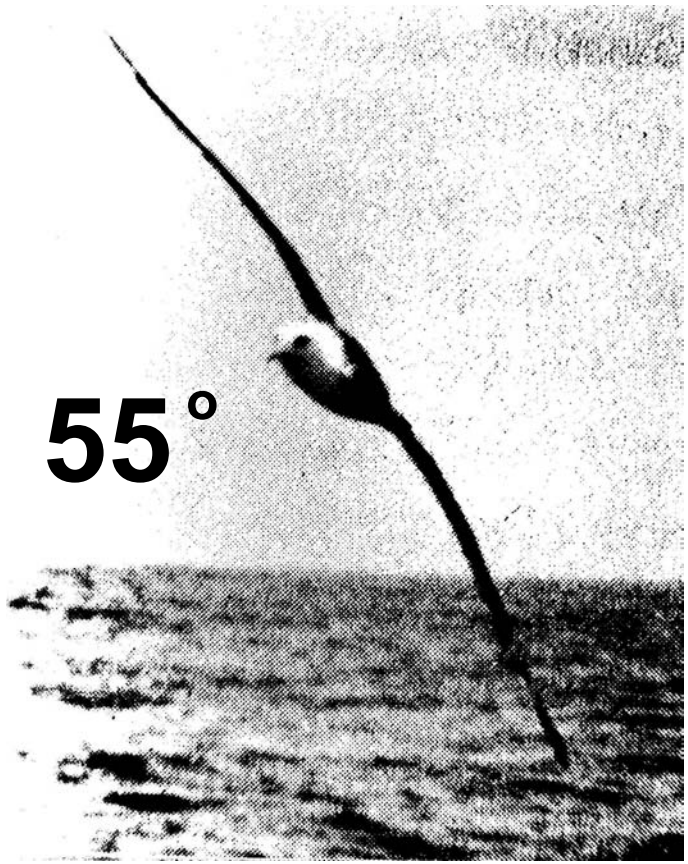
provided the angle of bank ψ *satisfies*

$$tg\,\psi = \sqrt{2}$$

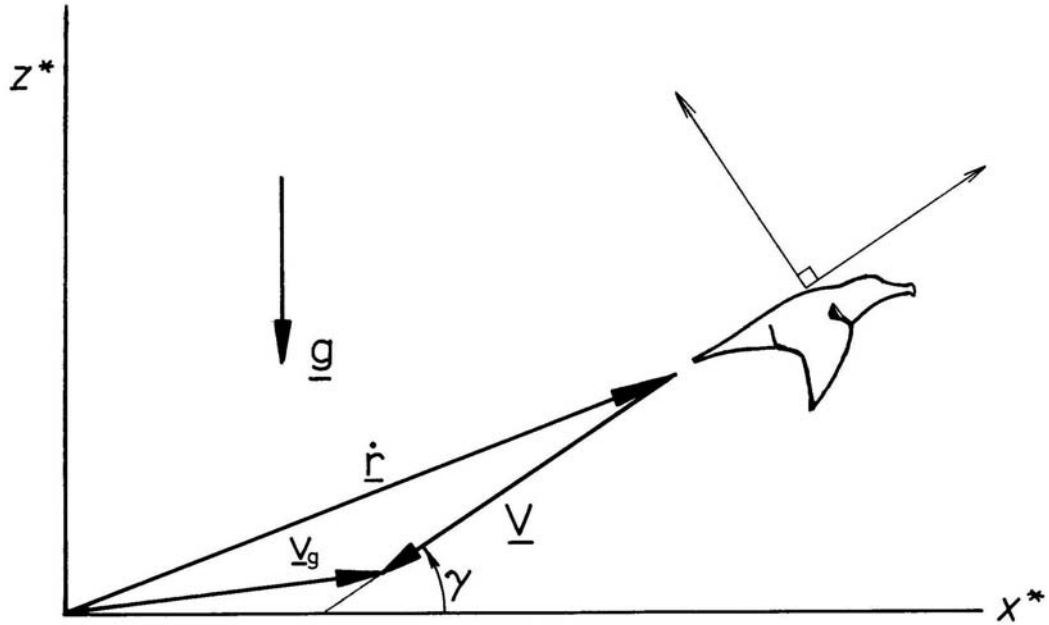
or

$$\psi = 55^o$$

This agrees with Idrac's observations!



