

Rotor–Rotor Interference Modeling for Flight Dynamics Analysis of a Mars Hexacopter Concept

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ABSTRACT

Characterization of rotor–rotor wake interactions and their influence on flight dynamics is an important step toward advancing control system design and evaluating the performance of next-generation Mars multirotors. In this work, a Viscous Vortex Particle Method (VVPM) is utilized to generate rotor–rotor interference data for the Chopper Mars Helicopter platform, a large-scale hexacopter concept designed to be capable of carrying payload and pursuing independent science tasks. A reduced-order model compatible with finite state dynamic inflow is derived from the database. Interpolation strategies for continuous look-up are evaluated, with Gaussian Process Regression providing up to 20% improvement in prediction accuracy over linear interpolation of the interference data, although its scalability is limited by the large number of output channels. The interference model is implemented in HeliCAT, the flight dynamics analysis framework used for the Ingenuity Mars Helicopter, to assess the impact of rotor–rotor interference on trim, open-loop response and key stability derivatives. For Chopper, the first-order impact of rotor–rotor interaction on flight dynamics in hover is small, but with an observed increased pitch and roll damping. In forward flight, on-axis bare airframe responses exhibit attenuation at the lower frequencies due to interference, and increased sensitivity of the pitch response to vertical perturbations in cruise. Finally, a real-time closed-loop simulation is performed with and without the interference model to assess the impact on rotor power during a representative science mission flight trajectory on Mars, showing that total increase in mechanical shaft power due to multirotor wake interactions does not exceed 5% throughout the flight.

NOMENCLATURE

a	Speed of sound, m/s
A	Rotor disk area, m ²
C_T	Rotor thrust coefficient, $T/(\rho A(\Omega R)^2)$
M	Interference gain matrix
M_{tip}	Blade tip Mach number
N_r	Number of rotors
p, q, r	Roll, pitch and yaw rate, rad/s
P	Rotor power, W
r	Rotor radial coordinate, m
R	Rotor radius, m
Re	Chord-based Reynolds number
RPM	Rotor rotational speed, rev/min
t	Time, s
T	Rotor thrust, N
u, v, w	Longitudinal, lateral and vertical velocity, m/s
v	Inflow velocity, m/s

V	Total airspeed, m/s
X	Flight condition
δ	Mixed control input signal, deg
θ_0	Rotor collective angle, deg
λ	Inflow ratio, $v/(\Omega R)$
μ	Rotor advance ratio
ρ	Atmospheric density, kg/m ³
σ	Rotor solidity (thrust-weighted)
χ	Wake skew angle, rad
ψ	Rotor azimuth angle, deg
Ω	Rotor rotational speed, rad/s

Sub- and superscripts

ind	Self-induced
$int f$	Interference
x, y, z	Longitudinal, lateral and vertical

INTRODUCTION

Next-generation Mars rotorcraft will fly farther and faster than the Ingenuity Mars Helicopter and carry out independent mis-

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sions and scientific tasks. To meet these objectives, vehicle designs are trending toward large-scale multi-rotor configurations. Multicopters introduce interactions between the induced wakes of the rotors that can have a significant impact on flight dynamics (Refs. 1–3). In addition, interference effects can lead to significant system-wide thrust degradation and therefore represent an important consideration in helicopter capability assessment. The effects depend strongly on both the vehicle configuration, such as relative rotor placements, shaft angles, and flight mode, as well as the instantaneous flight condition, including rotor thrust, wind, vehicle velocity and attitude. As a result, the rotor–rotor interference presents a high-dimensional, non-linear problem that is difficult to generalize across different aircraft.

Research applicable to multirotors operating in the extreme environment encountered on Mars is limited. The significantly lower atmospheric density, approximately 1 % of Earth, dictates the aerodynamic regime characterized by very low Reynolds numbers ($\sim 10^4$). While small Unmanned Aerial Vehicles (sUAV) may provide a closer aerodynamic comparison point, the flight dynamics of such vehicles differ significantly from a large-scale Mars hexacopter (Ref. 4). This highlights the need for dedicated models of rotor–rotor interference for multirotor Mars vehicle concepts that lend themselves to flight dynamics analysis, which will be important for successful control system design and performance evaluation.

Real-time capable flight dynamics simulations conventionally rely on finite-state dynamic inflow models, offering a simplified, global representation of the induced rotor wake that is readily linearizable. Such formulations are computationally efficient and practical for real-time simulations and flight dynamics analysis, but do not account for effects of multirotor wake interactions. The advent of advanced air mobility and associated vertical lift concepts, however, has spurred significant research efforts dedicated to analyzing aerodynamic interaction effects for multirotor systems. This includes experimental efforts (Refs. 5–7) as well as pursuits of higher-fidelity Computational Fluid Dynamics (CFD) solutions (Refs. 8–10). Such data provide important physical insight and enable point-comparison. Evaluating the impact on flight dynamics in real-time simulations and linearized model responses, however, is prohibited by the time cost of online computation and large number of states in higher order solutions. On the other hand, analytical closed-form approaches, specifically the use of combined momentum theory and simple vortex theory, offers a tractable and linearizable approach to multirotor wake interaction (Ref. 11) that is readily applicable to flight dynamics analysis (Ref. 12), but rely on inviscid flow assumptions violated in the Mars operating conditions.

Using surrogate models derived from higher-fidelity aerodynamics data to enhance lower-fidelity solutions has emerged as a means of increasing accuracy while retaining computational efficiency in the aerodynamic analysis, which has shown promising success in not only design optimization (Refs. 13–15) but also flight dynamics and control applications (Refs. 16–18). In context of the rotor wake problem,

the viscous vortex particle method (VVPM) is being recognized as a tractable mid-fidelity tool for generating and refining reduced-order inflow models to account for rotor–rotor interference effects and their impact on flight dynamics (Refs. 19–23). The applicability of VVPM to Mars rotorcraft was demonstrated in Ref. 24, which showed good agreement using a VVPM wake with available experimental data for coaxial rotor performance in hover under Mars atmospheric conditions.

The objective of the present work is to derive and implement a reduced-order rotor–rotor interference model to support flight dynamics analysis and closed-loop simulation of the Chopper Mars hexacopter concept. After an overview of the vehicle platform design, the rotor–rotor interaction model formulation is presented, including considerations on database generation from a VVPM wake model, parametrization and interpolation techniques. Predicted interference characteristics are presented, alongside sensitivities to model assumptions and limitations of the present model. The impact of rotor–rotor interference on flight dynamics are presented, including trim, open-loop response and key stability derivatives. Finally, results from a closed-loop real-time simulation of a representative flight trajectory for a science mission on Mars is demonstrated to assess the impact of multi-rotor interaction on vehicle performance limits.

THE CHOPPER PLATFORM

The sizing of a next-generation Mars hexacopter concept referred to as Chopper was described in Ref. 25. The introduced aerodynamic challenges associated with the Chopper vehicle were described in Ref. 26, where multirotor wake interaction was identified as a focal area for both numerical and experimental investigations. This section gives a brief overview of the Chopper platform, including vehicle characteristics and flight dynamics model.

Vehicle Overview

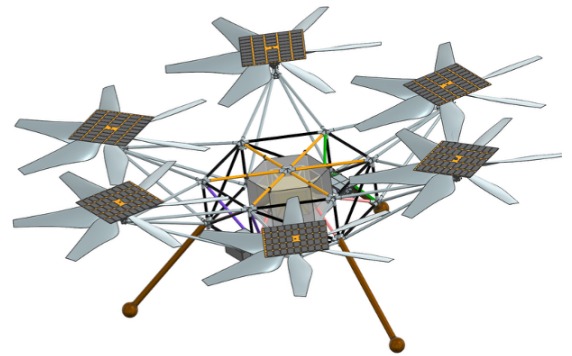


Figure 1. Rendering of the Chopper hexacopter concept.

A rendering of the Chopper hexacopter concept is illustrated in Figure 1, and a schematic of the rotor configuration is provided in Figure 2a, including definition of the body reference

frame. The rotor has a radius of $R = 0.675$ m and thrust-weighted solidity $\sigma = 0.3$, increased compared to Ingenuity to support the larger take-off mass. Counter-clockwise rotating rotors (with odd indices) are in a horizontal plane $0.15R$ above clockwise rotating rotors (with even indices). The thin Martian atmosphere results in poorly damped rotor-flapping modes. As with Ingenuity, Chopper's rotor system is significantly stiffened to shift these poorly damped modes well above the control system's bandwidth. As indicated in Figure 2a, the rotor disks have a non-zero overlap of $0.11R$ to minimize footprint so as to comply with the geometric constraints of the target aeroshell. For the benefit of the reader, rotors at the same longitudinal coordinate are paired in colors, with front (1, 6), mid (2, 5), and aft (3, 4) in green, orange and red, respectively.

