Simplified Model for Forward-Flight Transitions of a Bio-Inspired Unmanned Aerial Vehicle

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Robotics
Vision
Control

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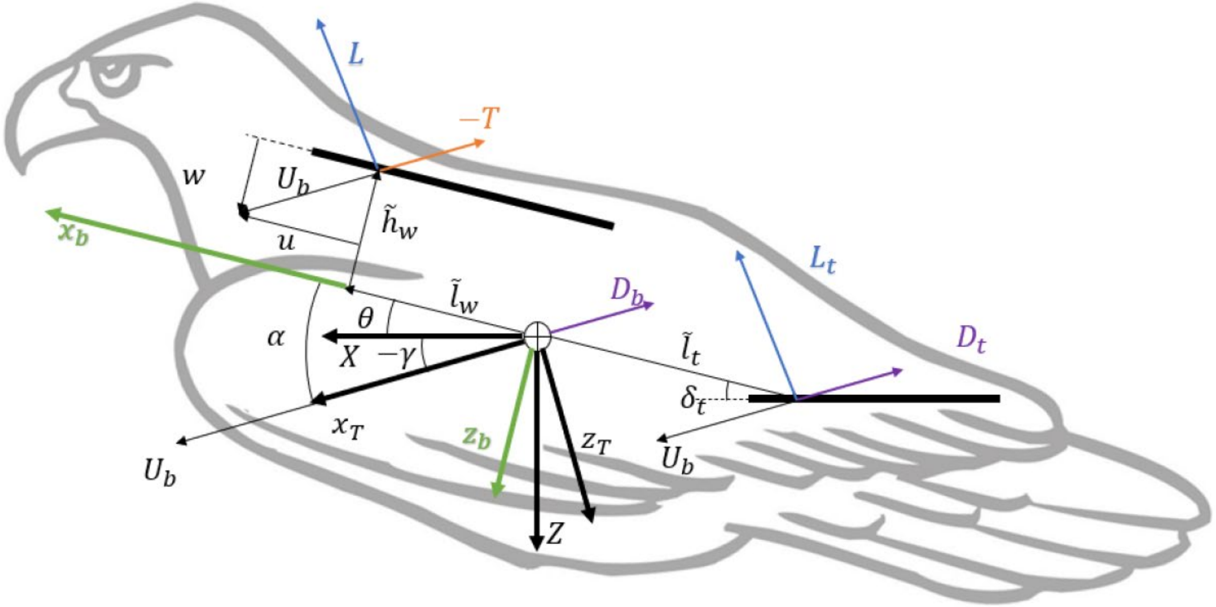
Characteristics

- Longitudinal flight model
- Forces from linear potential theory
- Small angle of attack and amplitude
- Rigid body equations
- Two control variables: tail + flapping
- Formulation in the trajectory frame (Newton-Euler equations)



Simplification: Non-dimensional parameters

- Velocity – Deflection of the tail
- Length – Half chord
- Time – Flapping frequency
- Reduced frequency – characteristic velocity
- Non-dimensional mass and inertia
- Modified force coefficients – order of magnitude of α, h_0, θ

$$U_c = \sqrt{\frac{mg}{\pi\rho S\delta_t}}, \quad L_c = \frac{c}{2}, \quad t_c = \frac{1}{\omega},$$

