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

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Introduction and motivations

- The goal is to find optimal energy extraction strategies in unsteady flows.
  - UAV energy saving
  - Vertical axis wind turbine
  - Helicopter rotor blade
- How do vehicle dynamics relate to unsteady aerodynamic effects?
- When do these unsteady effects start to become significant?

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Different types of soaring[1]

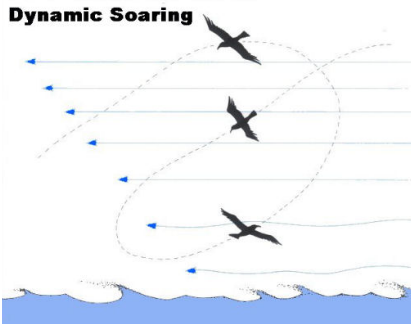


Figure : Dynamic soaring maneuver

Spatial wind gradients

- Thermal updrafts
- Horizontal wind gradients

Temporal wind gradients

- Natural turbulences
- Building and natural feature wake

[1] Rayleigh, *The soaring of birds*, Nature, 1883

Defining the energy extraction problem

What is an “optimal trajectory”?

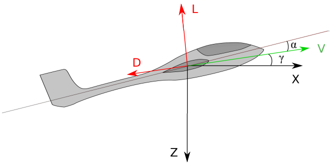
- Maximum energy at the end of the cycle
- Maximizing the energy gain at each instant of the cycle
- *Minimize the energy input needed for sustainable flight*

The neutral energy loop

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

Aircraft model[2]

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



Lissaman's non-dimensional variables

- Velocities with V^* the optimal glide speed
- Time with $T_c = \frac{V^*}{g}$
- Lift and drag coefficients $L = \frac{C_l}{C_l^*}$ $D = \frac{C_d}{C_l^*}$
- Dynamic pressure $Q = \frac{L'}{MgL} = \frac{\rho S V^2 C_l^*}{2Mg}$
  $Q = (U - U_g)^2 + (W - W_g)^2$

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

[2] Lissaman P and Patel C. Neutral energy cycles for a vehicle in sinusoidal and turbulent vertical gusts. 45th AIAA meeting,863, 2007

Quasi-steady lift and drag model

- NACA0009 characteristic

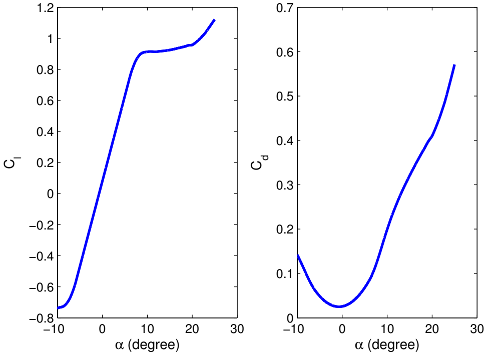


Figure : Simplified lift and drag for the NACA0009 airfoil

- Lissaman's quadratic drag

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

Wind profiles

We define three different wind profiles:

- Vertical wind gust:

$$W_g = W_a \cdot \sin(2\pi \frac{T}{T_g})$$
$$U_g = 0$$

- Horizontal wind gust:

$$W_g = 0$$
$$U_g = W_a \cdot \cos(2\pi \frac{T}{T_g})$$

- Combined wind gust:

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

With $T = \frac{t}{T_c}$.

Optimization algorithm - a minimization problem

- State vector

$$T_i = \frac{i}{N} T_g \quad x = \begin{bmatrix} \cdots \\ X_i \\ Z_i \\ U_i \\ W_i \\ L_i/\alpha_i \\ \cdots \\ W_a \end{bmatrix} \quad i \in [0, N]$$

- Cost function: W_a
- Constraints: equations of motion, limits on the range of angles of attack allowed, neutral energy loop conditions.

