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

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Introduction and motivations

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Different types of soaring

Figure : something about soaring

Spatial wind gradients

- Thermal updrafts
- Horizontal wind gradients

Temporal wind gradients

- Natural turbulences
- Building and natural feature wake

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 model

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

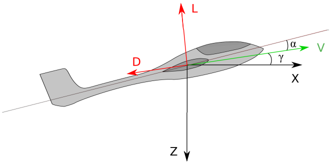

Figure : Coordinate system used for the optimization

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 $Q = \frac{L'}{MgL} = \frac{\frac{1}{2}\rho V^2 C_l C_l^*}{Mg}$

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

Quasi-steady lift and drag model

- NACA0009 characteristic

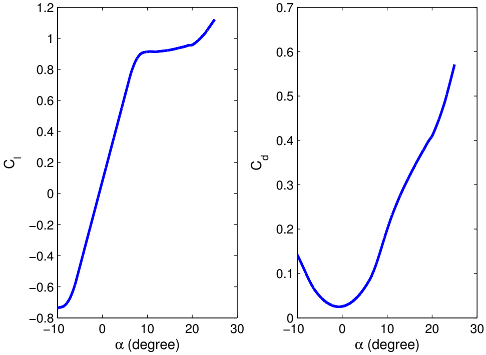

Figure : Simplified lift and drag for the NACA0009 airfoil

- Lissaman's quadratic drag

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

Wind profiles

We define three different wind profiles:

- Vertical wind gust:

$$W_g = W_a \cdot \sin(2\pi T)$$
$$U_g = 0$$

- Horizontal wind gust:

$$W_g = 0$$
$$U_g = W_a \cdot \cos(2\pi T)$$

- Combined wind gust:

$$W_g = W_a \cdot \sin(2\pi T)$$
$$U_g = W_a \cdot \cos(2\pi T + \varphi)$$

Optimization algorithm

The cycle is discretized

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

Constraints formulation

Comparison with Lissaman's results

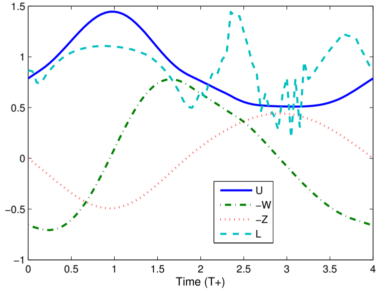

Figure : Optimization results for a $4T$ long vertical gust

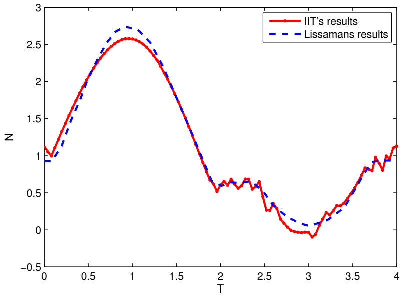

Figure : Comparison with Lissaman's non-dimensional normal force N for a $4T$ long vertical gust

Quasi-steady lift to drag model

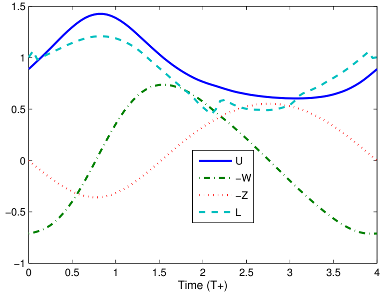

Figure : $4T$ long vertical gust for the NACA0009 airfoil, $W_a = 0.205$

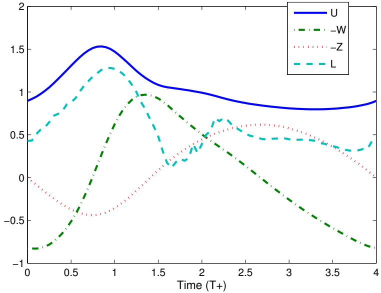

Figure : $4T$ long combined gust for the NACA0009 airfoil, $W_a = 0.387$

Tg dependency

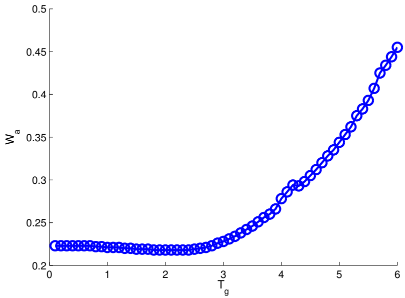

Figure : Influence of gust duration on the minimum gust amplitude for vertical gusts

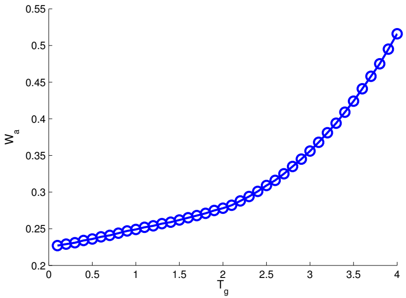

Figure : Influence of gust duration on the minimum gust amplitude for combined gusts