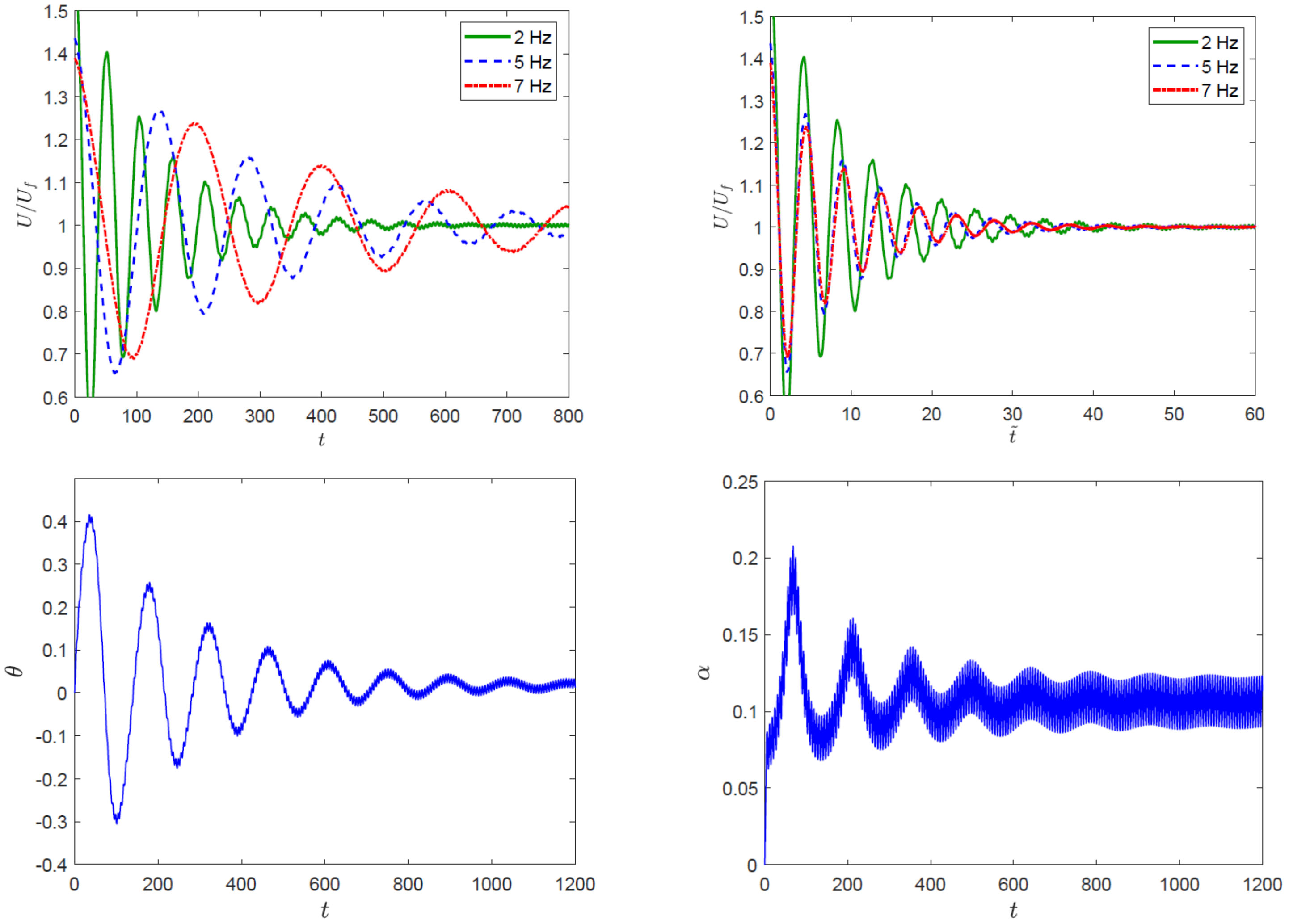
$$\mathcal{M} = \frac{2m}{\pi\rho Sc}, \quad \chi = \frac{\pi\rho S\left(\frac{c}{2}\right)^3}{2I_y}, \quad k_0 = \frac{\omega c}{2U_c},$$

$$C_L^* = \frac{L}{\pi\rho U_b^2 c}, \quad C_T^* = \frac{T}{\pi\rho U_b^2 c}, \quad C_D^* = \frac{D}{\pi\rho U_b^2 c}$$