Constraints formulation

- Equations of motion (with Simpson's discreet integral)

$$y_i = \begin{bmatrix} X_i \\ Z_i \\ U_i \\ W_i \end{bmatrix} \quad \dot{y_i} = \begin{bmatrix} U_i \\ W_i \\ -L_iQ_i \cdot sin(\gamma_i) + D_iQ_i \cdot cos(\gamma_i) \\ L_iQ_i \cdot cos(\gamma_i) - D_iQ_i \cdot sin(\gamma_i) - 1 \end{bmatrix}$$

$$0 = y_{i+1} - y_i - \frac{1}{6}(\dot{y_i} + 4\dot{y_m} + \dot{y_{i+1}})\delta t \quad \forall i \in [0, N-1]$$

- Neutral energy loop

$$\begin{aligned} Z_1 &= Z_N & L_1 &= L_N \\ W_1 &= W_N & U_1 &= U_N \end{aligned}$$

$$\begin{aligned} W_2 - W_1 &= W_N - W_{N-1} \\ U_2 - U_1 &= U_N - U_{N-1} \end{aligned}$$

- Limits in range of C_l

$$\begin{aligned} L_{\min} \leq L_i \leq L_{\max} \\ \alpha_{\max} \leq \alpha_i \leq \alpha_{\max} \end{aligned}$$

Comparison with Lissaman's results - Quadratic model

Lissaman found a gust amplitude $W_a = 0.128$ for this case

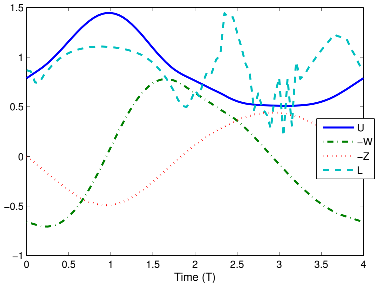


Figure : Optimization results for a $4T_c$ long vertical gust $W_a = 0.129$

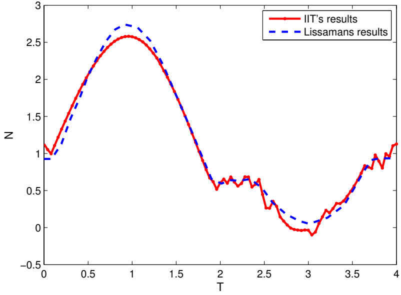


Figure : Comparison with Lissaman's non-dimensional normal force N for a $4T_c$ long vertical gust

Quasi-steady lift to drag model - NACA009

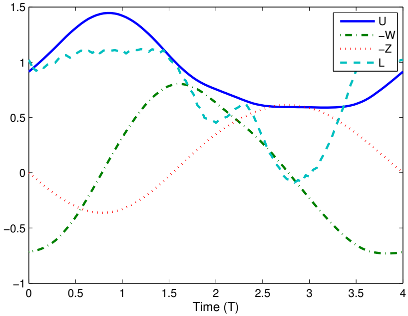


Figure : $4T_c$ long vertical gust for the NACA0009 airfoil, $W_a = 0.273$

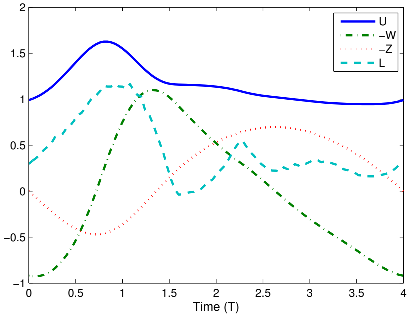


Figure : $4T_c$ long combined gust for the NACA0009 airfoil, $W_a = 0.516$

Gust duration (Tg) dependency

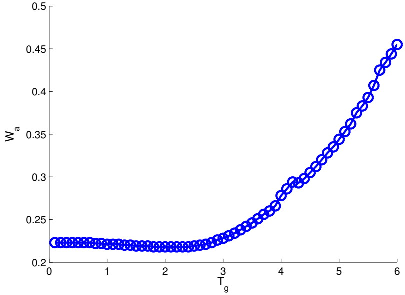


Figure : Influence of gust duration on the minimum gust amplitude for vertical gusts

