

Energy savings for UAV flight in unsteady gusting conditions through trajectory optimization

Lou Grimaud

Illinois Institute of Technology

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Introduction and motivations

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Defining the energy extraction problem

What is an “optimal trajectory”?

- ▶ Maximum energy at the end of the cycle
- ▶ Maximizing the energy gain at each instant of the cycle
- ▶ *Minimize the energy input needed for sustainable flight*

The neutral energy loop

Finding the minimal wind gust that allows to maintain altitude and speed over a gust.

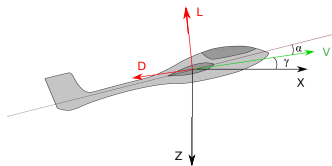
Aircraft model¹

$$m\ddot{x} = -L' \cdot \sin(\gamma) + D' \cdot \cos(\gamma)$$

$$m\ddot{z} = L' \cdot \cos(\gamma) - D' \cdot \sin(\gamma) - m \cdot g$$

Lissaman's non-dimensional variables

- ▶ Velocities with V^* the optimal glide speed
- ▶ Time with $T = \frac{V^*}{g}$
- ▶ Lift and drag coefficients $L = \frac{C_l}{C_l^*}$ and $D = \frac{C_d}{C_d^*}$
- ▶ Dynamic pressure $Q = \frac{L'}{MgL} = \frac{\frac{1}{2}\rho V^2 C_l C_l^*}{Mg}$



$$\frac{dU}{dT} = -LQ \cdot \sin(\gamma) + DQ \cdot \cos(\gamma)$$

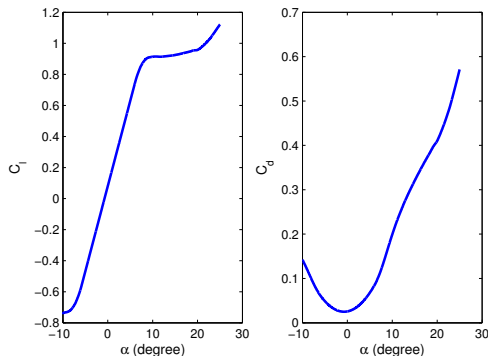
$$\frac{dW}{dT} = LQ \cdot \cos(\gamma) - DQ \cdot \sin(\gamma) - 1$$

¹Lissaman P. 43rd AIAA Aerospace Sciences Meeting and Exhibit, 241, 2005.

Quasi-steady lift and drag model

- ▶ NACA0009 characteristic

- ▶ Lissaman's quadratic drag



$$D = \frac{1+L^2}{2G^*}$$

Figure : Simplified lift and drag for the NACA0009 airfoil

Wind profiles

We define three different wind profiles:

- ▶ Vertical wind gust:

$$\begin{aligned}W_g &= W_a \cdot \sin(2\pi T) \\U_g &= 0\end{aligned}$$

- ▶ Horizontal wind gust:

$$\begin{aligned}W_g &= 0 \\U_g &= W_a \cdot \cos(2\pi T)\end{aligned}$$

- ▶ Combined wind gust:

$$\begin{aligned}W_g &= W_a \cdot \sin(2\pi T) \\U_g &= W_a \cdot \cos(2\pi T + \varphi)\end{aligned}$$

Optimization algorithm

The cycle is discretized

$$x = \begin{bmatrix} \dots \\ X_i \\ Z_i \\ U_i \\ W_i \\ L_i/\alpha_i \\ \dots \\ W_a \end{bmatrix} \quad i \in [1, N]$$

Constraints formulation

Comparison with Lissaman's results

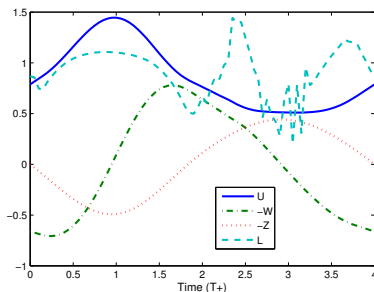


Figure : Optimization results for a $4T$ long vertical gust

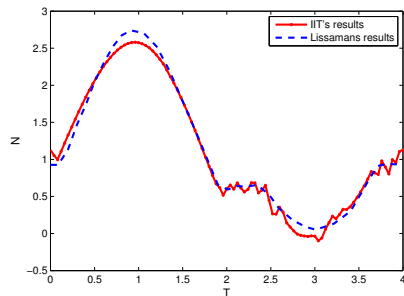


Figure : Comparison with Lissaman's non-dimensional normal force N for a $4T$ long vertical gust