Difference between short and long gusts

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

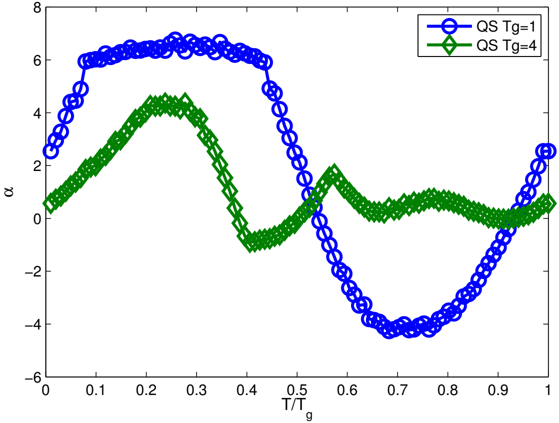

Figure : Difference between short and long gust angle of attack profile for combined gusts

Angle of attack limitation

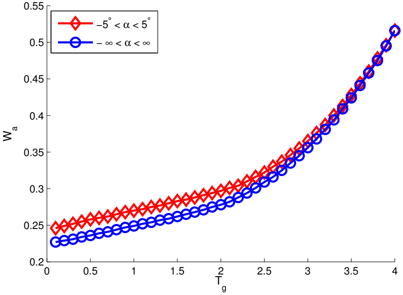

Figure : Difference in performance for combined wind gusts if no high angle of attack are allowed

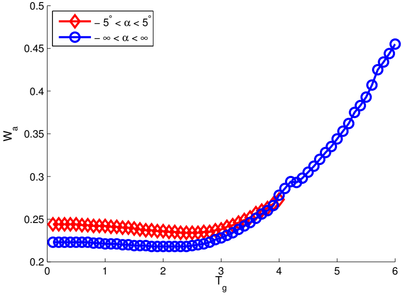

Figure : Difference in performance for vertical wind gusts if no high angle of attack are allowed

Phase influence

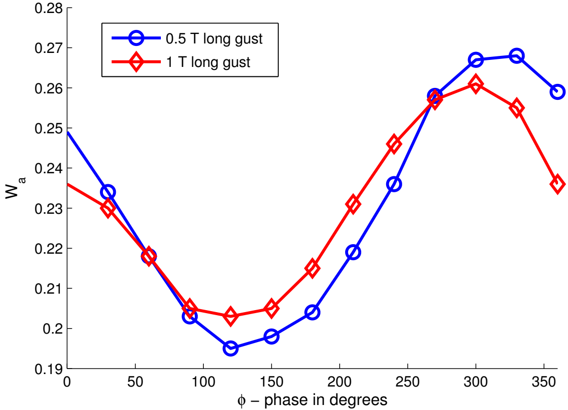

Figure : Influence of the phase between the components of the combined gust

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Pitching mechanism and experimental conditions

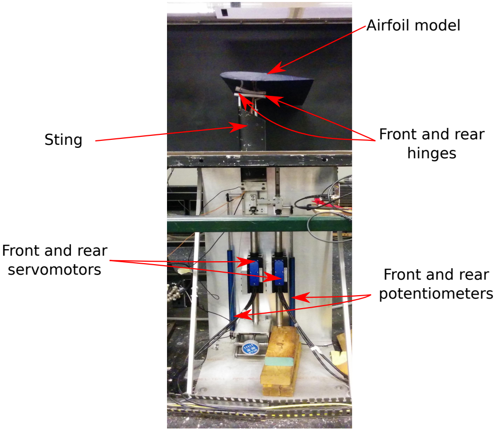


Figure : Airfoil model inside the wind tunnel

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

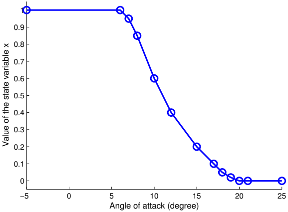
The Goman and Khrabrov model[1] - a non-linear state space model

$$C_l = f(\alpha, x(\alpha))$$
$$C_d = g(\alpha, x(\alpha))$$
$$\tau_1 \frac{dx}{dt} + x = x_0(\alpha - \tau_2 \dot{\alpha})$$

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

[1] Goman M and Khrabrov A. *Journal of Aircraft*, 31(5):11091115,1994.

Quasi-steady map and state variable

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

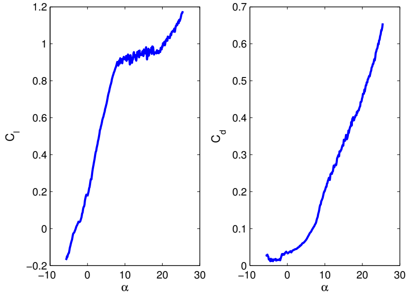


Figure : Lift and drag coefficient in the quasi-steady case

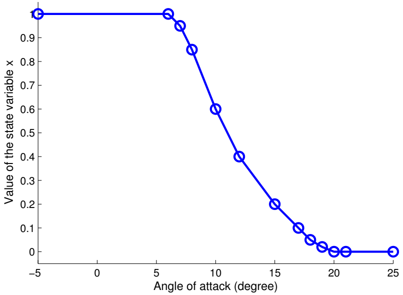


Figure : Quasi-steady profile for the state variable x

Time constant determination

Comparison with periodic measurements

Pseudo-random case

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Froude number equivalence

Global results

Tg=0.5

Tg=0.1

put Wa vs Tg curve and alpha tg to explain on the same slide?

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