Numerical simulations

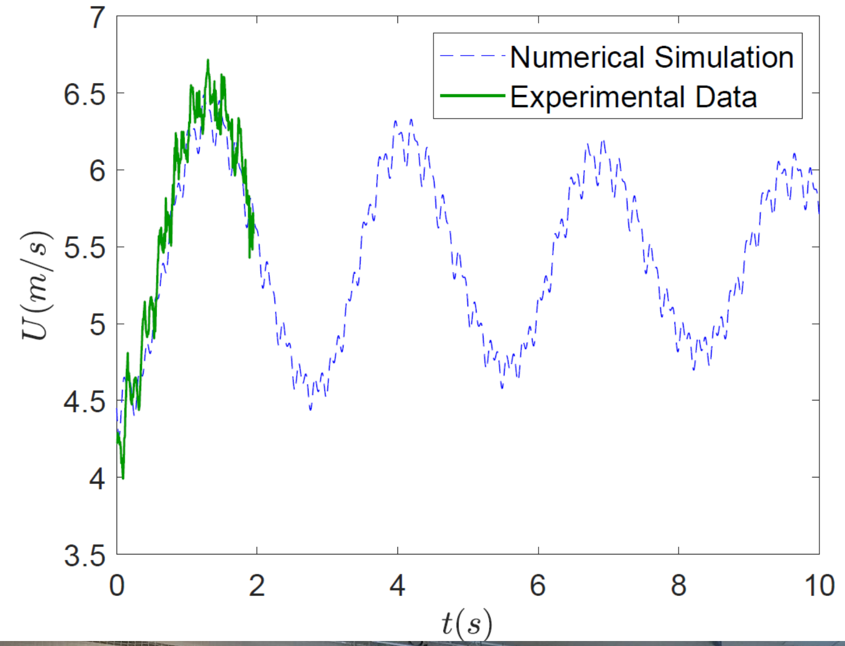
Simulations computationally expensive:

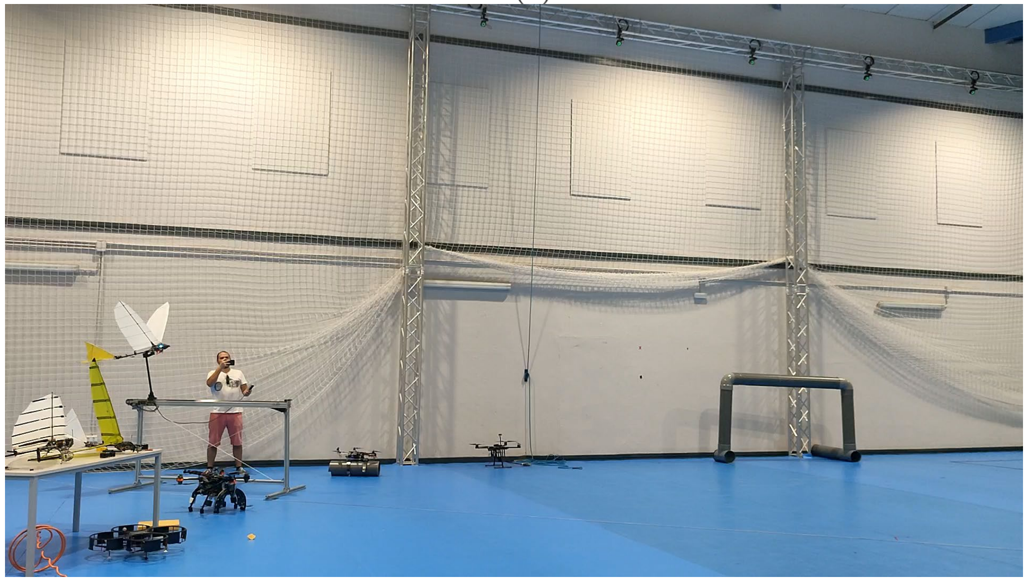
- Non-linear equations
- Dynamics-aerodynamics interaction
- Different timescales