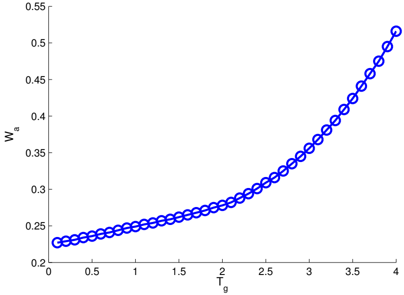


Figure : Influence of gust duration on the minimum gust amplitude for combined gusts

Difference between short and long gusts

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

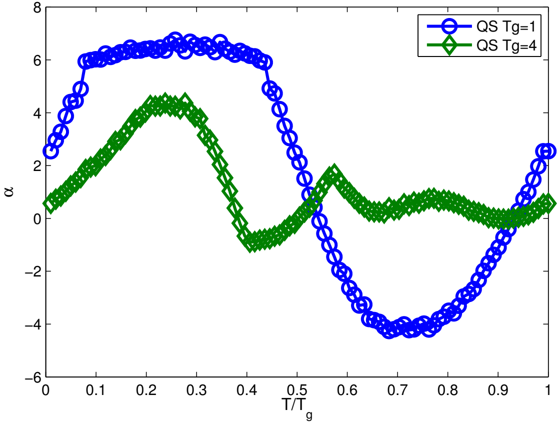


Figure : Difference between short and long gust angle of attack profile for combined gusts

Angle of attack limitation

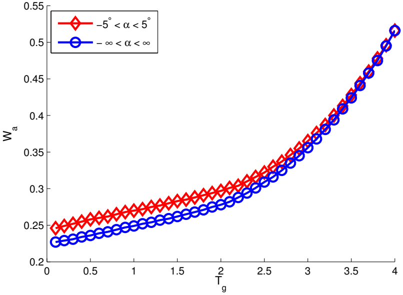


Figure : Difference in performance for combined wind gusts if no high angle of attack are allowed

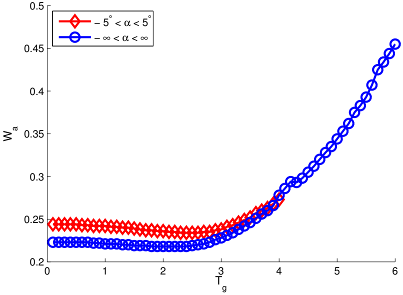


Figure : Difference in performance for vertical wind gusts if no high angle of attack are allowed

Phase influence

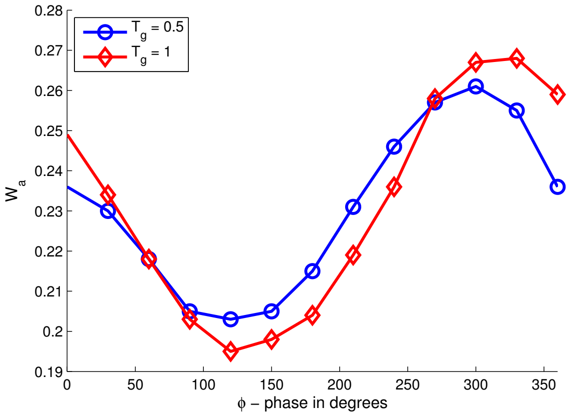


Figure : Influence of the phase between the components of the combined gust

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Pitching mechanism and experimental conditions