Quasi-steady lift to drag model

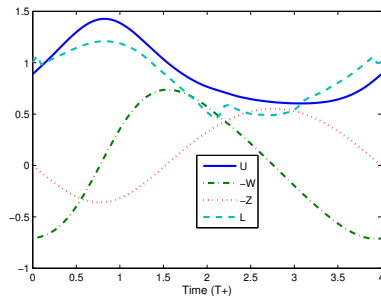


Figure : $4T$ long vertical gust for the NACA0009 airfoil, $W_a = 0.205$

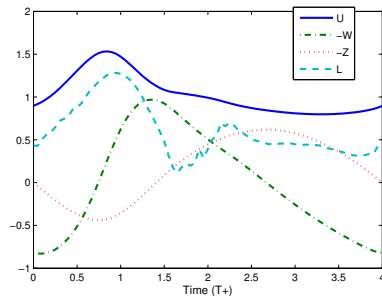


Figure : $4T$ long combined gust for the NACA0009 airfoil, $W_a = 0.387$

T_g dependency

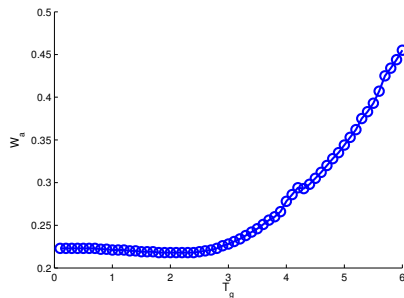


Figure : Influence of gust duration on the minimum gust amplitude for vertical gusts

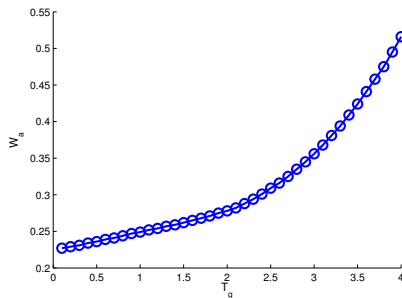


Figure : Influence of gust duration on the minimum gust amplitude for combined gusts

Difference between short and long gusts

We can see that there is tipping point around $T_g = 2.5$

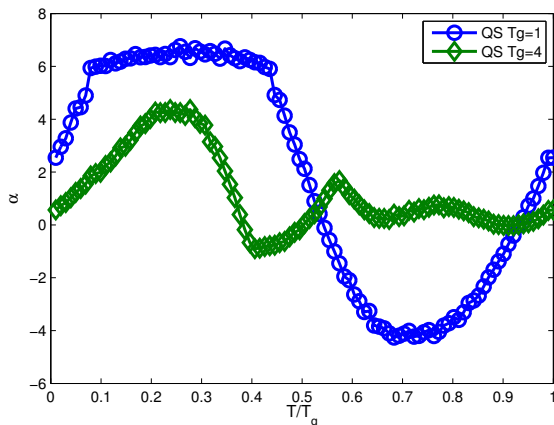


Figure : Difference between short and long gust angle of attack profile for combined gusts

Angle of attack limitation

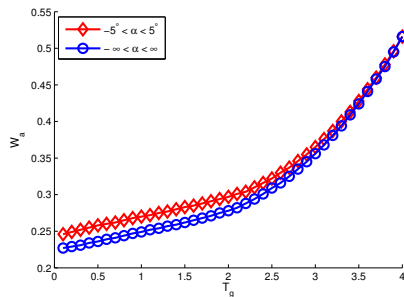


Figure : Difference in performance for combined wind gusts if no high angle of attack are allowed

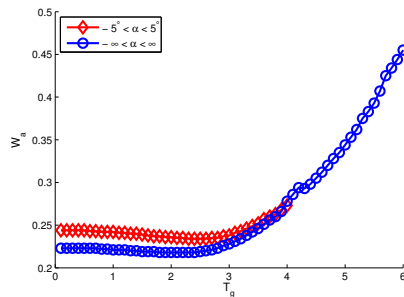


Figure : Difference in performance for vertical wind gusts if no high angle of attack are allowed