Experimental Validation

- Optitrack flights
- Rigid wings (thicker ribs)
- Open loop control (fixed for small angle of attack)
- Data obtained directly from motive
- Short flight time





Scales analysis

- Small parameter: $h_0 \equiv \epsilon$
- Small flight angles: $\gamma \sim \theta \sim \alpha \sim \delta_t \sim \epsilon$
- Lift coefficients: $C_L^* \sim C_{Lt}^* \sim \epsilon$
- Thrust coefficient: $C_T^* \sim \epsilon^2$
- Drag coefficient: $C_D^* \sim C_{Dt}^* \sim Li^* \sim \epsilon^2$
- Mass parameters: $\mathcal{M}^2\chi \sim \mathcal{M}k_0 \sim 1$

- First timescale (flapping oscillations):
  t
- Second timescale (transient oscillations):
  $\tau_{c1} = \mathcal{M}k_0/\epsilon$
- Third timescale (transient damping)
  $\tau_{c2} = \mathcal{M}k_0/\epsilon^2$

Formulation

Perturbative expansion

$$U = U_0(t,\tau_1,\tau_2) + \epsilon U_1(t,\tau_1,\tau_2) + \epsilon^2 U_2(t,\tau_1,\tau_2) + \cdots$$

$$\theta = \epsilon(\theta_1(t,\tau_1,\tau_2) + \epsilon\theta_2(t,\tau_1,\tau_2) + \cdots)$$

$$\alpha = \epsilon(\alpha_1(t,\tau_1,\tau_2) + \epsilon\alpha_2(t,\tau_1,\tau_2) + \cdots)$$

$$\gamma = \epsilon[\theta_1(t,\tau_1,\tau_2) - \alpha_1(t,\tau_1,\tau_2)] + \epsilon^2[\theta_2(t,\tau_1,\tau_2) - \alpha_2(t,\tau_1,\tau_2)] + \cdots$$

Frequency expansion

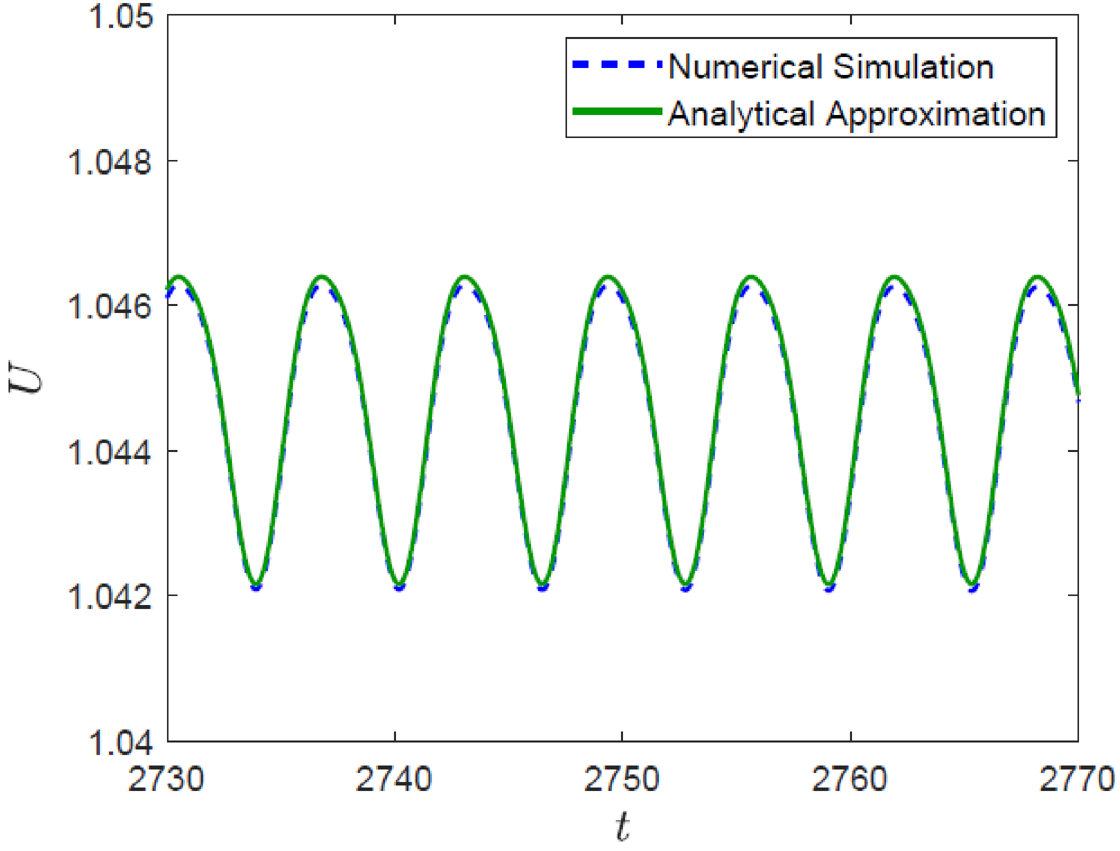
$$U_0 = V_0(\tau_1,\tau_2) + V_1(\tau_1,\tau_2)e^{it} + \cdots + V_n(\tau_1,\tau_2)e^{int}$$