DS in GUSTS, 2D



$$\underline{V}(t) = \underline{v}_g(t)\left\{x^*\right\}_{\underline{x}^* = \underline{r}(t)} - \dot{r}(t)$$

DS in gusts – Non-dim. eqns of motion in wind-fixed frame

$$\dot{V} = -V\left\{u_{g_x}\cos^2\gamma + \left(u_{g_z} + w_{g_x}\right)\sin\gamma\cos\gamma + w_{g_z}\sin^2\gamma\right\} +$$

gust/glider

$$-\left\{\left(u_g w_{g_x} + w_g w_{g_z}\right)\sin\gamma + \left(u_g u_{g_x} + w_g u_{g_z}\right)\cos\gamma\right\} +$$

gust/gust

$$-c_D V^2 - \sin\gamma$$

gravity

drag

$$V\dot{\gamma} = V\left\{u_{g_z}\sin^2\gamma + \left(u_{g_x} - w_{g_z}\right)\sin\gamma\cos\gamma - w_{g_x}\cos^2\gamma\right\} +$$

gust/glider

$$+\left\{\left(u_g u_{g_x} + w_g u_{g_z}\right)\sin\gamma - \left(u_g w_{g_x} + w_g w_{g_z}\right)\cos\gamma\right\} +$$

gust/gust

$$+c_L V^2 - \cos\gamma$$

gravity

lift

$$\dot{x} = u_g + V\cos\gamma$$

$$\dot{z} = w_g + V\sin\gamma$$

DS in gusts – Solution outline

$$Expand\ in\ terms\ of\ \varepsilon = \left(v_g\right)_{rms} / V_c \quad (weak\ gusts)$$

$$V = V_0 + \varepsilon V_1 + \ldots$$

$$\gamma = \varepsilon \gamma_1 + \ldots$$

$$u_g = \varepsilon u$$

$$w_g = \varepsilon w$$

$$c_L = c_{L_0} + \varepsilon c_{L_1} + \ldots$$

control

$$c_D = \varepsilon^2 c_{D_2}$$

$$Turbulent\ energy\ has\ the\ Kolmogorov\ form$$

$$E(k) = \bar{\alpha}\, \varepsilon^{2/3} k^{-5/3}$$

Gusts appear more energetic to
Gliders with small char. length (short, fast phugoid)

$$\varepsilon = \frac{\varepsilon_{\dim}}{l_{char}^{1/2}\, g^{3/2}}$$

Turbulent dissipation rate

$$Turbulence\ is\ "frozen"\ and\ gusts\ are\ sampled\ along\ a\ straight\ line$$

DS in gusts – control

Try the feedback control

$$c_{L_1} = AV_1 - B\gamma_1$$

then, after eliminating V_1 *and using* $d/dt = V_0\ d/dx$

$$\gamma_{1_{xx}} + B\gamma_{1_x} + K^2\gamma_1 = -\frac{w_{xx}}{V_0} - K^2 V_0 u_x \quad (B \text{ acts as artificial damping})$$

where

$$K = \frac{1}{V_0}\left\{2c_{L_0} + AV_0\right\}^{1/2} \quad (\text{n.d. waveno. of phugoid})$$

Solve for γ_1 *using Fourier transforms and use it in the* $O\left(\varepsilon^2\right)$ *eqns*

after much reduction we find the turbulence / drag balance satisfied for sustained horizontal flight:

$$B\int_{-\infty}^{\infty}\frac{k^4 W(k)\,dk}{\left(K^2-k^2\right)+B^2k^2} + BK^2\int_{-\infty}^{\infty}\frac{k^2 U(k)\,dk}{\left(K^2-k^2\right)+B^2k^2} - c_{D_2}V_0^{\ 2} = 0$$