Phase influence

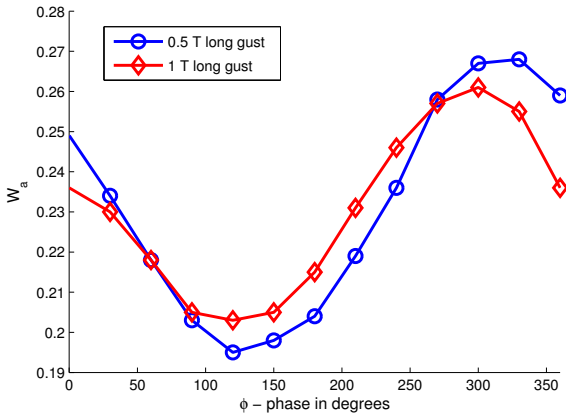


Figure : Influence of the phase between the components of the combined gust

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Pitching mechanism and experimental conditions

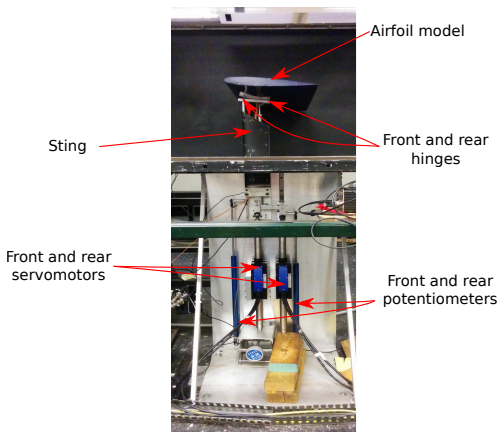


Figure : Airfoil model inside the wind tunnel

Experimental conditions

- ▶ Free stream velocity: 3 m/s
- ▶ Airfoil: NACA0009
- ▶ Reynolds number 50000

Controller and data acquisition

- ▶ Angle of attack controlled by simulink[®] and two servomotors
- ▶ Servos position measured by two linear potentiometers
- ▶ Piezoelectric force balance (NANO17) to measure the forces on the airfoil

The GK model concept

The Goman and Khrabrov model² - a non-linear state space model

$$C_l = f(\alpha, x(\alpha))$$

$$C_d = g(\alpha, x(\alpha))$$

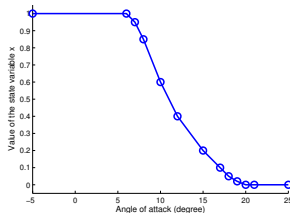
$$\tau_1 \frac{dx}{dt} + x = x_0(\alpha - \tau_2 \dot{\alpha})$$

► Lift and drag model

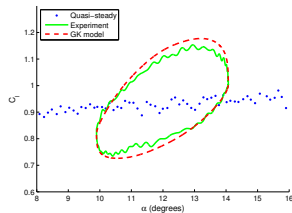
$$C_l = 2\pi\alpha(0.6x + 0.4) + C_{l0}$$

$$C_d = \frac{((2-x)C_l)^2}{G_{\max}} + C_{d0}$$

► Non-linear state map



► Time constants τ_1 and τ_2



²Goman M and Khrabrov A. *Journal of Aircraft*, 31(5):1109-1115, 1994.

Quasi-steady map and state variable

$$C_l(\alpha, x) = 2\pi \cdot \alpha(0.6x + 0.4) + C_{l0}$$

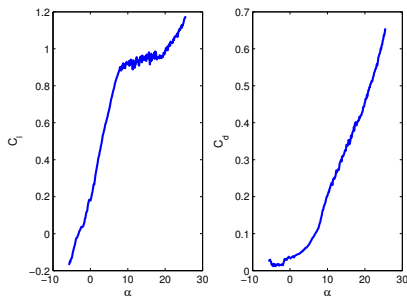


Figure : Lift and drag coefficient in the quasi-steady case

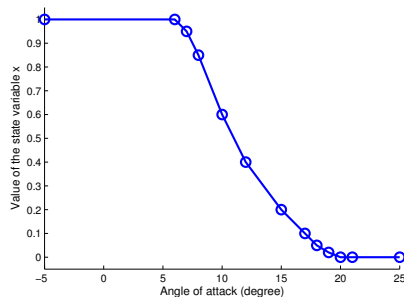


Figure : Quasi-steady profile for the state variable x

Time constant determination

Comparison with periodic measurements

Pseudo-random case

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Froude number equivalence

Global results

$T_g=0.5$

$T_g=0.1$

put W_a vs T_g curve and α t_g to explain on the same slide?

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