

Trajectory Generation for Distributed Electric Propulsion Vehicles with Propeller Synchronization

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In this paper, we propose a method for generating dynamically feasible trajectories for an acoustically aware vehicle with propeller phase control. The trajectory generation procedure allows both propeller phase control and navigation objectives to be considered simultaneously. The presented method is demonstrated where the mission objectives are given as a desired position and phase trajectory. From these trajectories, the full desired state of the vehicle is calculated. Furthermore, the control inputs that realize the desired mission objectives are computed. The acoustic performance for the given trajectory is estimated in terms of sound pressure level as a function of tracking performance. The method is demonstrated in simulation, where the vehicle must navigate through an urban environment with both spatial and acoustic constraints. In the presented scenario, the vehicle must follow a given flight path, and can only reduce sound pressure level by changing the propeller phase targets.

I. Introduction

The number of unmanned air vehicles (UAVs) operating in urban environments is expected to increase dramatically in the near future [1]. These vehicles are proposed as a solution to transportation challenges such as last mile delivery and on-demand mobility, which will require operation in densely populated communities. For example, commercial drone operations could reduce delivery expenses by using small air vehicles to deliver packages, reducing the need for ground-based delivery vehicles. Additionally, taxi and public transportation services can be augmented with air vehicles to reduce road congestion. However, full deployment will require that UAVs operate safely without being a nuisance to the community. The additional noise generated by air vehicles is one such nuisance [2, 3]. Methods that reduce aircraft noise can be classified as either active or passive. Passive methods change the structure of the vehicle to reduce noise and are often fixed during the vehicle design phase. Active methods require power and involve moving the vehicle to reduce noise during the mission planning phase, or using a powered acoustic source to cancel out the undesired sounds. To meet community acoustic standards, both types of methods may be deployed simultaneously.

In this work, we focus on an active noise reduction method called phase synchronization. Phase synchronization is applicable to any vehicle with multiple identical propellers rotating at the same rate. With this method, the propellers are treated as independent acoustic sources, and by adjusting the phase separation between blades, their radiated sound can be made to destructively interfere. This interference can reduce the sound pressure levels at the blade pass frequency. Figure 1 shows the phase separation between two propellers.

Previous work on phase synchronization was implemented via mechanical linkages in the drive-train on transportation aircraft such as the AP-3C Orion and C-130J-30 Hercules by Blunt [4]. Both of these aircraft have four propellers and the phase synchronization method was demonstrated to reduce cabin noise and aircraft vibration. The reduction

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was achieved by closed loop feedback from microphones and accelerometers in the cabin to the propeller phase synchronization controller.

Compared to reducing aircraft cabin noise, community noise reduction using phase synchronization has two additional challenges. The first is that the noise generated must be estimated rather than measured. The noise in the environment cannot be directly measured with microphones, and so an acoustic estimation procedure was proposed by Pascioni and Rizzi [5]. The authors' method models the noise generated by each propeller and combines the model with the propeller phase angle measurements and vehicle orientation to estimate the noise heard by an observer on the ground. The second challenge is that the vehicle is moving relative to the listeners on the ground. As a result, phase synchronization angles will have to change and compensate for both the listener and the vehicle's movement. Alternatively, the phase synchronization angles will have to yield noise reduction in all directions, rather than just in a specific direction. Generating these phase synchronization angles will be referred to as acoustic control. In Ref. [6], four sets of phase angles are generated for a ten-propeller vehicle, which minimize emitted noise in four different directions. This acoustic control method is referred to as directivity-based acoustic control. In Ref. [7], a directivity-based acoustic control method is verified for a system with two propellers in an anechoic chamber. The acoustic testing verifies the correspondence between the measured and predicted sound levels. These results are generated by using a single drive motor and an adjustable drive belt to fix the phase angle for testing. In addition, Ref. [7] tests a global noise reduction method which reduces the radiated sound power in all directions. Both of these methods rely on the ability to enforce relative phase angles between propellers while also meeting both vehicle stability requirements and mission objectives.