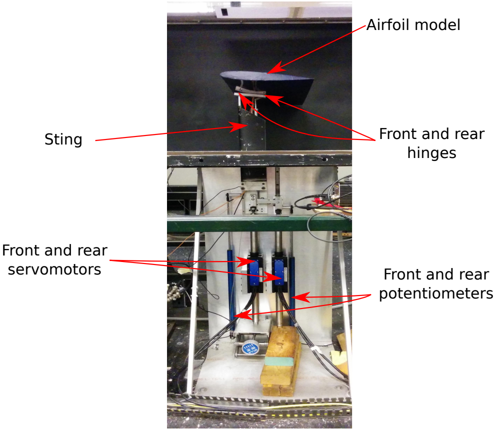


Figure : Airfoil model inside the wind tunnel

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

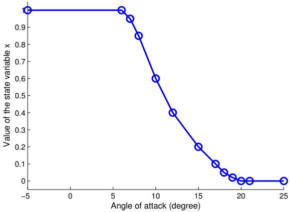
The GK model concept

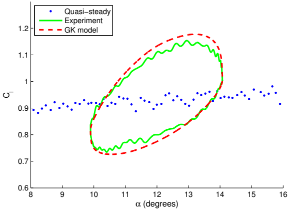
The Goman and Khrabrov model[3]

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

- **Lift and drag model**
- **Non-linear state map**
- **Time constants τ_1 and τ_2**

$$C_l = 2\pi\alpha(0.6x + 0.4) + C_{l0}$$
$$C_d = \frac{((2-x)C_l)^2}{G_{\max}} + C_{d0}$$





[3] Goman M and Khrabrov A. *Journal of Aircraft*, 31(5):1109 âĂŞ 1115,1994. - a non-linear state space model

Quasi-steady map and state variable

$$C_l = 2\pi\alpha(0.6x + 0.4) + C_{l0}$$
$$C_d = \frac{((2-x)C_l)^2}{G_{\max}} + C_{d0}$$

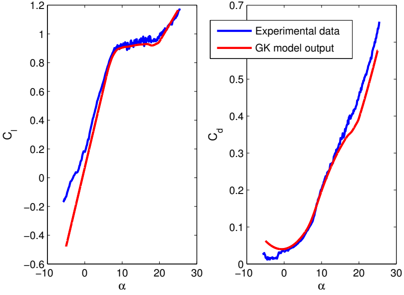


Figure : Lift and drag coefficient in the quasi-steady case

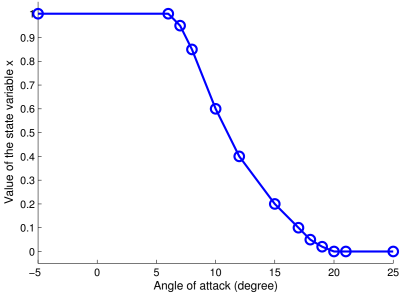


Figure : Quasi-steady profile for the state variable x

Time constant determination

Periodic sinusoidal pitching at different frequencies $k = \pi \frac{cf}{u}$

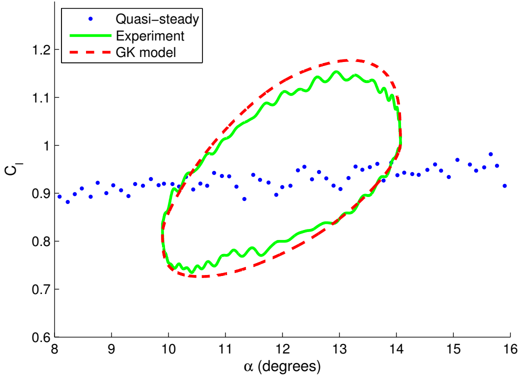


Figure : Comparison of experimental lift coefficient and model prediction after tunning of the time constant at $k = 0.128$

We find $\tau_1 = \mathbf{3.1t}^+$ and $\tau_2 = \mathbf{4.29t}^+$ (with $t^+ = \frac{c}{u}$)