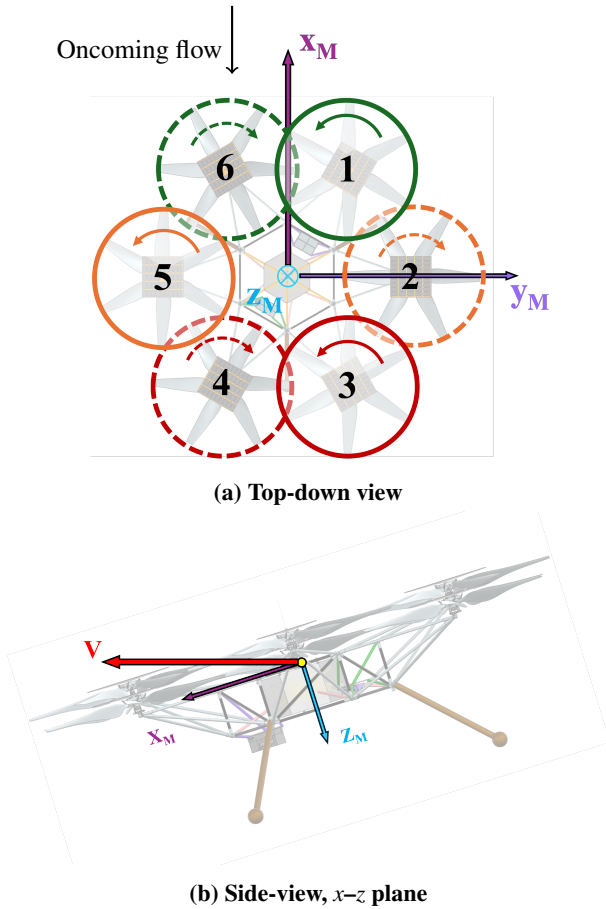


Figure 2. Chopper concept rotor layout and reference body-frame.

The ~ 30 kg Chopper concept is designed to be able to perform a range of potential science-driven missions that require 3+ kg of science payload and up to 3 km/sol flights (Ref. 25). The Chopper team has performed detailed concept of operations (CONOPS) exercises for two applications, shown in Figure 3. One application demonstrates a Chopper role in a hypothetical stand-alone mission to retrieve sample tubes from a depot in Jezero Crater and bring them to a Martian lander's

location. Another studied application would use the Chopper concept to execute the Condor science mission (Ref. 27). In this studied application, the Chopper would target areas of interest near the bottom of Valles Marineras, the vast Martian canyon that is 6 times deeper than the Grand Canyon on Earth. Both studied concepts have an initial egress from a jet-pack (Ref. 28) that brings the helicopter to within its normal flight envelope, allowing the helicopter to land as it would on any other flight. Both scenarios would also involve an unguided entry that could result in an initial landing location tens of kilometers away from the target area of interest, which requires a long traverse from the initial egress location to the start of the science mission and drives the 20 m/s nominal horizontal ground speed requirement, which has been translated into a need to tolerate air speeds up to 40 m/s when accounting for winds. The range of potential applications drives a need for assessing performance from densities of 0.012 kg/m^3 up to 0.025 kg/m^3 , with Jezero being on the lower end and Valles Marineras expected to be on the higher end. Although there are other similarities across the studied mission CONOPS, the Condor mission in particular requires accessing terrain further upslope from the valley floor where the vehicle would land, resulting in a unique flight type known as the “Wall Traverse” that gets the vehicle from the floor up on to a ledge where the science sites are. The Wall Traverse is a driving case for the aerial design, and is thus used as a canonical example of a stressing flight type when evaluating metrics on the project. This wall traverse involves a ~ 2 km flight with over 700 m in elevation change, where the density can vary by over 10% from the bottom to the top of the climb. Larger vertical flight speeds support more efficient trajectory design, with a current design limit of 5 m/s to bound the problem.

Flight Dynamics Modeling in HeliCAT

The Helicopter Control Analysis Tool (HeliCAT) served as the primary framework for flight dynamics and control system development of the Ingenuity Mars Helicopter (Ref. 29). It has since been expanded to support modeling and simulation also of the Chopper hexacopter concept. Built upon JPL's DARTS/DSHELL multibody simulation environment (Refs. 30, 31), HeliCAT enables end-to-end, closed-loop simulations incorporating actuator and sensor models, wind disturbances, contact dynamics, and flight software integration. The vehicle, rendered in HeliCAT in Figure 4, is represented as a multibody system of rigid or flexible components, including the rotors, mast, landing gear, and fuselage, connected through hinged joints. Aerodynamic loads on the rotors are computed using blade-element theory, coupled with a Peters–Pitt finite-state dynamic inflow model with modifications accounting for wake distortion in maneuvering flight to capture wake-induced effects on vehicle dynamics. HeliCAT also provides tools for linearization about trimmed flight conditions, yielding both full- and reduced-order models for control and stability analysis. To trim, an optimization routine is performed in HeliCAT to find conditions in which the vehicle is in equilibrium at a chosen airspeed and atmospheric

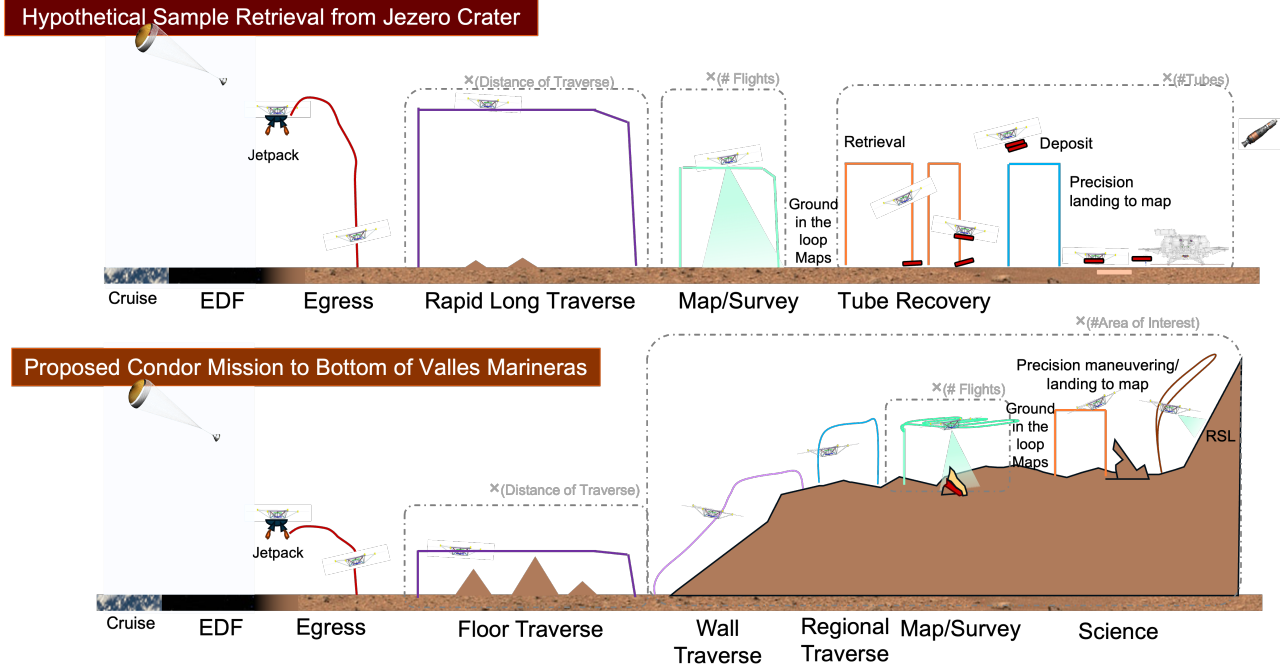


Figure 3. Potential Chopper CONOPS. Top: Sample retrieval from Jezero Crater. Bottom: Condor mission to bottom of Valles Marineras.

density. For Chopper, the rotor speed is fixed, and a trimmed state is achieved by adjusting the six rotor collectives. Using DARTS/DSHELL's linearization capabilities to find sensitivities to inputs, model states, and multibody states, linearizations are found at a set of azimuths over a rotor revolution. The resulting linear time-periodic (LTP) dynamics of the system are transformed into linear time-invariant (LTI) representations through harmonic state expansion, as described in Ref. 32.

