

Trajectory Generation for Distributed Electric Propulsion Vehicles with Propeller Synchronization

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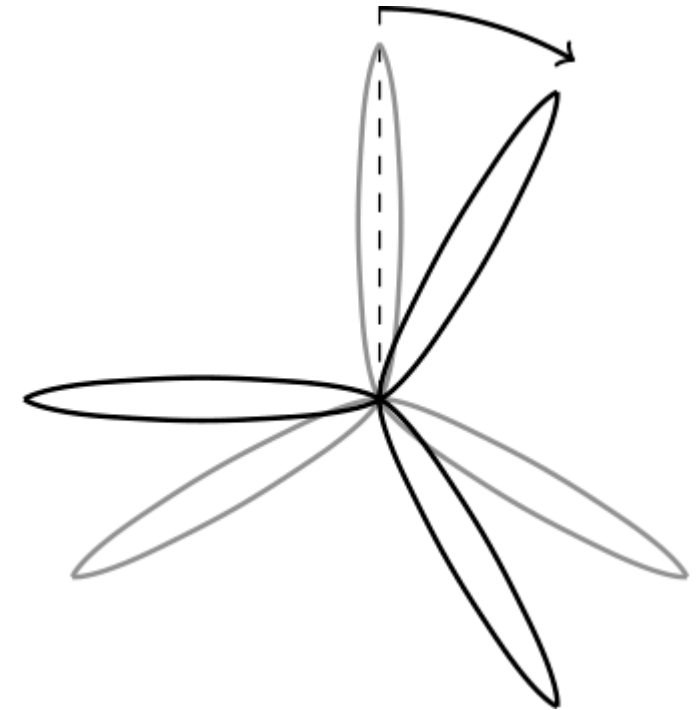
Background

Noise reduction is critical for urban communities to accept new urban air mobility operations.

Propeller phase synchronization can be used to reduce the tonal noise generated by propellers through destructive interference.

However, phase control cannot prevent normal vehicle operation.

Goal: Generate dynamically feasible trajectories for acoustically aware vehicles with phase control and demonstrate simultaneously meeting spatial and phase control constraints.

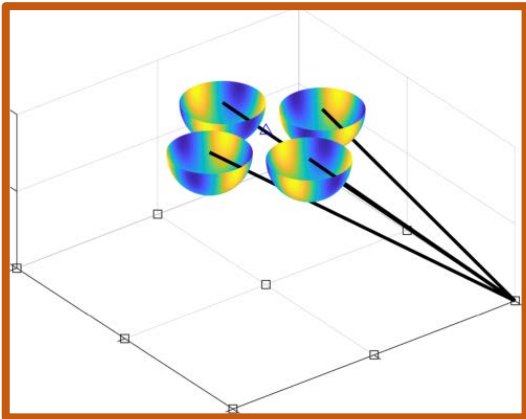


Propeller phase measured between azimuth of grey propeller and azimuth of black propeller.

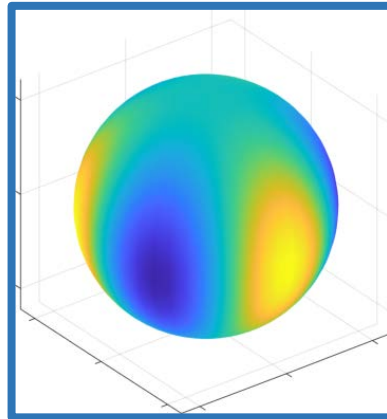
Acoustic Model

Three-part model for tonal acoustic pressure at k^{th} observer:

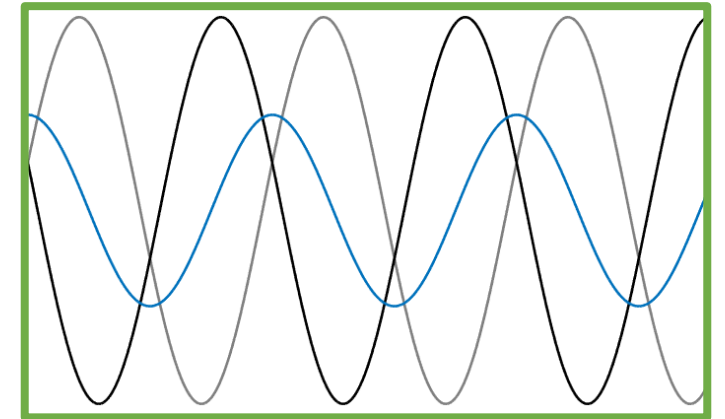
$$p_k(t) = \sum_{n=1}^N \beta_n(t) \mathcal{S}_n(\Theta, \omega_n, v_n, \alpha_n) \sin(\omega_n(t - \tau) + \theta_n)$$



Source noise addition and attenuation for four vertically oriented propellers.