Prior work has used mechanical linkages to enforce phase synchronization of propellers; however, these linkages often lack the range or resolution to track a changing phase angle. To use phase synchronization, the propellers must be driven by high bandwidth actuators that can realize any desired phase change. Electric propulsion vehicles are therefore a prime candidate for propeller synchronization-based noise reduction. Popular configurations for proposed urban air transportation vehicles take advantage of distributed electric propulsion. In this configuration, multiple small, independent electric motors are used to power propellers. This configuration comes with many benefits including propulsion-aerodynamic coupling, propulsion redundancy, and more airframe design freedom [8]. These benefits allow UAVs to be designed to be safe and efficient in urban environments, taking advantage of design freedom to create simple and efficient VTOL designs. The two benefits most critical to phase control are the redundancy in the propellers and the motor bandwidth, which allow the motor to quickly change speed. Taking advantage of the motor bandwidth, an initial proof of concept for phase control using electric motors was demonstrated by Patterson et al. [9], where the performance of the controller is given in terms of steady-state offset and tracking error variance. While this method demonstrated the feasibility of phase control for electric motors, the acoustic performance was not directly measured. The acoustic performance of electronic phase control was demonstrated in Ref. [10]. To demonstrate the acoustic performance of phase control using electric motors, a two-propeller system was tested in an anechoic chamber and the recorded performance for both directivity and radiated sound power matched the simulated estimates.

Prior work focuses on phase control as a parallel objective to vehicle stability and mission performance. In Refs. [9, 10], the presented phase controllers are given full control authority over the motor speed targets, and while they can track small variations of motor speed, only the performance of the phase controller is considered. The vehicle's mission objectives are not considered. In this work, we consider an acoustically aware trajectory generation method that ensures that both the flight control and phase control objectives are jointly feasible. This architecture is shown in Figure 2, which shows the necessity of jointly feasible control considering that both the flight and phase controllers send control inputs to the motors. In this framework, the trajectory and acoustic constraints are expressed in terms of desired positions and phases, assumed to be provided by a mission planner. The trajectory generation stage must therefore generate a feasible state trajectory that includes both propeller phase angles and the vehicle position.

The trajectory generation method is presented for a ten-propeller tilt-wing vehicle in forward flight. A differentially flat vehicle model is used to derive state trajectories that are feasible given the differential equations that describe the

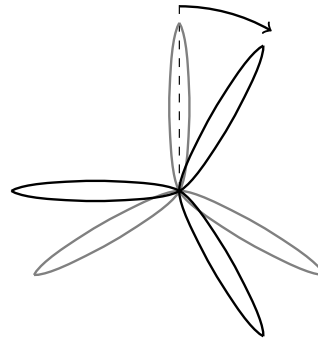
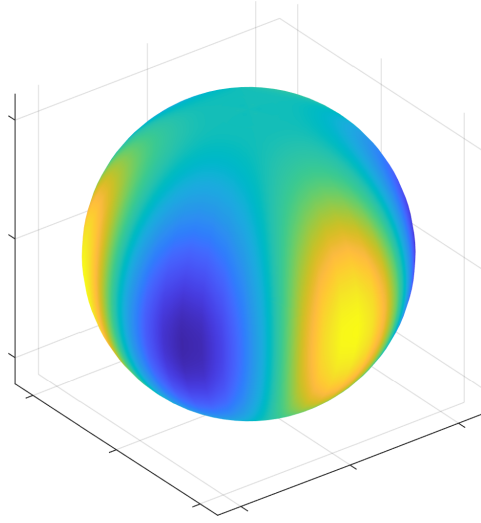
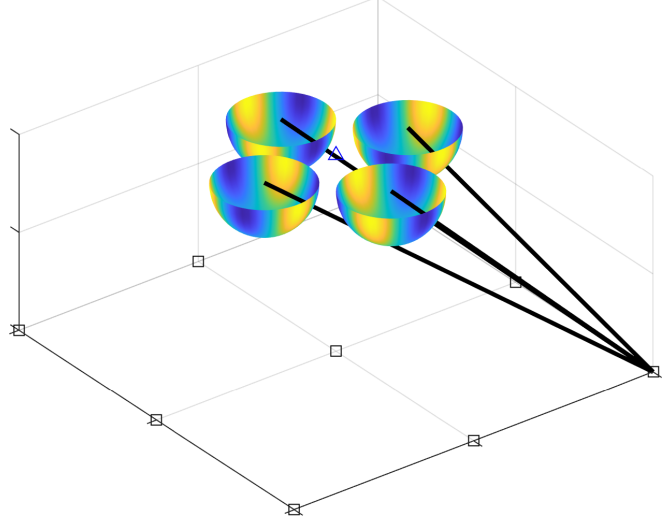


Figure 1 Propeller phase measured between azimuth of gray propeller to azimuth of black propeller.