Comparison with periodic measurements - Lift

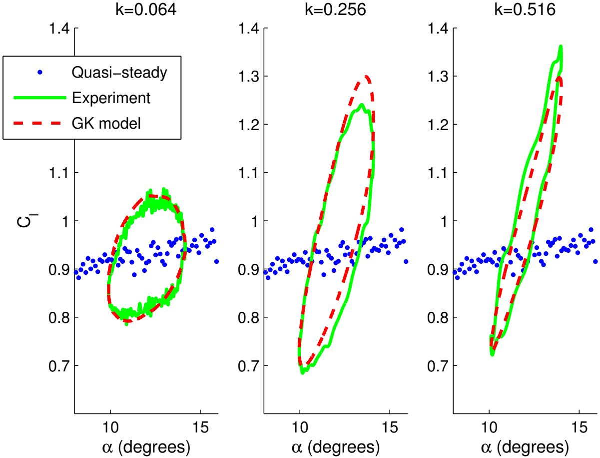


Figure : Lift measurement and prediction during sinusoidal pitching around 12 degree

Comparison with periodic measurements - Drag

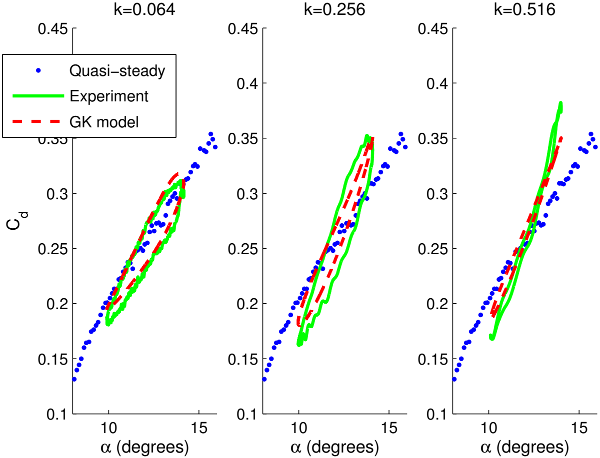


Figure : drag measurement and prediction during sinusoidal pitching around 12 degree