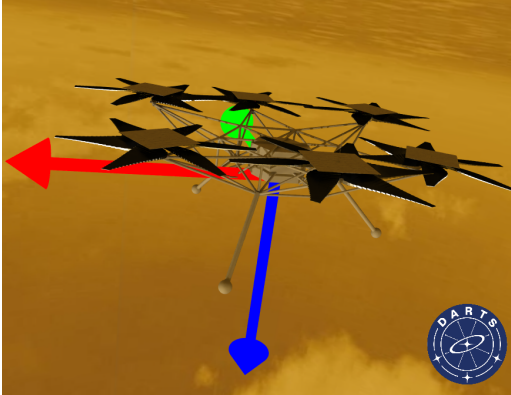


Figure 4. Rendering of the Chopper hexacopter concept in HeliCAT.

When finding a trim solution, static mixing of the rotor collectives decouples the controlled input-output pairs and eliminates the extra degrees of freedom Chopper would have with six independent rotor collective choices. The on-axis aligned control inputs, denoted by $\delta_w, \delta_r, \delta_q, \delta_p$ for heave, yaw, pitch

and roll respectively are defined through Equation (1).

$$\begin{bmatrix} 1 & 1 & 1 & 0.5 \\ 1 & -1 & 0 & 1 \\ 1 & 1 & -1 & 0.5 \\ 1 & -1 & -1 & -0.5 \\ 1 & 1 & 0 & -1 \\ 1 & -1 & 1 & -0.5 \end{bmatrix} \begin{bmatrix} \delta_w \\ \delta_r \\ \delta_q \\ \delta_p \end{bmatrix} = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \\ \theta_5 \\ \theta_6 \end{bmatrix} \quad (1)$$

The origin of the body frame is equidistant from all rotors in the xy plane, with the y -axis pointing in the direction of Rotor 2's axis of rotation. The z -axis points downward so that the rotors rotate in either the $+z$ or $-z$ direction in the body frame, such that $w > 0$ for vertical descent, illustrated in Figure 2b, where total velocity is denoted by V .

THE ROTOR-ROTOR INTERFERENCE MODEL

This section presents an extension of the preliminary, generic formulation outlined in Ref. 24. The derivation of the rotor-rotor interference model is accounted for, including mathematical formulation, generation and interpolation of the underlying VVPM interference data, as well as limitations of the present model.

Model Formulation

The inflow increment at rotor i attributed to interference from all other rotor wakes, denoted by v_i^{inf} , is superimposed to the self-induced inflow v_i^{ind} and vertical hub velocity $w_{h,i}$ (positive for climb) of each rotor, giving the total inflow,

$$v_i(r_i, \psi_i, t) = v_i^{ind}(r_i, \psi_i, t) + v_i^{inf}(r_i, \psi_i, t) + w_{h,i}, \quad (2)$$

where r_i and ψ_i are the radial and azimuthal locations on the i :th rotor disk. Interference velocity distributions are represented in state-space form. While the proposed formulation allows for higher-order truncation for non-uniform interference distributions, only uniform interference $v_i^{intf}(r_i, \psi_i, t) \cong v_{i,0}^{intf}(t)$ is considered in this paper.

Thrust of the rotors drive the interference model, and are mapped to interference states through a variable block matrix denoted by M . Given a flight condition, denoted generically by X , the total aerodynamic interference acting on rotor i is evaluated through Equation (3).

$$\frac{v_i^{intf}}{R\Omega} = \lambda_i^{intf} = \sum_j \lambda_{ij}^{intf} = \sum_j M_{ij}(X)C_{T,j} \quad (3)$$

In Equation (3), the gain matrix coefficients modulate the aerodynamic load coefficients of the interfering rotor j onto the receiving rotor i , in a manner conceptually akin to finite-state dynamic inflow formulations. Specifically, the coefficient M_{ij} relates the thrust coefficients $C_{T,j}$ to their interference contributions onto rotor i denoted by $\lambda_{ij} := M_{ij}C_{T,j}$. For a hexacopter assuming uniform interference, M is a 6×6 square matrix.

Data Generation

The interference gain matrices are extracted from wake solutions using VVPM, simulated under various flight conditions. VVPM is a mid-fidelity, first-principles solution to the wake problem. It solves a Lagrangian formulation of the incompressible Navier–Stokes equations in their vorticity–velocity form. Convection is represented implicitly, yielding a numerical solution that mitigates artificial dissipation, thus able to more efficiently retain vortex circulation strength over time. Effects of viscous diffusion are modeled throughout the flow-field, an important feature for Mars applications due to the markedly low Reynolds number. Its implementation as embodied in the rotorcraft analysis framework FLIGHTLAB (Refs. 33–35) is used throughout this work. The simulation parameters for numerical discretization and boundary conditions are tabulated in Table 1, guided by prior convergence studies in Ref. 24. The present wake model was further validated in a sub-scale water tank test campaign at matching Reynolds numbers, which will be detailed in a future publication.

Table 1. VVPM Simulation Parameters.

Particle cut-off distance	$\leq 7R$
Max number of particles	8×10^6
Far-field boundary condition	≤ 15 rev.
Particle Resolution	$\geq 0.03R$
Vorticity Source Resolution	$\geq 0.03R$

The process to derive the rotor–rotor interference data partially follows that of Gladfelter’s in Ref. 36. Isolating each

rotor’s effective contribution to the total interference velocities, as predicated by Equation (3), is achieved by comparing the VVPM predicted inflow distributions over the rotor disks in the presence of multiple rotors with that of isolated rotors. First, the full hexacopter model is trimmed with a VVPM wake in a prescribed flight condition. Next, using the time-averaged thrust and rotor advance ratios from the full vehicle runs, each rotor interference pair (i, j) is trimmed accordingly to determine the pairwise inflow distribution. Finally, isolated rotors are trimmed to estimate their self-induced velocity distributions, for the same thrust level but absent mutual wake effects. The resulting pairwise distributions, λ_{ij} are normalized by the interfering rotor thrust $C_{T,j}$ to derive the interference matrix coefficients, $M_{ij} = \lambda_{ij}/C_{T,j}$. This approach requires both a full-vehicle trim run, N_r isolated trim runs as well as a set of $\binom{N_r}{2}$ pairwise trim runs for every flight condition. So, for a hexacopter, each flight condition requires 22 cases in order to extract the interference matrix coefficients.

The coefficients of M are derived for a set of flight conditions covering the flight envelope. In total, 215 distinct flight conditions were simulated, including hover, cruise, lateral winds, climb and descent. The bounds of this flight envelope (especially forward flight speed and ascent speeds) were informed by the most extreme flight type the Chopper platform was designed to tolerate: the Wall Traverse. The database is further expanded based on a symmetry argument. A hexacopter enjoys 6 axes of aerodynamic symmetry. Due to the staggered vertical planes of rotors, this is reduced to 3 symmetry axes for the Chopper platform, giving a total 552 flight conditions comprising the database. The database point cloud is visualized in Figure 5, with projections onto the helicopter body-frame velocities relative to the wind normalized with tip-speed.

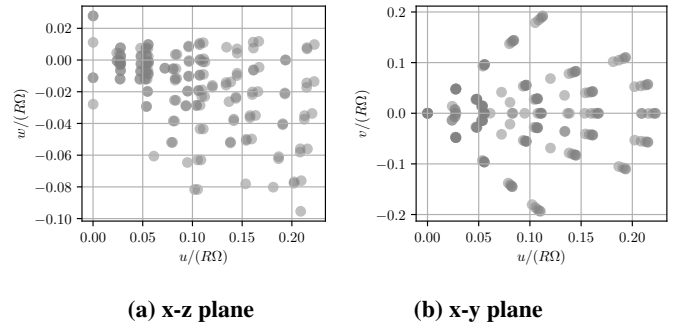


Figure 5. Projections of VVPM interference database onto normalized vehicle velocity planes.

All data points were simulated at a fixed atmospheric density at the lower end of what Chopper is predicted to experience on Mars, with $\rho = 0.0121 \text{ kg/m}^3$. For a given density, the RPM is fixed, set to achieve a target hover blade loading of $C_T/\sigma = 0.12$. With speed of sound $a = 232 \text{ m/s}$ on Mars, this results in a tip Mach number $M_{\text{tip}} = 0.748$.

Parametrization and Interpolation

The interference gain matrices are variable with flight condition, denoted generically by X . Two parametrization approaches for defining X were explored, contrasting a global, vehicle level and a local, rotor-level parametrization. The former considers the body-frame vehicle velocities relative to the wind normalized with tip speed, giving $X = [u, v, w]^T / (\Omega R)$. In contrast, the rotor-level model parameterization is queried based on individual rotor states, specifically advance ratios μ_x, μ_y, μ_z and wake skew angles $\chi = \arctan \frac{\mu}{\lambda}$ such that for the j :th rotor, $X_j = (\mu_{x_j}, \mu_{y_j}, \mu_{z_j}, \chi_j)$, and in total $X = [X_1, \dots, X_{N_r}]$.