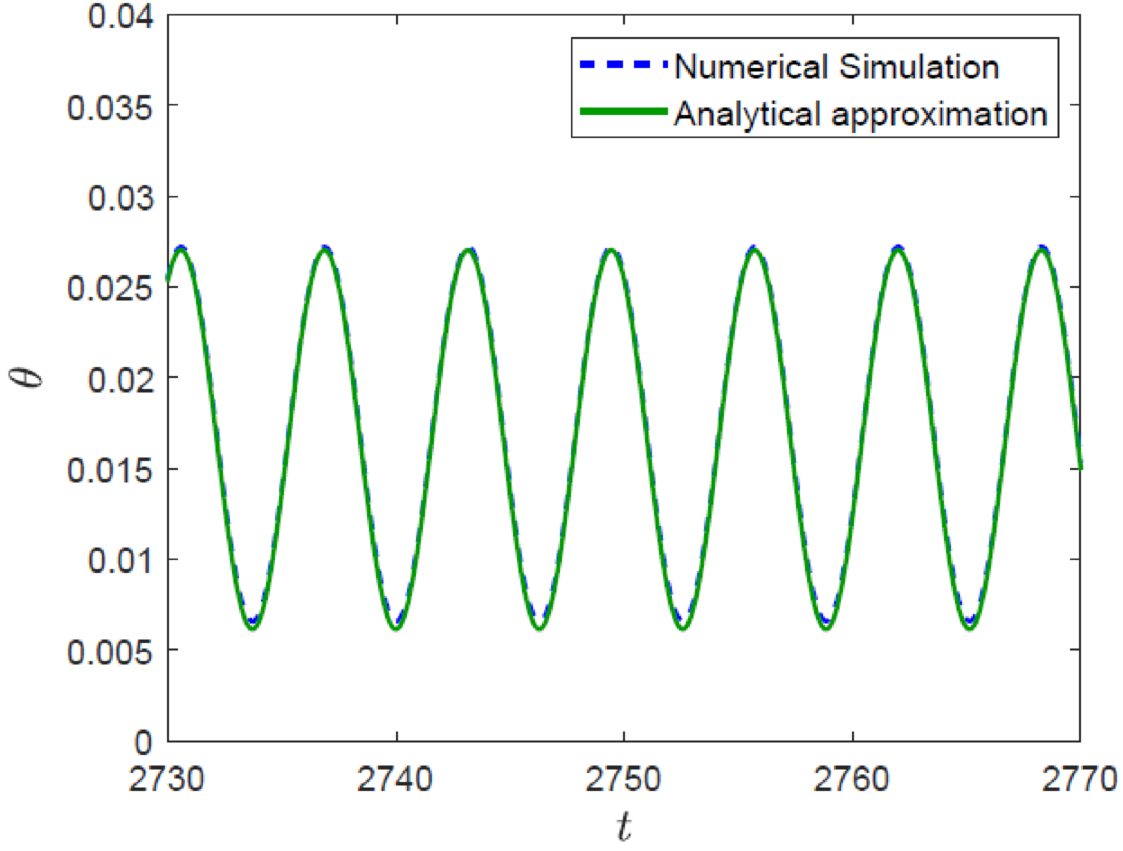
$$U_1 = V_{n+1}(\tau_1,\tau_2) + V_{n+2}(\tau_1,\tau_2)e^{it} + \cdots + V_{n+k+1}(\tau_1,\tau_2)e^{ikt}$$