Pseudo-random case - Lift

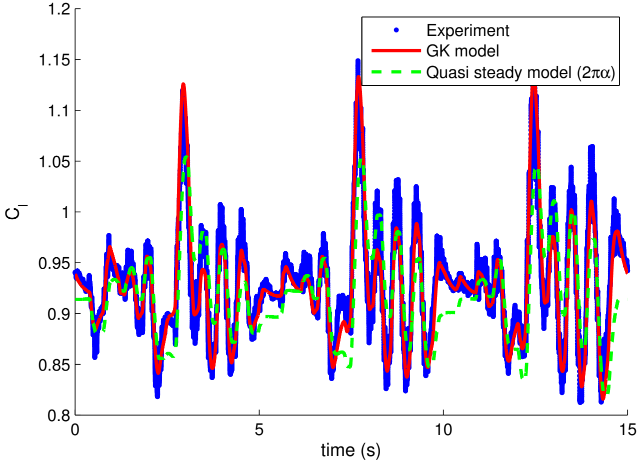


Figure : Unsteady effects of random pitching on the lift

Pseudo-random case - Drag

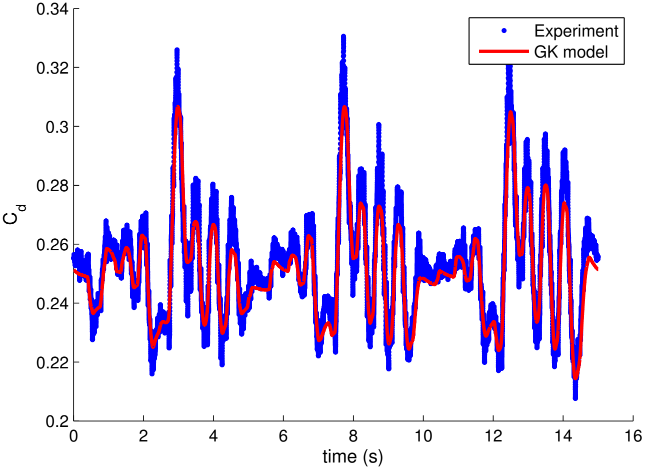


Figure : Unsteady effects of random pitching on the drag

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Froude number equivalence

Gliding vehicle time scale

$$T_c = \frac{V^*}{g}$$

Airfoil time scale

$$t^+ = \frac{c}{u}$$

For a vehicle flying at V^*

$$Fr = \frac{T_c}{t+} = \frac{V^{*2}}{g \cdot c}$$

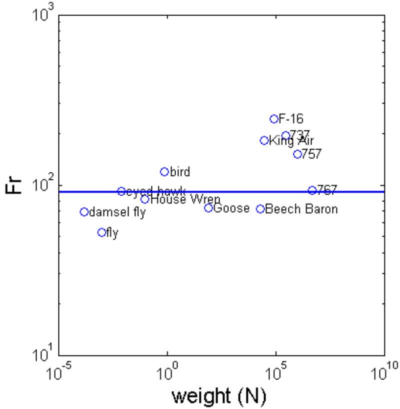

Figure : T_c to $t+$ ratio for various flying objects

Difference with the quasi-steady model optimization

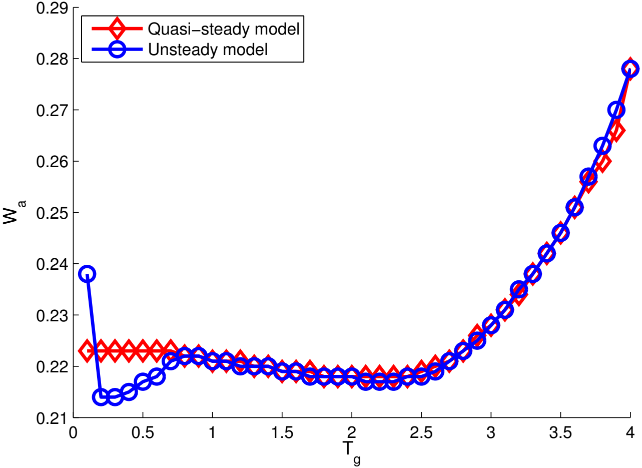

Figure : Performance difference between quasi-steady and unsteady model for vertical gusts

Difference with the quasi-steady model optimization

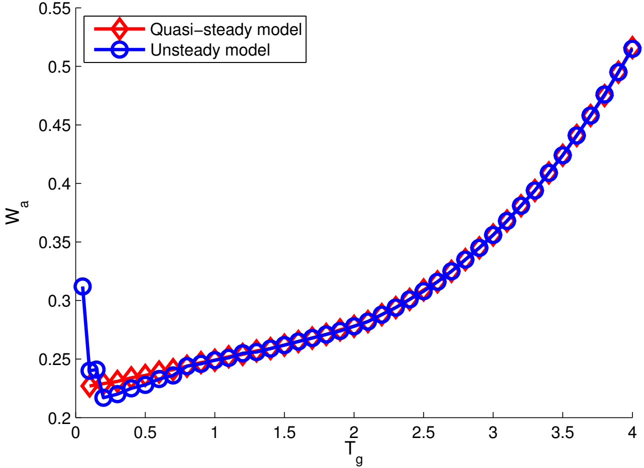

Figure : Performance difference between quasi-steady and unsteady model for combined gusts

A closer look at $T_g \in [0.2, 0.5]$ ($k \in [0.05, 0.175]$)