(a) Source noise sphere for a propeller with colors showing direction pressure amplitudes at a fixed instant in time.



(b) An example of source noise addition for four, vertically oriented propellers.

Figure 3 Example source noise spheres. Color values show relative acoustic pressure levels for a single time instant (heat map with increasing values from blues to yellows).

time-step. These assumptions have been tested and shown to hold for far field noise estimation of a two-propeller system in an anechoic chamber by the authors of [7]. The pressure peaks around the sphere correspond to the blade passages, and as the blades pass, the peaks rotate. We denote the pressure amplitude with the function $\mathcal{S}(\Theta, \omega, v, \alpha)$, where Θ is the propagation direction, ω is the propeller speed, v is the flight speed and α is the angle of incoming airflow.

With each propeller simulated individually, the sound heard by the observers must be combined. These pressure levels are scaled by the propagation model and summed into a single pressure level. This single pressure level at an observer location k , is given by the equation

$$p_k(t) = \sum_{n=1}^N \beta_n(t) \mathcal{S}_n(\Theta, \omega_n, v_n, \alpha_n) \sin(\omega_n(t - \tau) + \theta_n), \quad (2)$$

where N is the number of propellers, ω_n is the propeller speed of the associated motor and θ_n is the motor phase. An example addition is shown for four propellers in Figure 3b.

B. Vehicle Model

In order to demonstrate phase control concepts in conjunction with flight and navigation objectives, the dynamics of interest are fixed. A common navigation model will focus on the vehicle's rigid body dynamics, directly controlled by thrust vectors. However, to consider phase control, the model must be extended to consider the dynamics of the motors and propellers that generate thrust. The motor-propeller model used in this work is based on a previously identified second-order linear model, used in Ref. [9]. Phase between any two propellers is calculated as shown in Ref. [10].

The vehicle dynamics are based on GL-10 as described in Refs. [11] and [12]. The GL-10 is a ten-propeller vehicle, making it a good candidate for phase control, where increasing the number of propellers increases the effectiveness of phase control. Furthermore, as a tilt-wing vehicle, different operating regimes can be considered for acoustic performance. These regimes include hover, transition and forward flight. This work focuses on the forward flight regime, where the wings are providing lift, and the propellers are providing forward thrust. This flight regime will allow more control authority to be given to the propellers, since the stability of the vehicle is not directly dependent on the propeller speeds.

The vehicle is given by a set of nonlinear equations adapted from Refs. [13, 14]. The vehicle position dynamics are

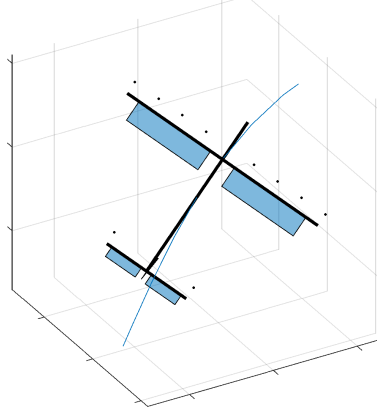


Figure 4 Vehicle appearance. The blue patches are the vehicle control surfaces; the black points are the propeller locations.

given by

$$\dot{x} = \begin{bmatrix} V \cos \chi \cos \gamma \\ V \sin \chi \cos \gamma \\ V \sin \gamma \end{bmatrix}, \quad x(0) = x_0, \quad (3)$$

where x is the vehicle position, V is the vehicle airspeed, χ is the heading angle, and γ is the flight path angle. The vehicle orientation and speed dynamics are given by the equations:

$$\begin{aligned} \dot{V} &= \frac{1}{m} (F_{thrust} - F_{drag}) - g \sin \gamma, & V(0) &= V_0, \\ \dot{\chi} &= F_{lift} \frac{\sin \phi}{mV \cos \gamma}, & \chi(0) &= \chi_0, \\ \dot{\gamma} &= \frac{F_{lift}}{mV} \cos \phi - \frac{g}{V} \cos \gamma, & \gamma(0) &= \gamma_0, \end{aligned} \quad (4)$$

where m is the vehicle mass, F is the indicated force, ψ is the heading angle and g is the acceleration due to gravity. The control variables are $u = [T \quad C_L \quad \phi]^\top$, the throttle, lift coefficient and bank angle respectively.