Perturbation solution

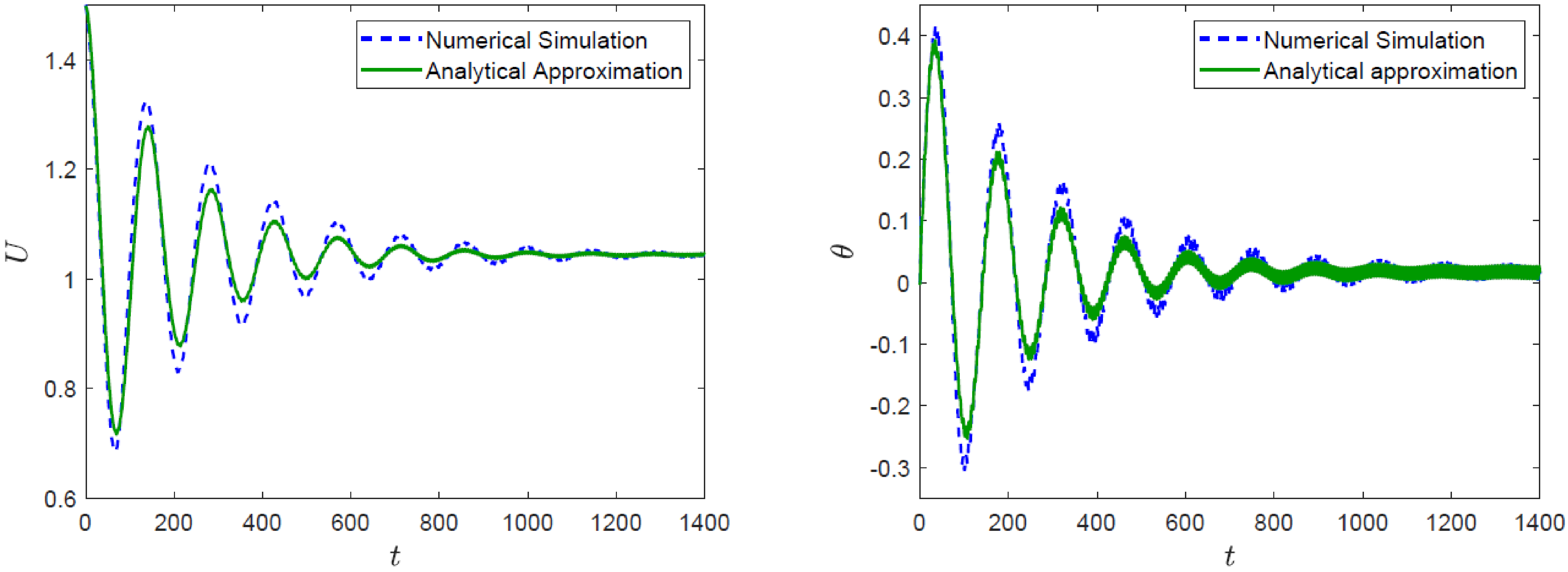
- First non-linear algebraical system
- Linear equations or system of equations
- Large-time asymptotic values: Terms up to order ϵ^2 for θ, and order ϵ^3 for U and α
- Transient terms: Terms up to order ϵ for U and θ, and order ϵ^2 for α
- Harmonic oscillations: Terms up to order ϵ^2 for the three variables