Source noise sphere for a single propeller, at a single flight condition, and at a fixed time. Colors show the current pressure amplitudes in each direction.



Phase shifted sine waves representing the rotation of the propeller blades.

Vehicle Model

Spatial Position Dynamics

$$\dot{x} = \begin{bmatrix} V \cos \chi \cos \gamma \\ V \sin \chi \cos \gamma \\ V \sin \gamma \end{bmatrix}, \quad x(0) = x_0,$$

Acceleration and Orientation Dynamics

$$\dot{V} = \frac{1}{m} (F_{thrust} - F_{drag}) - g \sin \gamma,$$

$$\dot{\chi} = F_{lift} \frac{\sin \phi}{m V \cos \gamma},$$

$$\dot{\gamma} = \frac{F_{lift}}{m V} \cos \phi - \frac{g}{V} \cos \gamma,$$

$$V(0) = V_0,$$

$$\chi(0) = \chi_0,$$

$$\gamma(0) = \gamma_0,$$

Simplified vehicle dynamics for path planning applications.

Environmental noise highly dependent on vehicle position, orientation and speed.

Control Input $u = [T \quad C_L \quad \phi]^\top$

Vehicle Model

Aerodynamic Forces

$$F_{lift} = \frac{1}{2}\rho V^2 SC_L,$$

$$F_{drag} = \frac{1}{2}\rho V^2 SC_D,$$

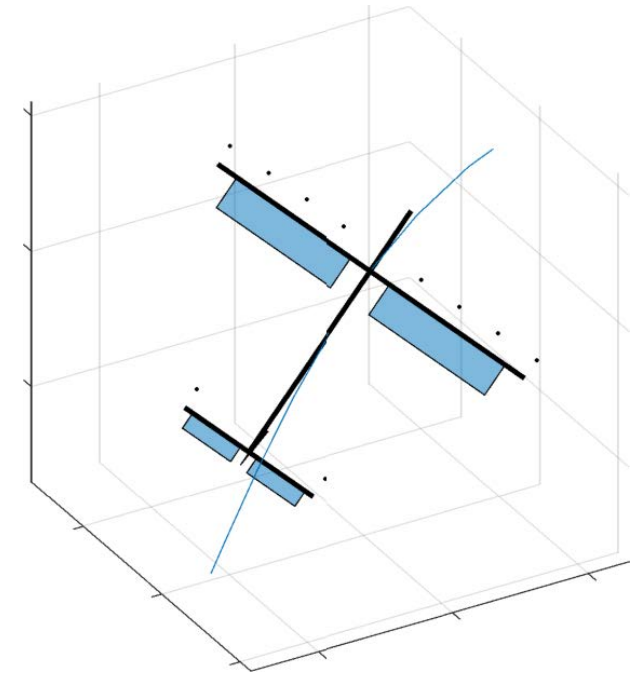
Propeller Forces

$$\dot{q}_n = A_n q_n + [0 \quad 0 \quad 1]^\top T_n, \quad q(0) = q_0,$$

$$F_{thrust} = \sum_{n=1}^N F_n(\omega_n)$$

Control Input

$$u = [T \quad C_L \quad \phi]^\top$$



Vehicle appearance. Blue patches are control surfaces; the black points are propeller locations.

Trajectory Generation

Spatial Position Dynamics

$$\dot{x} = \begin{bmatrix} V \cos \chi \cos \gamma \\ V \sin \chi \cos \gamma \\ V \sin \gamma \end{bmatrix}, \quad x(0) = x_0,$$



$$\begin{aligned} V &= \sqrt{\dot{x}_1^2 + \dot{x}_2^2 + \dot{x}_3^2}, \\ \gamma &= \arcsin(\dot{x}_3/V), \\ \chi &= \arcsin[\dot{x}_2/(V \cos \gamma)], \end{aligned}$$

Acceleration and Orientation Dynamics

$$\begin{aligned} \dot{V} &= \frac{1}{m} (F_{thrust} - F_{drag}) - g \sin \gamma, \\ \dot{\chi} &= F_{lift} \frac{\sin \phi}{mV \cos \gamma}, \\ \dot{\gamma} &= \frac{F_{lift}}{mV} \cos \phi - \frac{g}{V} \cos \gamma, \end{aligned}$$



$$\begin{aligned} \phi &= \arctan \frac{\dot{\chi} V \cos \gamma}{V \dot{\gamma} + g \cos \gamma}, \\ F_{lift} &= \frac{mg \cos \gamma + mV \dot{\gamma}}{\cos \phi}, \\ F_{thrust} &= F_{drag} + m\dot{V} + mg \sin \gamma \end{aligned}$$