Lift and drag forces are given by the equations:

$$F_{lift} = \frac{1}{2} \rho V^2 S C_L, \quad (5)$$

$$F_{drag} = \frac{1}{2} \rho V^2 S C_D, \quad (6)$$

where ρ is the atmospheric density, S is the effective surface area of the control surfaces and C_D is the coefficient of drag.

To consider phase control methods, the dynamics must be extended down to the level of the propeller positions. The thrust force acting on the vehicle is therefore given by the contributions of each of the individual propellers. The thrust contributions of the individual propellers are determined from the motor speeds given the quadratic thrust curve functions, $F_n(\cdot)$, for each of the propellers. The propeller speeds, and associated thrust, are determined by the dynamic equations:

$$\begin{aligned} \dot{q}_n &= A_n q_n + [0 \quad 0 \quad 1]^\top T_n, \quad q(0) = q_0, \\ F_{thrust} &= \sum_{n=1}^N F_n(\omega_n), \end{aligned} \quad (7)$$

where $q_n = [\theta_n, \omega_n, i_n]^\top$ is the motor state, θ is the motor position, ω is the motor speed and i is the motor electrical state. The system dynamics matrices, A_n , are assumed to be Hurwitz matrices. The full state of the vehicle is then given by $X = [x, V, \chi, \gamma, q]^\top$, where q is all of the motor states concatenated.

III. Trajectory Generation

In order to ensure that the phase controller does not interfere with the mission or stability of the vehicle, the desired state trajectory must be feasible. To generate feasible trajectories for nonlinear systems, we consider the trajectory generation methods presented in Ref. [14, 15], which apply to differentially flat vehicle models. The differential flatness of the vehicle allows the control inputs and state trajectories to be determined from a subset of the state. We choose this subset of the state to be the vehicle position and motor phase angles. By determining this relationship, the trajectories are guaranteed to be feasible and can be directly checked for satisfying spatial safety constraints. In addition, other state and acoustic constraints can be checked based on the designed trajectory.

The state and input trajectories are denoted by $X(t)$ and $u(t)$ respectively. To find these trajectories, we use the flatness of the vehicle dynamics. A system is said to be differentially flat if there are flat outputs $\sigma = h(X, u, \dot{u}, \dots, u^{(p)})$, so that the state and control input can be written in terms of the flat outputs:

$$\begin{aligned} X &= \Phi_X(\sigma, \dot{\sigma}, \dots, \sigma^{(m)}), \\ u &= \Phi_u(\sigma, \dot{\sigma}, \dots, \sigma^{(m)}), \end{aligned} \quad (8)$$

where p and m are the finite order of derivatives. Note that the derivatives of the flat outputs must be defined up to this order. In this work, we consider polynomials which satisfy this requirement.

Feasible state and input trajectories can be directly computed from the flat outputs by evaluating functions Φ_X and Φ_u . In this work, we choose our vehicle position, x , and motor orientation, θ_n . The correspondence between these flat outputs and the full state and input is shown in the following derivations. From Equation (3), note that (V, γ, χ) can be written as a function of $\dot{x}$:

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

where x_1, x_2 and x_3 are the world frame coordinates of the vehicle. The speed and orientation dynamics, given in Equation (7), can then be used to find $(\phi, F_{lift}, F_{thrust})$ as shown in the following equations:

$$\begin{aligned} \phi &= \arctan \frac{\dot{\chi} V \cos \gamma}{V \dot{\gamma} + g \cos \gamma}, \\ F_{lift} &= \frac{mg \cos \gamma + mV \dot{\gamma}}{\cos \phi}, \\ F_{thrust} &= F_{drag} + m\dot{V} + mg \sin \gamma. \end{aligned} \quad (9)$$

Furthermore, the aerodynamic forces can be calculated with the following equations:

$$\begin{aligned} C_L &= \frac{2F_{lift}}{\rho S V^2}, \\ C_D &= C_{D0} + k_1 C_L^2, \\ F_{drag} &= \frac{1}{2} \rho S C_D V^2, \end{aligned} \quad (10)$$

where ρ is the air density, S is the effective surface area of the lifting surface, C_{D0} and k_1 are coefficients.