Results: permanent state

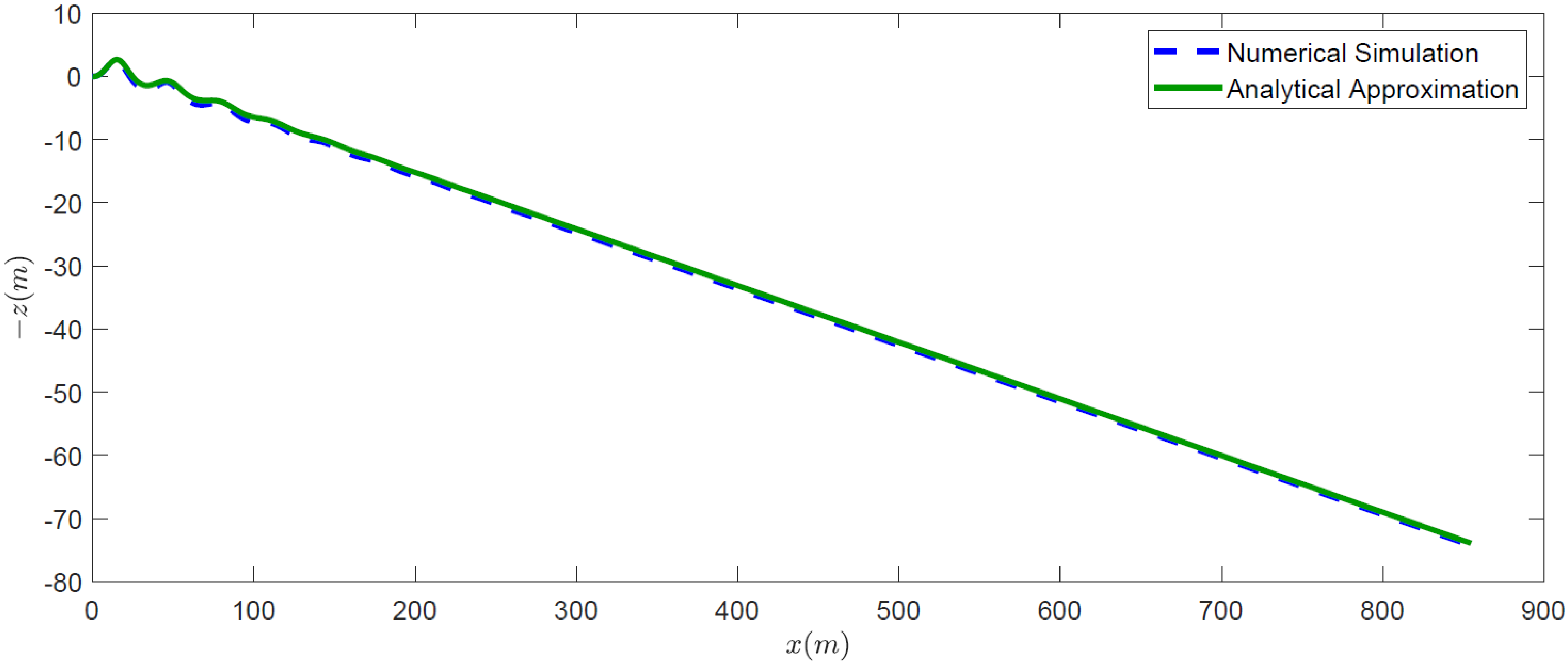




Results: transient phase



Results: trajectory



Conclusion

- Simplified model: reduced to linear equations
- First model with results from aerodynamic potential theory
- Analytical solution of the flapping permanent state
- Direct insight into the influence of control and design variables
- Model defined for cruise flight: no aggressive maneuvers
- Simplification can be generalized for pitching and flexible wings