Given a choice of dependent variables, the discrete set $\{M(X_n)\}_n$ must be interpolated to enable continuous, real-time evaluation within the flight dynamics simulation. With the rotor-level parametrization approach, each column of $M = [M_1, \dots, M_{N_r}]$ is interpolated separately. Because the chosen parametrization (e.g., body velocities, rotor advance ratios, and wake skew angles) depends on the trim Euler angles and thrust, which are unknown a-priori, the resulting data reside on an unstructured and non-uniform grid. At each instantaneous vehicle state, the model must predict an interference gain matrix comprising 36 output components, whereas the available training set remains comparatively limited in size considering the high-dimensional input and output spaces. Linear interpolation offers robustness under these constraints and is considered as a baseline. The underlying aerodynamic interactions are nonetheless highly nonlinear with flight condition, and capturing these effects would require an impractically fine grid. To better represent the nonlinear dependencies, non-linear interpolation and surrogate-modeling techniques are investigated in this paper as well. Specifically, Radial Basis Function (RBF) interpolants and Gaussian Process Regression (GPR) models are evaluated against the baseline linear interpolation. The associated interpolation error is assessed section using a leave-one-out cross-validation (LOOCV) procedure. Let $X \in \mathbb{R}^{N \times d}$ denote the input states and $Y \in \mathbb{R}^{N \times 6 \times 6}$ the corresponding interference gain matrices. For these tests, the baseline vehicle-level parametrization was used. For each point $i = 1, \dots, n$, the corresponding input-output pair $(X_f^{(i)}, Y_f^{(i)})$ is withheld, while the remaining $n - 1$ samples are then used to train each model. The trained model is subsequently queried at the withheld input to generate a prediction $\hat{M}(X^{(i)})$, which is compared with the true output $M(X^{(i)})$.

Model Limitations

The current model formulation has known limitations. Future work will consider augmentations to the model to address some of these limitations, listed below.

- The assumption of uniform interference will not fully capture interference-induced hub moments. A linear interference variation over the rotor disks is underway as future work.

- By design, all data points are extracted in trimmed, steady-state flight. Under the assumption that the controller has a much faster bandwidth than the wake interference dynamics, this yields an efficient characterization of rotor-rotor interactions within the flight conditions at which the vehicle predominantly operates. The applicability of the resulting model beyond trimmed conditions is, however, likely limited, and needs to be investigated.
- No formal sampling strategy was considered for this work; a semi-uniform distribution was employed, with increased point densities around nominal operating flight conditions. The number of cases was ultimately restricted by compute time.
- The model relies on the underlying assumption that interference velocity contributions are pair-wise independent. Separating the individual rotor contributions allows assessment of how aerodynamic interference influences the vehicle's response to each rotor swashplate inputs, thus the impact on the individual rotor control derivatives. In flight conditions characterized by formation of global wake structures and strong correlations among rotors, however, this simplification no longer holds, which is an inherent limitation of the present model and will be discussed in more detail in the subsequent section.
- No dynamic effects are included in Equation (3). For some interaction characteristics, in particular for rotors with a larger spatial separation, lagged interference may have a non-negligible effect on the vehicle response. Introducing a time delay is expected to yield a more physically coherent phase response.

MODEL PREDICTION RESULTS

Hexacopter Interference Characteristics

Following the data generation procedure, the steady-state uniform interference velocity contributions, denoted by λ_0^{inf} , are derived. In hover and low-speed forward flight, the interference components are generally small relative to the self-induced inflow for the Chopper concept. Rotor-rotor interactions at these conditions are predominantly local to the rotor disk overlaps, where blade-vortex interactions result in unsteady vertical loading as found in Ref. 24. The total, integrated contribution of these interactions to the uniform interference component is minor, however.

In forward flight however, interference pattern grow in strength and complexity for the hexacopter. To illustrate, a compound interference phenomena for one of the downstream rotors (Rotor 3) is sketched in Figure 6. A convected wake from upstream rotor (Rotor 1) induces a downwash, denoted by red, thus increasing the total inflow on the receiving rotor (Rotor 3). In contrast, in a side-by-side configuration like that of Rotor 3 and Rotor 4, each rotor operates in the upwash flow field of the other. This results in a net favorable interference

effect from a power perspective, mutually decreasing the total inflow, which is illustrated with blue.

In Figure 7, the resulting matrices of λ_0^{intf} are presented for cruise (20 m/s) and high-speed forward flight (50 m/s) conditions. Rows corresponding to the receiving rotors, whereas a column corresponds to a rotor giving interference.

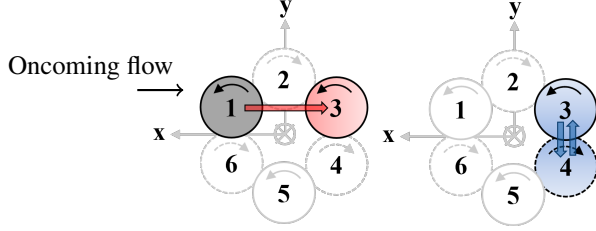
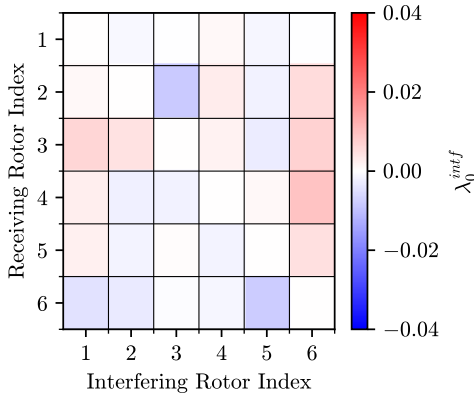
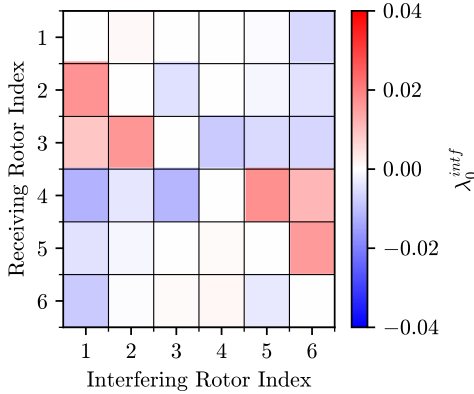


Figure 6. Counteracting interference effects for aft-most rotors in forward flight.



(a) Cruise, $V = 20$ m/s.



(b) High-speed forward flight, $V = 50$ m/s.

Figure 7. Interference component demonstration.

The vertical staggering of rotors results in asymmetrical interference characteristics shown in Figure 7. In cruise, illustrated in Figure 7a, downwash effects emerge from the most upstream rotors (Rotor 1 and 6), onto downstream rotors; primarily on the aft rotors in the same lateral corridor (Rotor 3 and 4). Rotors 2 and 6 show a noteworthy net decrease in

inflow due to interference from Rotor 3 and 5, respectively. Although the receiving rotors are effectively upstream, they are laterally aligned with the advancing side of the interfering rotor, which occupy a higher horizontal plane; thus partially in the upwash flow field of the downstream rotors.

The downwash from front to aft rotors is more pronounced with increased forward flight speed shown in Figure 7b, seen as the apparent red, L-shapes in the matrix heatmap. The side-by-side upwash between rotor pairs (1,6) and (3,4) are also dominant. The strong net decrease inflow at the upstream Rotor 1 in the presence of Rotor 4 is a counterintuitive observation. This effect is unlikely to arise from direct upstream convection of the downstream wake. Instead, it appears to result from pressure-field coupling, and potentially downstream vortex-interaction mechanisms, that alter the inflow distribution of the upstream rotor.

Assumption of Pairwise Independent Interference

The present model assumes that interference contributions from each rotor are pairwise and uncorrelated. To assess the validity of this assumption across different regions of the flight envelope, reconstructions based on the sum of pairwise interference components, $\sum_j \lambda_{ij}$, are compared to the ‘true’ interference increment when all rotors are present (Figure 8). Results are shown for Rotor 6 (upstream) and Rotor 3 (downstream) over a forward-flight sweep up to cruise speed. The combined effect of side-by-side upwash and front-to-aft downwash on Rotor 3 is accurately captured, showing near-perfect agreement with the hexacopter ‘ground truth.’

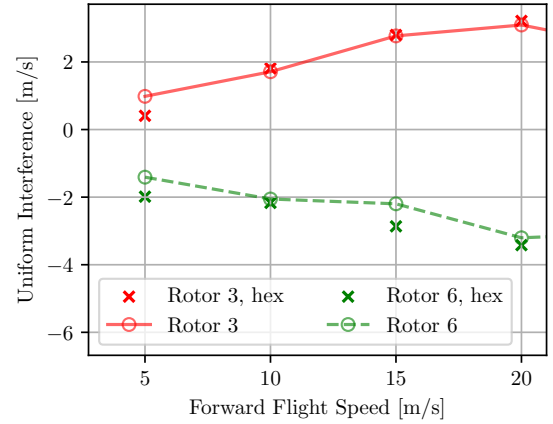


Figure 8. De-correlated pairwise interference assumption holds in low speed forward flight up to cruise.