To determine the motor speeds and throttle inputs required to achieve the thrust necessary for flight, consider Equation (7). In this equation, the individual propeller thrusts are each computed with a separate quadratic equation. The thrust necessary for flight is given by Equation (9) and the sum of the individual propeller contributions must add up to this desired thrust. To limit the possible solutions to this over-determined equation, we consider pairs of neighboring propellers. Each pair is responsible for one-fifth of the total thrust. These pairs are also chosen to be linked by a phase shift, ξ_r , where r is the number of propeller pairs. Using this offset, which is a flat input, we can determine the motor speeds necessary for each motor pair. Consider the first pair and note that $\xi_1 = \theta_1 - \theta_2$ and further that $\omega_2 = \omega_1 - \dot{\xi}_1$. By substitution, we have that $F_{thrust}/5 = F_1(\omega_1) + F_2(\omega_1 - \dot{\xi}_1)$, which we can solve using the quadratic formula for ω_1 , taking the appropriate solution. Likewise, for each pair of propellers the speeds can be determined that meet both thrust and phase offset constraints. With the motor speeds and positions determined, the linear dynamics of the motor can be used to determine the motor speeds.

IV. Results

To demonstrate the effectiveness of the trajectory generation method for planning, we compare two feasible trajectories. Recall that the trajectory is completely determined by the flat outputs of spatial position and motor phase. In the two cases considered, the spatial trajectories are the same but the motor phases are allowed to change. The first trajectory considers a smooth transition from no phase offsets to a pre-selected set of phase angles. This type of transition is expected to be typical of vehicle behavior, where the phase set-points change based on the acoustic requirements in the community around the vehicle. The second trajectory demonstrates arbitrary phase changes throughout flight to demonstrate the flexibility of the proposed method.

The first scenario is shown in Figure 5. In this scenario, the propeller phase angles smoothly transition between no offset and some desired offset, as shown in Figure 5a. This transition occurs by changing the motor speeds, but without affecting the total thrust produced. For identical propellers, this means that if a propeller is slowing down to change phase, its counterpart's speed must increase to make up for the loss in thrust. For this reason, Figure 5b shows that the propeller speeds diverge when the phase transition is occurring. Despite these speed changes, the vehicle orientation, shown in Figure 5c, and position are not affected.

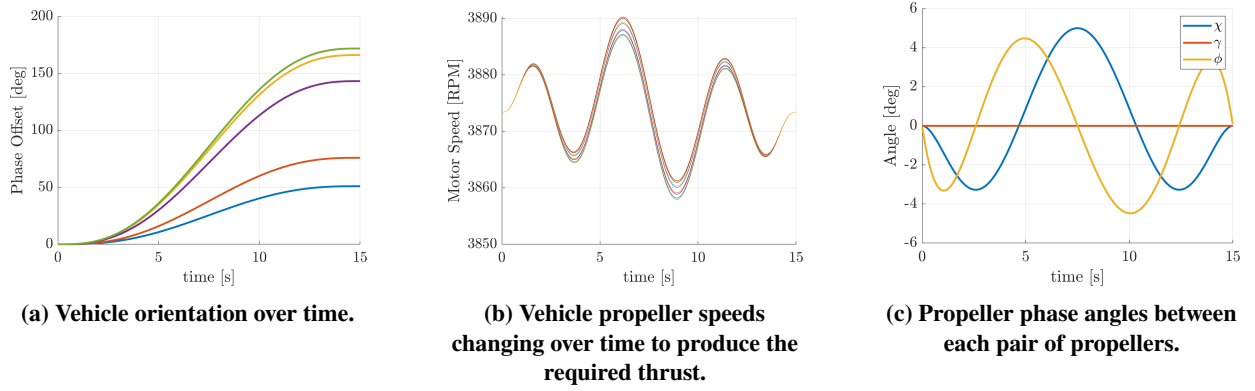


Figure 5 State trajectories of interest for phase transition case.