Trajectory Generation

Aerodynamic Forces

$$F_{lift} = \frac{1}{2}\rho V^2 S C_L,$$
$$F_{drag} = \frac{1}{2}\rho V^2 S C_D,$$



$$C_L = \frac{2F_{lift}}{\rho S V^2},$$
$$C_D = C_{D0} + k_1 C_L^2,$$

Propeller Forces

$$\dot{q}_n = A_n q_n + [0 \quad 0 \quad 1]^T T_n,$$
$$F_{thrust} = \sum_{n=1}^N F_n(\omega_n)$$



Example Propeller Pair

$$\xi_1 = \theta_1 - \theta_2 \quad \text{Phase: difference in propeller positions}$$

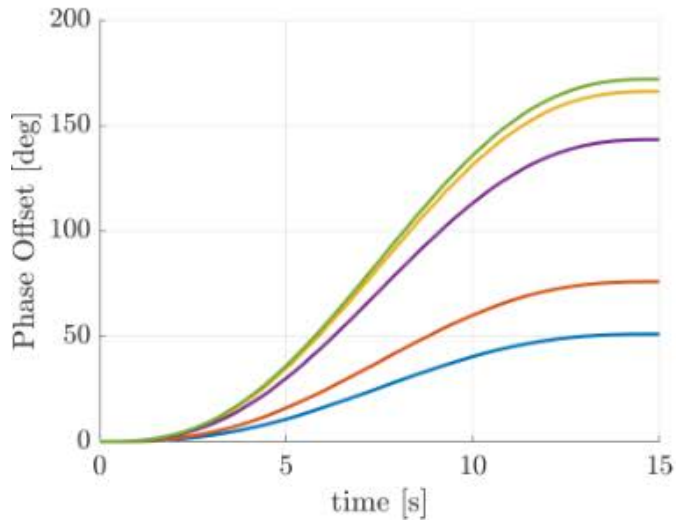
$$\omega_2 = \omega_1 - \dot{\xi}_1 \quad \text{Motor speed}$$

Calculate Speed from Thrust Allocation

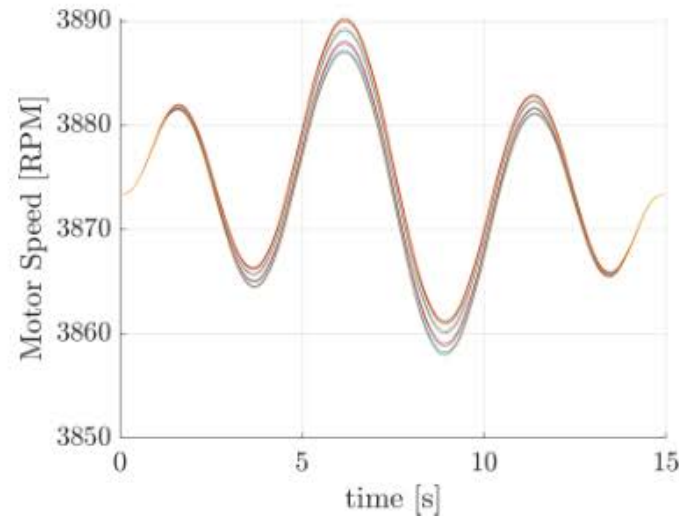
$$F_{thrust}/5 = F_1(\omega_1) + F_2(\omega_1 - \dot{\xi}_1) \quad \text{Quadratic Equation}$$

Results: Trajectories

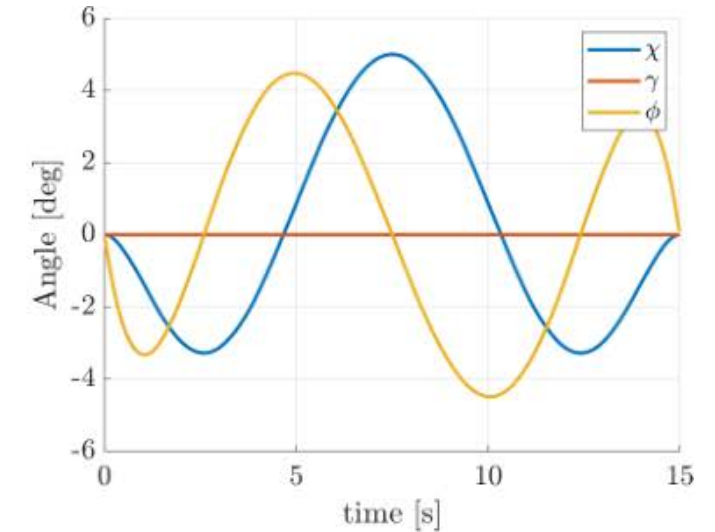
Scenario: Vehicle must follow fixed spatial trajectory, while adjusting propeller phase angles.