At instances when global wake structures form, the assumption of de-correlated interference contributions is violated. This was observed in high-speed descent flight conditions. An illustration of the wake geometry at 20 m/s flight speed along a 30 deg descending flight path angle ($v_z/v_h \approx 0.43$, with momentum theory hover induced velocity $v_h = \sqrt{T/(2\rho A)}$) is shown in Figure 9, clearly demonstrating the roll-up of ‘global’ super-vortices and multirotor interactions that cannot

be captured in pairwise simulations. Downstream wake distortion due to tip-vortex interactions affects the overall flow field but may not be captured in the current model. Moreover, extracting meaningful steady-state data in this flight regime is challenging, both physically and numerically. The solution is inherently unsteady and noisy, as rotors ingest not only the wakes of interfering rotors but also their own. This was reflected in increased difficulty achieving numerical convergence under these conditions. The derivation of M relies on time-averaged thrust coefficients, which exhibit large fluctuations at this flight condition. Small changes in parameters such as trim thrust coefficients lead to large variations in wake geometry and inflow velocities, resulting in noisy gain matrices and requiring stricter convergence tolerances. Introducing additional correction factors may therefore be necessary in these flight conditions, or alternative modeling approaches beyond those presented here should be explored. These challenges highlight the limits of the current interference model under highly unsteady flight regimes, where strongly correlated rotor to rotor wake dynamics dominate.

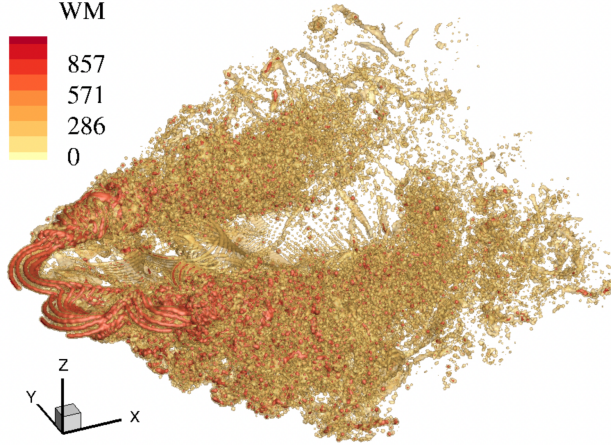


Figure 9. Wake geometry expressed in vorticity magnitude iso-surfaces WM . Global wake structure formation in descending forward flight violates model assumptions.

Applicability to Unseen Flight Conditions

The prediction accuracy of the current model is evaluated for flight conditions not explicitly included in the generated database, including errors due to interpolation over flight speeds, changes in atmospheric density, and variations in blade loading.

Interpolation Error Continuous look-up of the interference gain matrices as function of flight condition is predicated upon interpolation of the database. Three models for prediction at unseen flight speeds were considered; (1) A multivariate linear interpolator, (2) A Radial Basis Function (RBF) model with a cubic kernel, and (3) a Gaussian Process Regression (GPR) model, using a Matérn kernel with smoothness factor

$\nu = 1/2$. The present evaluation focuses on predicting a selected coefficient of the interference gain matrix to reduce dimensionality and improve interpretability of the results; considerations for full matrix predictions will be discussed. The prediction error for a validation point i is computed as the absolute scalar difference $|M_{ij} - \hat{M}_{ij}|$, evaluated only when the validation point lies within the convex hull of the training inputs to ensure a fair comparison among methods.

The resulting fraction of the mean absolute error (MAE) as found with linear interpolation is tabulated in Table 2 for two key coefficients, M_{31} and M_{46} , which dominate downwash on downstream rotors. As such, a fraction smaller than one indicates a smaller error with associated interpolation approach, compared to the linear. The RBF model shows inconsistent performance, with both reduction and increase in error compared to the baseline approach. For both of the presented entries, the GPR presents more than a 20% decrease in mean absolute error. GPR constitutes a probabilistic model that yields both a mean prediction and an associated estimate of epistemic uncertainty. The GPR model may outperform the RBF interpolation in this case because, while both use non-linear kernels, GPR explicitly accounts for observation noise and produces smoothed predictions, which can help mitigate the effects of noisy or irregular data, though the exact contribution of these factors is not quantified in the current paper. To

Table 2. Fraction of linear interpolation error during LOOCV for key interference gain matrix coefficients.

Method	MAE relative to linear interpolation	
	M_{31}	M_{46}
RBF	0.845	1.08
GPR	0.746	0.78

investigate the prediction errors in more detail, the error distribution for the coefficient M_{31} is shown in Figure 10, comparing the baseline linear interpolator (Figure 10a) with the GPR model (Figure 10b). For the baseline method, the errors are dominated by flight conditions in the upper-right quadrant, where $\mu_z > 0$ and $\mu_x \geq 0.1$, corresponding to mid- to high-speed forward flight in descent. The GPR improves the fit in this regime and performs comparably at most other evaluated test points, as seen qualitatively in Figure 10b. This observation aligns with the prior section, where this flight regime was identified as exhibiting non-linear, rapidly varying behavior and elevated levels of noise. Although these characteristics suggest that GPR better captures the complex trends and mitigate noise in rotor-rotor interaction data at such conditions, it was noted in the previous section that the data in this instance may, in the worst case, be erratic or non-physical. Thus, even if GPR appears to match the data more closely, this does not necessarily imply improved predictive accuracy of the physical interference itself.

As a final consideration for future interpolation strategies, the practicality of the interpolators must be addressed. RBF

interpolation circumvents triangulation but requires solving a dense linear system whose condition number and computational cost scale unfavorably with the size of the data set. Standard GPR is formulated for single-output regression, which would require building 36 separate models for the full interference matrix, unless extended to a multi-output framework. While predicting each column independently is feasible, the computational scaling may limit its usefulness for on-board or real-time applications. Nevertheless, the uncertainty estimates that are intrinsic to GPRs are valuable for identifying regions of sparse training data or potentially unreliable predictions, enabling uncertainty-aware analysis of the aerodynamic database.

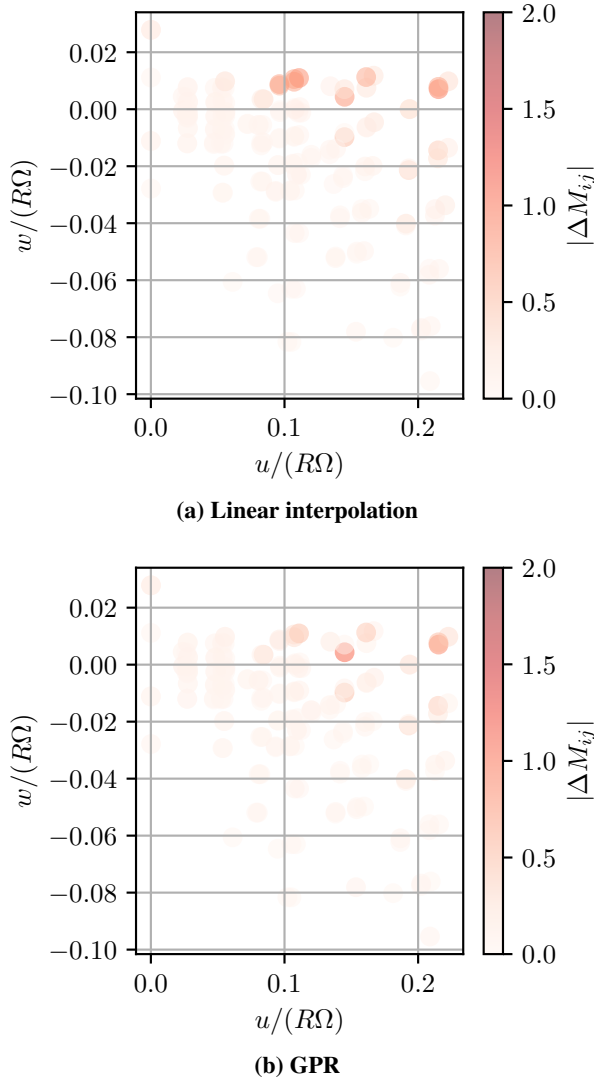


Figure 10. Prediction error in interference from Rotor 1 to Rotor 3, $|\Delta M_{31}|$.