The second scenario is shown in Figure 6. In this second scenario, the propeller phase angles change arbitrarily throughout the flight. The phase changes are shown in Figure 6a. Since the phase angles are constantly changing, the propeller speeds must be continuously changing to compensate. In Figure 6b, the motor speeds are shown, and the difference between them can be seen to be proportional to the rate of change of the phase. Notice that the difference in speed is less than one percent, even for the largest phase change. Though this difference will increase for faster phase transitions, it demonstrates that only a small portion of the control authority is needed to realize phase transitions. In Figure 6c, the vehicle orientation is shown again, unchanged despite the difference in propeller speeds.

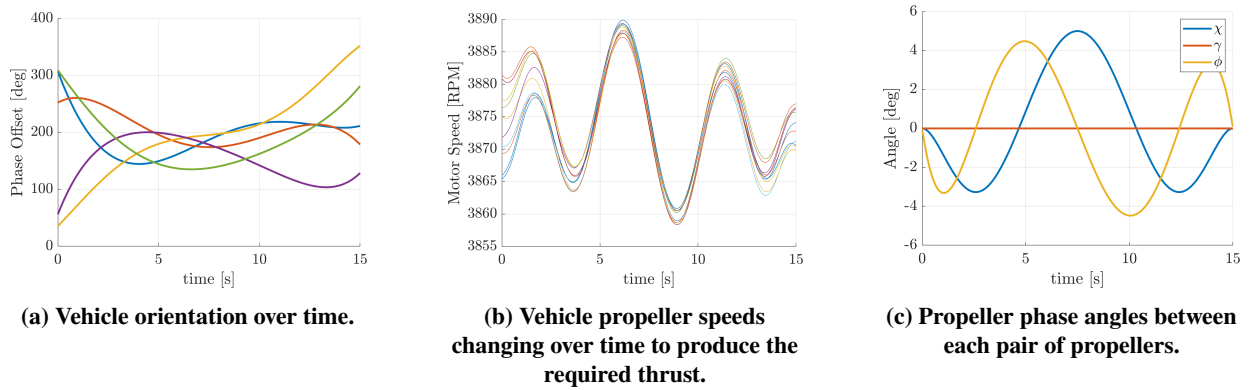


Figure 6 State trajectories of interest for arbitrary phase trajectory case.

In Figures 7 and 8, the trajectory position, orientation and acoustic performance is shown. The vehicle position trajectory is shown as a black line, and the vehicle orientation is shown at equally spaced time points along the trajectory. The acoustic performance is simulated for each simulated state of the vehicle. Since the sound heard at the observer locations changes drastically based on the position and orientation of the vehicle, the plotted SPL is the maximum value heard during the entire flight duration. Though this visualization does not directly show the acoustic effect of a particular vehicle state, the information is still somewhat localized, since the attenuation due to distance prevents distant states contributing to the maximum.

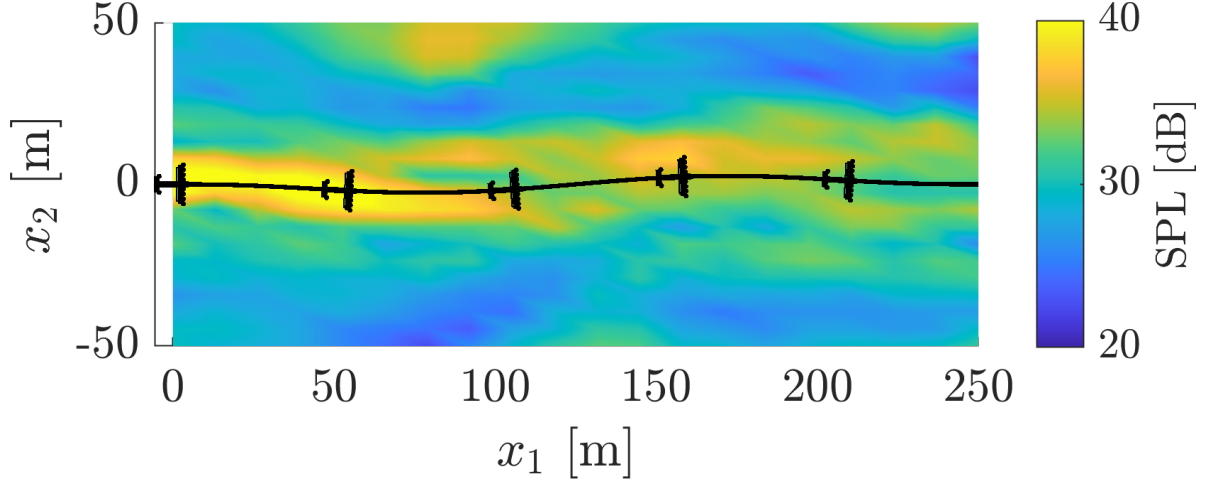


Figure 7 Acoustic performance of the phase transition scenario. The color shows the maximum SPL heard over the full duration of the flight.