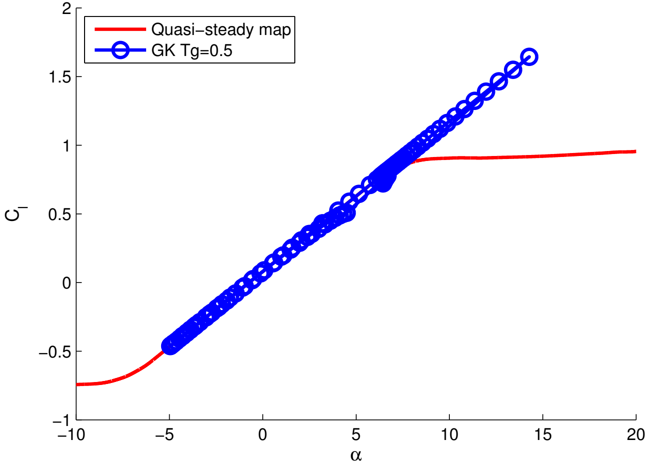

Figure : Lift coefficient versus angle of attack for $0.5T_c$ long vertical wind gusts with the unsteady model

A closer look at good performing short gusts

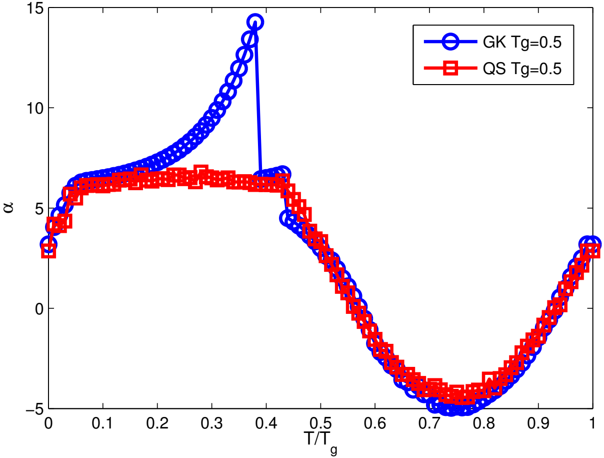

Figure : Angle of attack for short vertical gusts with the quasi-steady (QS) and unsteady (GK) model

Difference around $T_g \leq 0.2$ ($k \geq 0.175$)

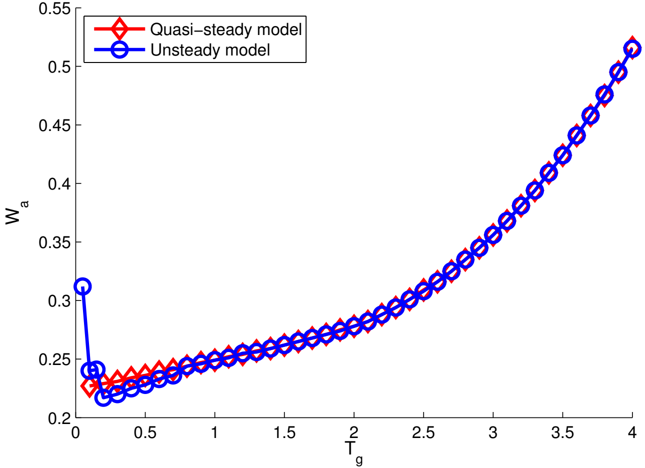

Figure : Performance difference between quasi-steady and unsteady model for combined gusts

Difference around $T_g \leq 0.2$

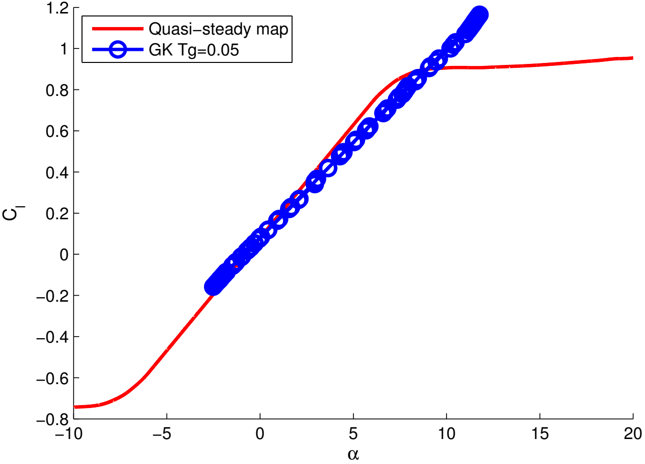

Figure : Lift coefficient versus angle of attack for a $0.05T_c$ long combined gust