Perturbed Density and Blade Loading The interference database was derived at a fixed atmospheric density. In reality, the density on Mars varies with altitude, geographic location, time of flight, and season. The ability to predict interference at varying densities is investigated. To this end, in-

terference gain matrices were recomputed at flight speeds already included in the database, but with the density increased by +40% from the nominal value $\rho = 0.012 \text{ kg/m}^3$. The rotor RPMs were adjusted to retain the nominal blade loading. The prediction delta in interference velocity is defined as $\Delta \mathbf{v} = R\hat{\Omega}(M - \hat{M})\hat{C}_T$, where $\hat{C}_T$ is the trim thrust coefficient corresponding to the perturbed density, and $\hat{M}$ is the interference gain matrix obtained at that density. In Figure 11, the total interference error, averaged over the six rotors, is shown as a function of flight speed. For low to moderate flight speeds, the error is small. At higher flight speeds, however, a more significant error develops, showing a clear bias. Recall, that induced velocities scale inversely with the square root of the density (hover induced velocity $v_h = \sqrt{T/(2\rho A)}$). Thus, increasing density reduces inflow velocity and therefore produces a larger wake-skew angle for a given flight speed. This comparison in Figure 11 highlights the importance of explicitly accounting for wake skew, in particular at varying atmospheric density, as provided by the rotor-level parametrization.

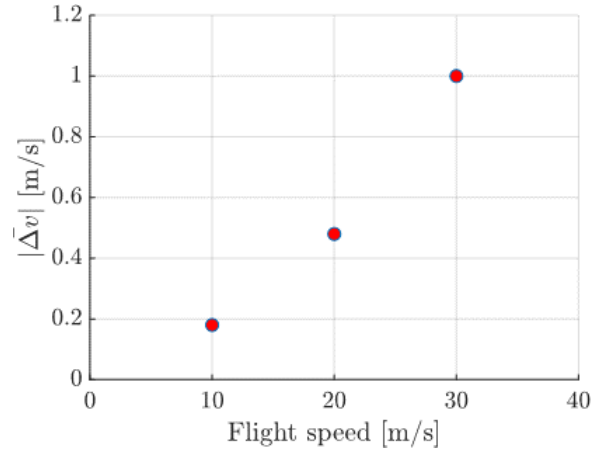


Figure 11. Interference velocity prediction error at +40% density as function of flight speed.

Similarly, the database was generated at a fixed blade loading, which requires knowledge of the prevailing air density at the time of flight in order to set the RPM appropriately. In practice, the vehicle will operate at a blade loading that deviates from this design point. The sensitivity to this assumption was examined. To that end, interference gain matrices were recomputed at flight speeds already contained in the database, but with perturbed blade loadings of ± 0.02 from the nominal value $C_T/\sigma = 0.12$ in the simulation. These perturbed matrices are denoted by $\hat{M}$. Define the (dimensionalized) prediction delta in interference velocity $\Delta \mathbf{v} = R\hat{\Omega}(M - \hat{M})\hat{C}_T$, where $\hat{C}_T$ refers to the trim thrust coefficient at the perturbed blade loading. The resulting prediction errors are presented in Figure 12. Slightly larger errors are observed for the reduced blade loading, but both perturbations remain within the typical magnitude of the interpolation error, and it is therefore concluded that the fixed-blade-loading assumption is acceptable.

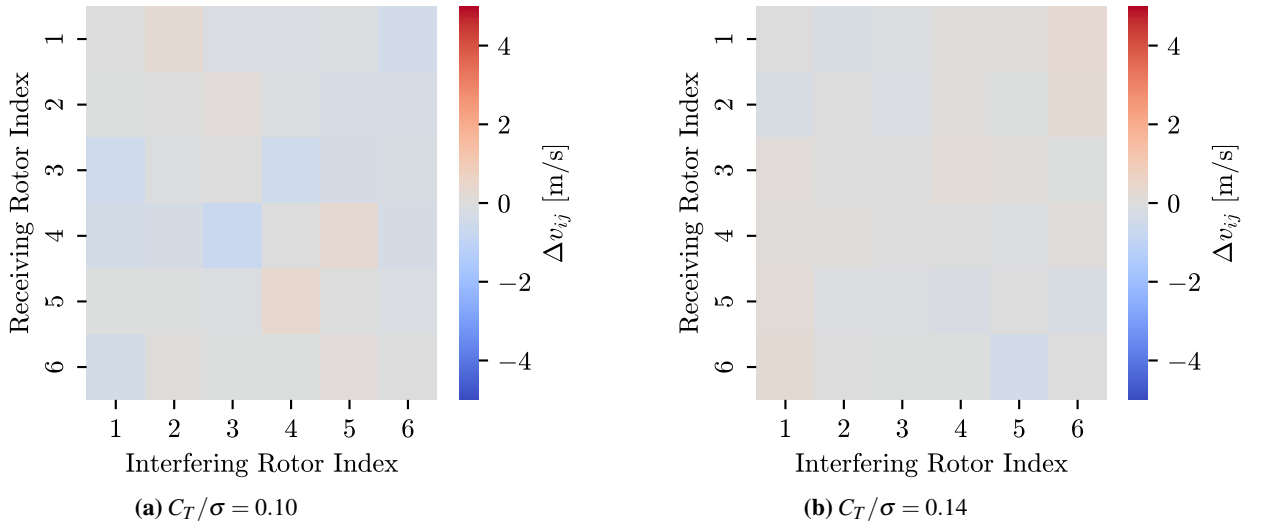


Figure 12. Interference velocity prediction error for perturbed blade loading in cruise conditions.

FLIGHT DYNAMICS WITH ROTOR-ROTOR INTERFERENCE

Following a brief account of the model integration into HeliCAT, the impact of multirotor wake interactions on trim, linearized open-loop response in hover and cruise is assessed. A closed-loop simulation of the Wall Traverse (see Figure 3) is demonstrated, to assess how rotor-rotor interaction may impact requirements of representative science mission flight trajectory on Mars.

Implementation Considerations

HeliCAT divides the computation of aerodynamics rotor loads into “models”, which implement self-contained physics and exchange information between each other. Four models are the main constituents and shown in Figure 13; self-induced inflow, in-ground-effect correction, rotor-rotor interference model, and finally the blade element theory model, which takes as input the inflow and interference to integrate the total rotor loads. The added rotor-rotor interference formulation is readily accommodated within this architecture. In the “model” paradigm, it fits in place of heritage interference models (such as those developed for Ingenuity’s coaxial rotor system) without requiring changes to other models.

The baseline model implemented in HeliCAT relies on the global parametrization with wind-relative vehicle velocities in the body-frame. This approach was chosen in part for ease of implementation, and justified by the observation that in steady-state flight, the advance ratios of the rotors coincide with the body-frame velocities normalized by tip-speed. The baseline model is used for trim and analysis and linear open-loop responses. Motivated by the observed sensitivity to density variation, the rotor-level parametrization was implemented and used in the non-linear closed-loop simulation to disambiguate flight conditions at varying densities.

Multidimensional linear interpolation of the interference gain matrices was used in this study, but is notoriously inefficient on an unstructured grid. The procedure requires constructing a Delaunay triangulation and performing simplex searches to locate the appropriate interpolation cell for each query point. This approach imposes a substantial runtime cost, which grows with the number of data points, as a naïve implementation leads to traversing over every simplex. To mitigate this, the unstructured interpolation is used to generate a much finer rectangular, axis-aligned grid, which enables fast, constant-time look-up. While this additional interpolation step increases overall interpolation error, this additional error is reduced as the number of grid points is increased. It was found that with enough points, but still reasonable memory usage, the additional error becomes negligible.

Trim

The collective angles for a longitudinal trim sweep are shown in Figure 14, comparing with and without the rotor-rotor interference model enabled. The rotors placed in the upper horizontal plane (odd indices), are illustrated with solid lines, and lower rotors are denoted with dashed lines. The color scheme follows that of Figure 2a. The impact of interference on the collective trim in hover is minimal, and the solutions are in principle identical. As advance ratio grows, trends consistent with the results presented in previous section are observed. Mutual tandem upwash on front rotors (1 & 6, in green) gives an effectively larger angle of attack, such that the required collective for the same thrust is smaller. As expected, this effect grows with forward flight speed, with a max delta of approximately -1 degree collective at 30 m/s. The aft-most rotors are subject to the downwash from the wake convected rearward in forward flight, which expresses itself as an increase in trim collective for these rotors (3 & 4, in red) when interference is accounted for. Consistent with the trends shown in Figure 6, this phenomena is partially counteracted by side-by-side upwash at increased flight speeds. Peaking at 20 m/s,