Propeller phase angles
between each pair of
propellers.

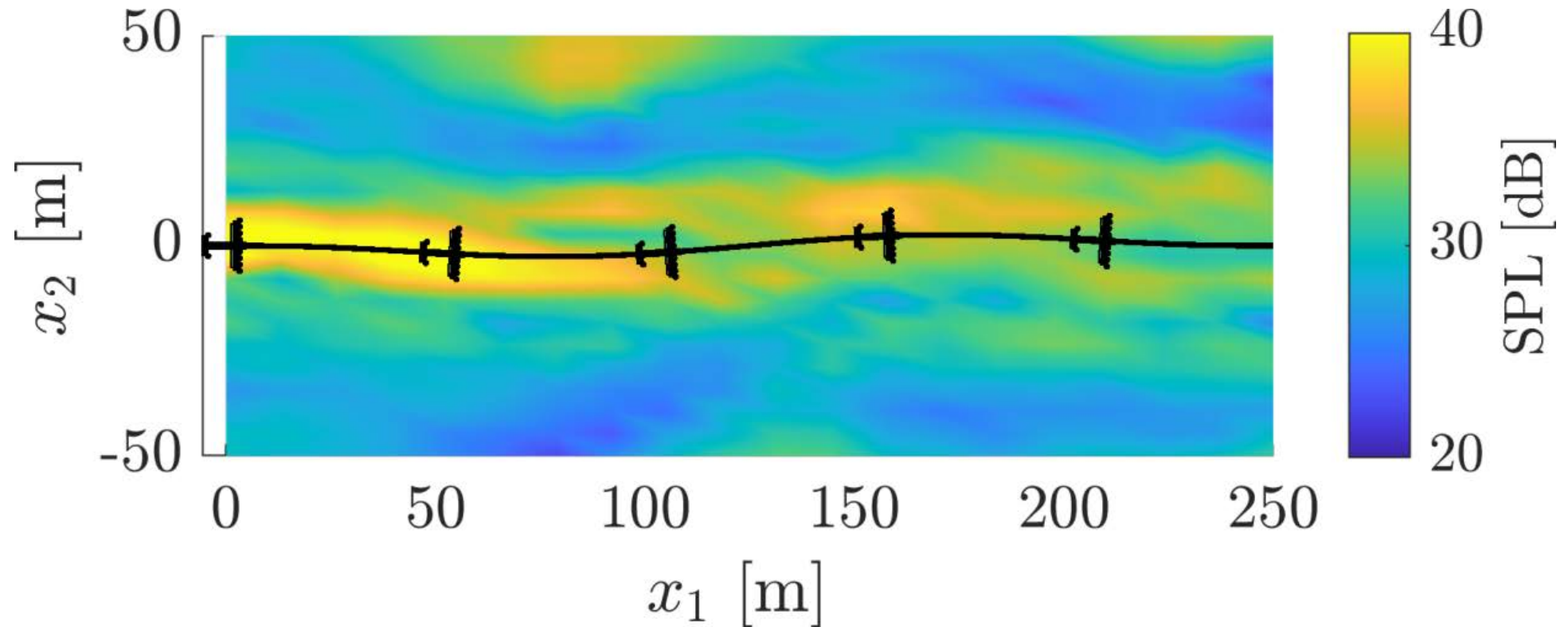


Vehicle propeller
speeds, changing to
meet both thrust and
phase requirements.



Vehicle orientation over
time, changing to meet
spatial constraints.

Results: Acoustics



Acoustic performance for the phase transition scenario. The colors show the maximum Sound Pressure Level (SPL) heard over the full duration of the flight.

Conclusion

We have presented a trajectory generation method for acoustically aware vehicles.

The trajectory generation method allows both mission and acoustic objectives to be met simultaneously.

The feasible trajectory generation method is demonstrated in simulation to show how propeller phase angles can be modified during flight, without affecting the spatial trajectory or orientation of the vehicle.

Future work will focus on planning methods for generating phase angle trajectories.

Thank You!