DS rule: Maximize artificial damping of the phugoid

DS in gusts – final turbulence/drag balance

$U(k)$ and $W(k)$ are the longitudinal and lateral turbulence spectra

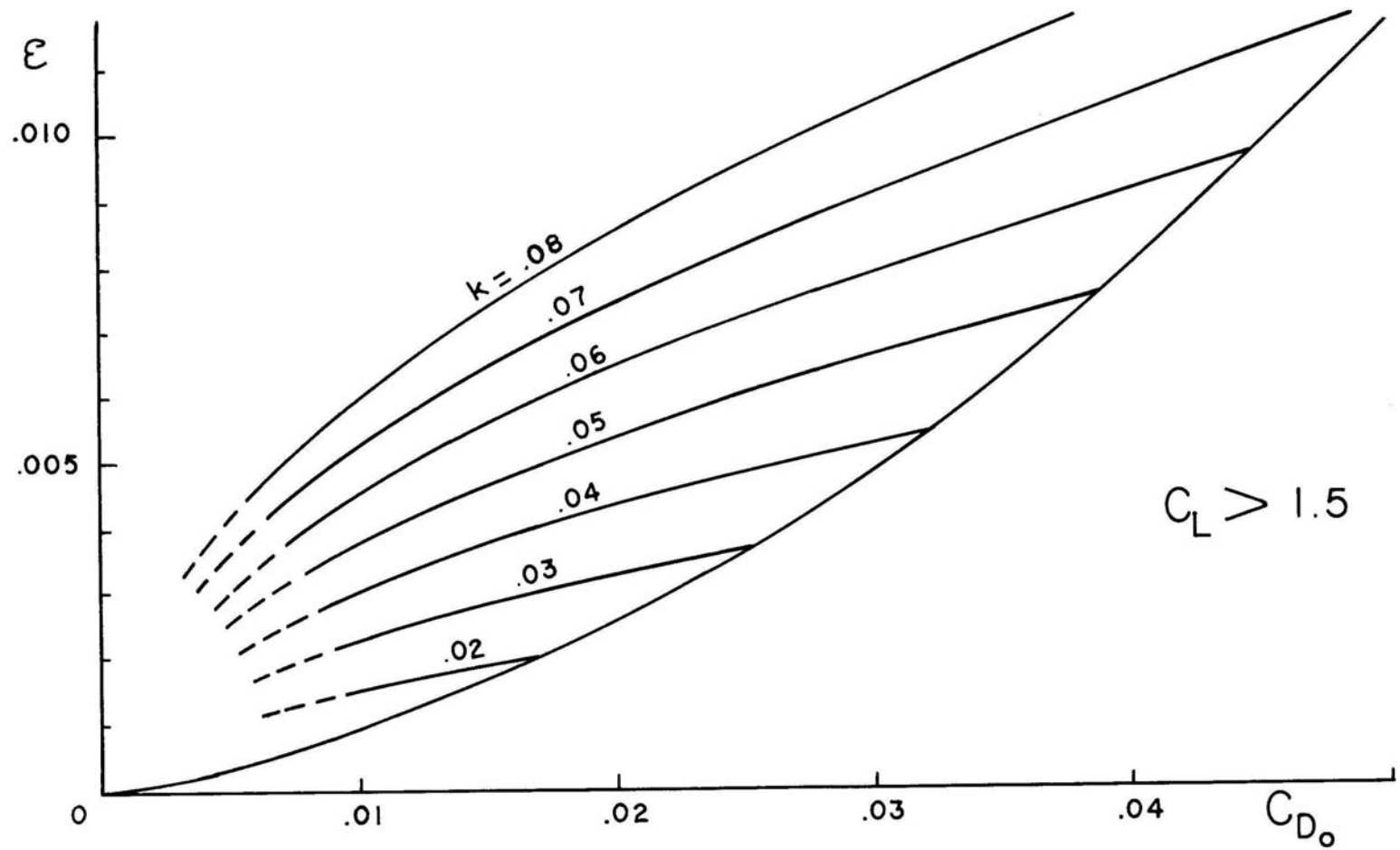
Both can be expressed in terms of the turbulent dissipation rate $\mathcal{E}$

For example, after (rather arbitrarily) choosing $B = 2K$ we get

$$\frac{4}{15}\pi\sqrt{3}\,\bar{\alpha}\mathcal{E}^{2/3}K^{1/3} - c_{D_2}V_0^{\,2} = 0$$

Using realistic values that approximate a Frigate bird flying at $30\,m$ altitude in turbulence we require $\mathcal{E} = .795\,m^2/\sec^3$

DS in gusts – Required turbulent dissipation for given aerodynamic properties



Conclusions

- DS in shear is feasible for RC gliders and birds in naturally occurring wind gradients. High glide speeds are required. Theoretical predictions are being confirmed but not under controlled conditions.

- A figure of merit was derived for shear-soaring gliders

- A simple strategy for DS in (linear) shear is to synchronize the turning motion with the phugoid oscillation. This happens at a bank angle of 55 degrees.

- DS in turbulence requires low speed. Theoretical analyses with fewer restrictions must be done. Artificial Damping of the phugoid motion appears to be a promising control strategy.