In Figure 7, the acoustic response is shown for a phase transition. In this figure, we see that near the beginning of the trajectory, when the propellers have no phase separation, there is a large SPL under the vehicle. As the phase angles change, and by the end of the trajectory, the chosen phase angles have spread the sound out around the vehicle, reducing the noise directly under the aircraft by 5 dB. Similarly, in Figure 8, we see that the vehicle trajectory and orientation are unchanged by the different phase targets but the acoustic performance is different. This phase trajectory results in the sound being more spread out in the environment but does reduce the SPL under the vehicle by almost 10 dB at certain times during the flight.

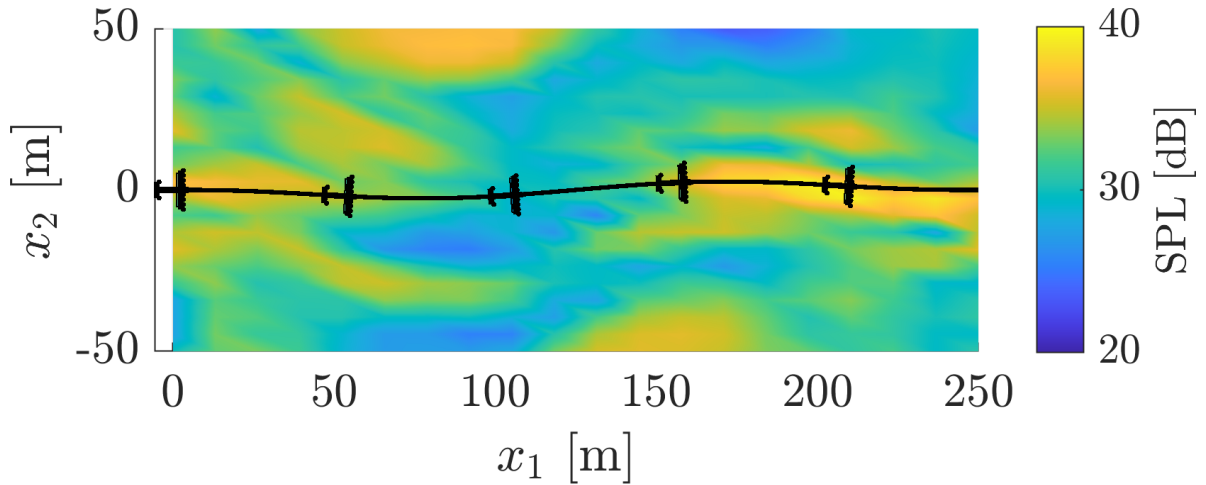


Figure 8 Acoustic performance of arbitrary phase change scenario. The color shows the maximum SPL heard over the full duration of the flight.

V. Conclusion

This paper presents a method of generating dynamically feasible trajectories for an acoustically aware vehicle using propeller phase control. This trajectory generation method allows the vehicle to incorporate phase control without sacrificing performance or safety considerations. The presented method is demonstrated in a scenario where the vehicle is constrained to a fixed spatial path but can change phase angles to adjust the community noise created by its trajectory. In this scenario, two phase trajectories are considered. The first is a transition from no phase offset between propellers to a prescribed set of phase angles, expected to be typical of phase control in a dynamic environment. The second phase trajectory considered demonstrates the flexibility of the method by considering arbitrary phase trajectories. These types of trajectories may be generated by a planning method that is searching for a trajectory that minimizes community noise. Using this method, we see that the phase angle trajectories can be chosen arbitrarily from sufficiently smooth functions. Future work will focus on creating a planning method to determine the phase and position trajectories that best reduce community noise and creating tracking control laws to compensate for disturbances during flight.

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