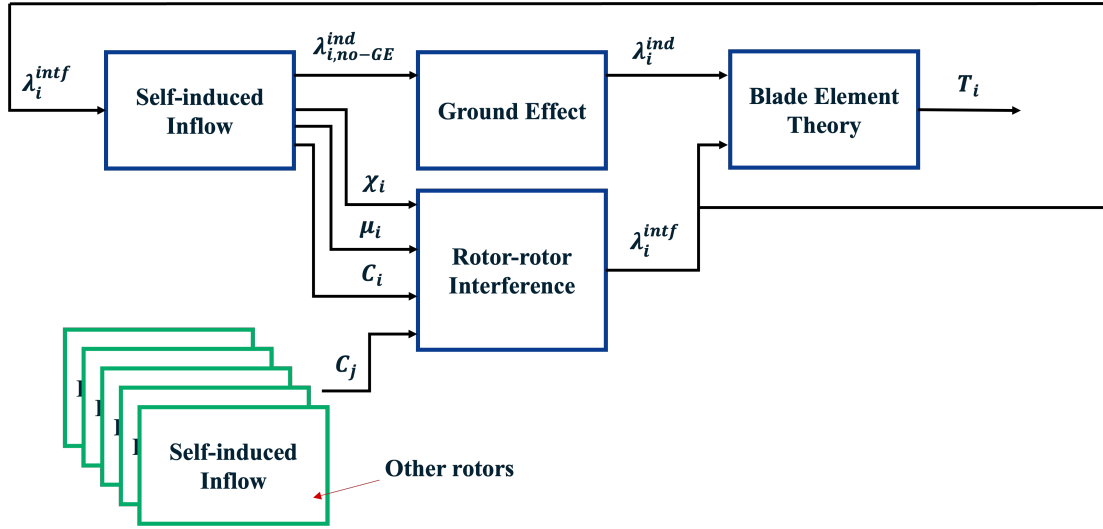


Figure 13. Schematic of aerodynamic rotor loads module as implemented in HeliCAT, including the additional rotor-rotor model.

a max collective increase of around 0.5 degrees is observed. As forward flight speed increases, there is a small break in symmetry with the "No Interference" model due to the center of mass not being perfectly aligned with the geometric center line of the helicopter. It is offset by about -0.02 m in x and -0.01 m in y , placing it closest to Rotor 4. This effect is partially cancelled when interference is included, likely due to the staggered arrangement of the rotors, which experience different levels of interaction depending on whether they are in the upper or lower horizontal plane. Overall, accounting for rotor-rotor interference has a noticeable but modest effect on trim.

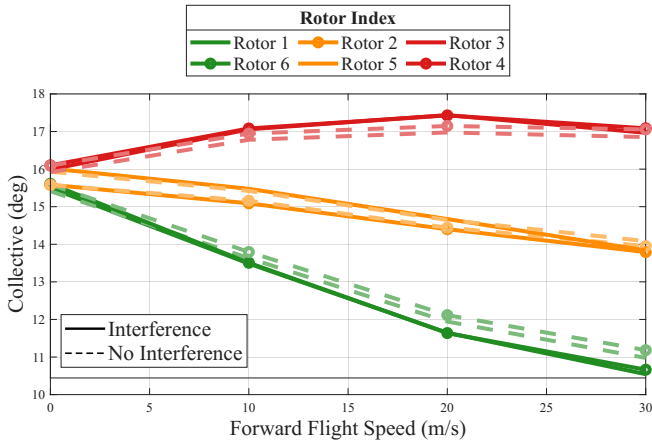


Figure 14. Trim collectives as function of forward flight speed.

Linearized Dynamics

Linearized models from HeliCAT, with and without including interference, are compared in hover and cruise conditions to assess the impact on the bare airframe open-loop response and

stability characteristics. It is noted, that all results presented in this section used the parametrization with body-frame velocities.

Hover A root locus of the reduced order linearized model in hover is presented in Figure 15. Inclusion of rotor-rotor interaction disambiguates the rotor speed degrees of freedom and disperses the associated roots. A subset of the unstable mode(s), specifically the roll and pitch oscillation modes, experience a slight change in natural frequency. Overall, the impact of rotor-rotor interaction on the bare-airframe eigenvalues in hover is small. This conclusion is reflected in the on-axis open-loop responses, shown in Figure 16.

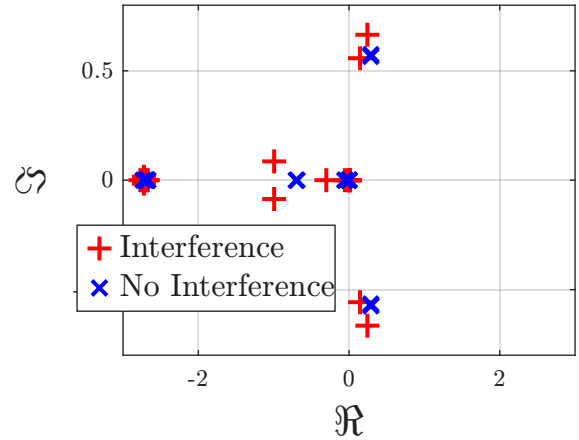


Figure 15. Bare airframe root locus in hover.

The heave response to heave aligned input, w/δ_w , is presented in Figure 16a. The responses compare very closely at higher frequencies. At lower frequencies, a phase increase and minute attenuation is observed. The same is true for the on-axis pitch response in Figure 16b, where response magnitude is virtually unaffected, and phase increase is observed at

the lower frequencies, between 0.1-0.3 Hz. It is noted, that the interference states are currently modeled based on an instantaneous assumption. Introducing a time delay may alter the phase of the response.

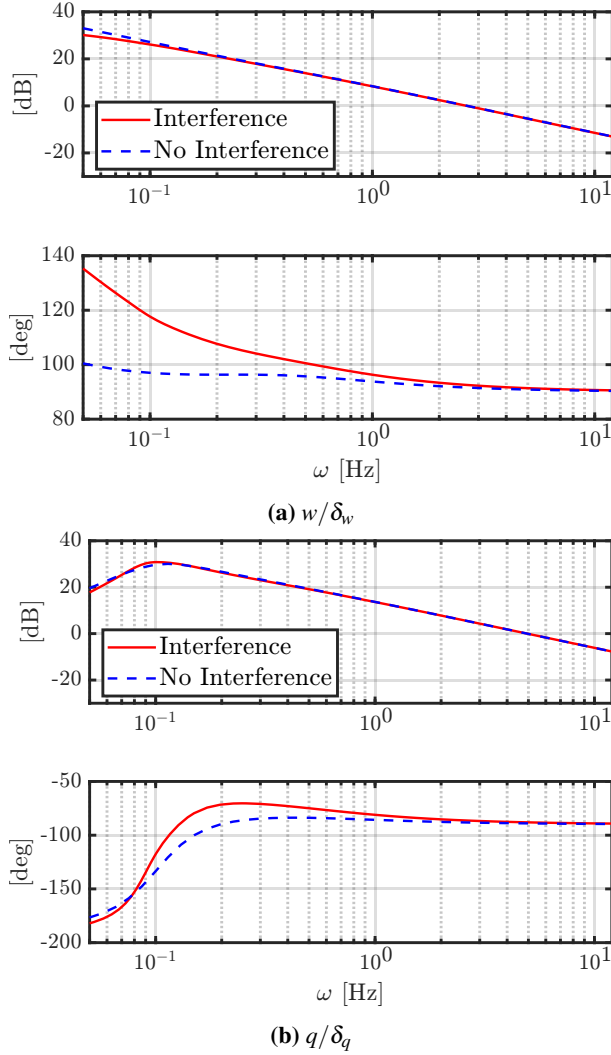


Figure 16. Open-loop response in hover with and without interference.

Forward Flight The root locus of the linearized, reduced model in cruise condition ($V = 20$ m/s) is presented in Figure 17. Changes in stability characteristics when interference is accounted for are more prominent in this flight condition, as expected, considering that interference velocities were found generally larger in magnitude in this regime. Notably, rotor-rotor interference causes a faster unstable longitudinal phugoid mode at the given forward flight speed. As implied in Figure 17, the impact of rotor-rotor interactions are more noticeable in the open-loop responses in forward flight, presented in Figure 18. Response attenuation below 0.4 Hz is observed with interference in both heave and pitch response (Figure 18a and Figure 18b, respectively). The longitudinal response to longitudinal wind u/u_{wind} is included in Figure 18c, which also exhibit a response attenuation. For all

responses, impact on phase is seen only at the lowest frequencies.

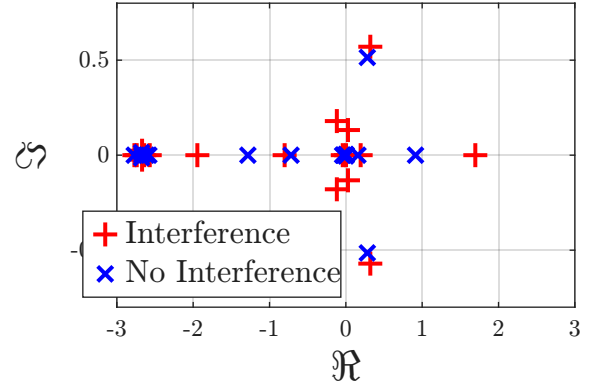


Figure 17. Bare airframe root locus in forward flight with and without interference, ($V = 20$ m/s).