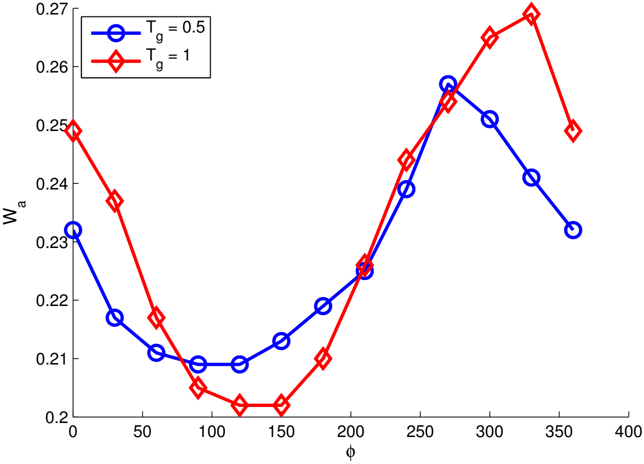

Figure : Influence of the phase between the components of the combined gust in the unsteady model case

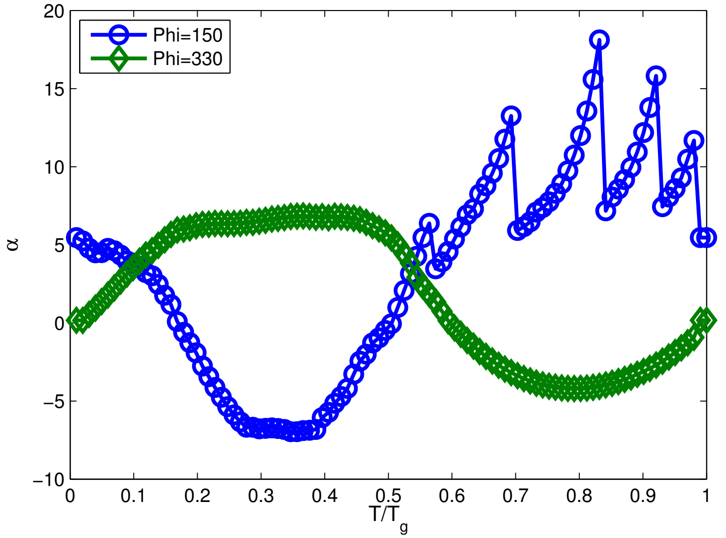

Figure : Angle of attack profile for different phase angle when $T_g = 1$

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GK model predictions:

- Accurate prediction of lift and *drag* for arbitrary pitch motion
- The drag coefficient shares the same state variable as the lift
- The model is fast enough to be used for optimization algorithms

Trajectory optimization

- Neutral energy flight is possible through combinations of vertical and horizontal gusts
- Vehicle and airfoil time scale are related through the Froude number
- Unsteady aerodynamic effects are seen for gusts shorter than $0.7T$
- The unsteady effects are beneficial for $T_g \in [0.2, 0.7]$ as they let the airfoil achieve higher C_l values
- The unsteady effects are detrimental for T_g smaller than 0.2, where the "angle of attack lag" becomes significant

Possible improvements

GK model prediction:

- Extending the GK model to a plunging and surging flow
- Devise a more rigorous way to obtain the time constants
- Implement a model for the moment coefficient
- Link the state variable and the flow configuration

Trajectory optimization

- Further investigations should be performed for very short gusts
- The effects of surging and plunging are not considered
- Introduce a 3rd degree of freedom to account for the moment of inertia