The impact of rotor-rotor interference is also investigated by comparing key stability derivatives in hover and forward flight in Figure 19. The pitch damping M_q in Figure 19a, shows an increase in magnitude in hover, whereas the difference to the no interference case is much smaller in forward flight. An identical trend is seen for the roll damping, L_p , in Figure 19b. The pitch response to longitudinal velocity, M_u , in 19c is increased slightly with interference at slower speeds, but both lines trend to a decrease with flight speed.

In general, the emergence of a positive M_w governs the unstable longitudinal phugoid mode in the root locus in Figure 17. This instability arises from the coupling between vertical and longitudinal rotor dynamics, which increases sensitivity to pitch moments induced by vertical airspeed perturbations (Ref. 37). The M_w derivative is more susceptible to interference effects and exhibits greater variability with forward flight speed, seen in Figure 19d. Consistent with the observations in Figure 17, M_w is significantly increased at cruise speed (20 m/s) when the interference model is enabled. A similar trend with tandem helicopters in forward flight was accounted for in Ref. 1 and observed in Ref. 38, where increased downwash from the front to aft rotor due to a positive w (yielding a thrust increase on the rotors) impinge a destabilizing pitch-up moment, thus adversely influencing the angle-of-attack instability. Interestingly, in contrast to the monotonic trend in M_w with forward flight speed predicted by interference-agnostic models, the derivative decreases again at higher flight speeds, and rotor-rotor interference has a small stabilizing effect again. It is possible, that counteracting interaction effects are present in addition to the front-to-aft downwash at the higher flight speeds. Further understanding of this instability's susceptibility to interference as a function of forward flight speed will be important for evaluating stability margins and flight qualities.

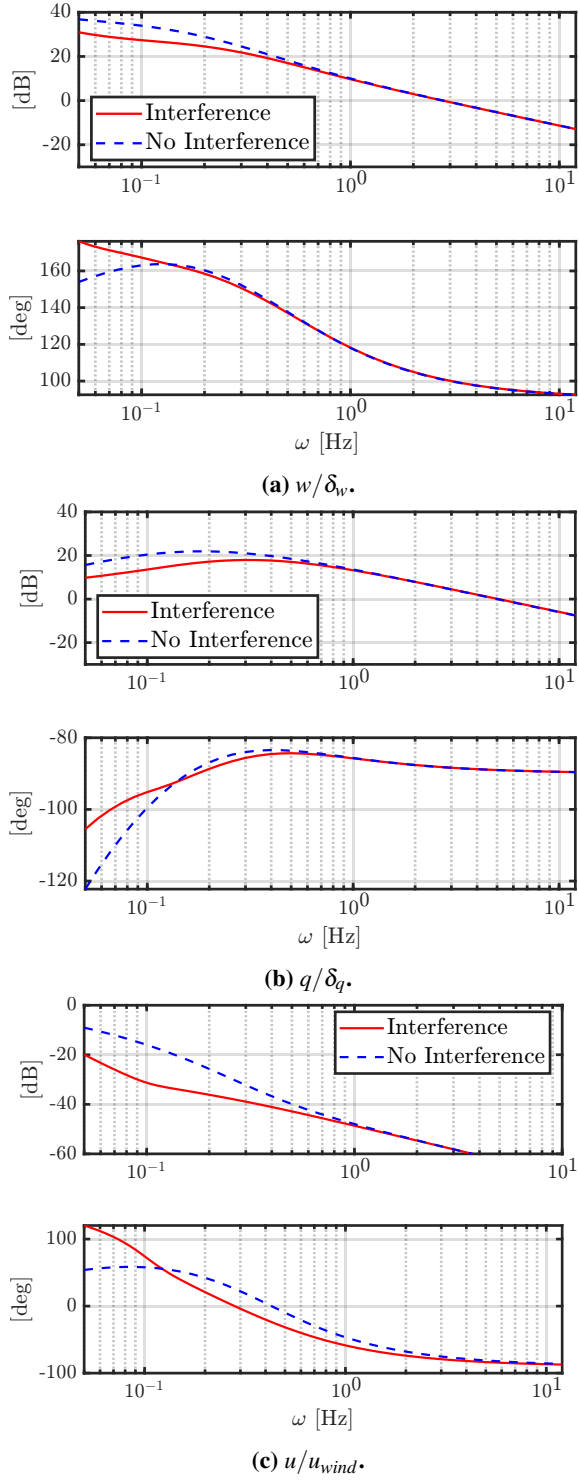


Figure 18. Open-loop response in cruise with and without interference, $V = 20$ m/s.

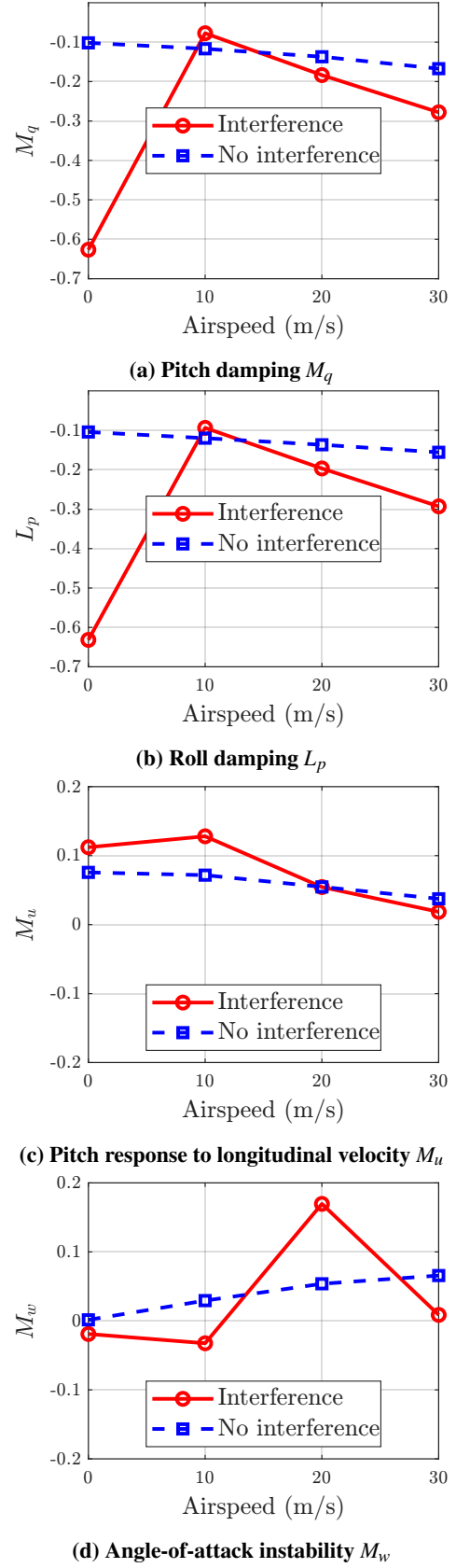


Figure 19. Stability derivatives with and without interference effects.

Real-time Closed-Loop Simulation A closed-loop simulation of the Wall Traverse (see Figure 3) is performed with and without the rotor-rotor interference model. This taxing flight trajectory drives the performance limits and is therefore an important point to evaluate when interference effects are accounted for, to ensure fair system margin assessment. It is not directly aimed, however, to fully expose the most critical flight conditions from a flight dynamics point of view; climb conditions are likely not the most dire for rotor-rotor interference and its impact on flight dynamics. A closer examination of such conditions will be considered in future work.

The presented simulation used the rotor-level parametrization to better accommodate the varying atmospheric densities experienced during the flight. Figure 20 shows the flight trajectory in the ground frame during the simulated wall traverse. The time from take off to spin down was approximately 200 seconds.

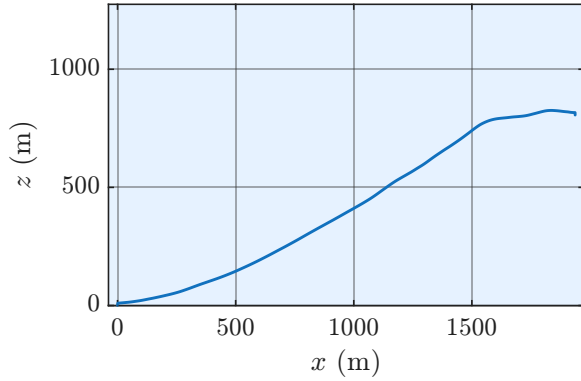


Figure 20. Simulated helicopter trajectory (blue line) during Wall Traverse, expressed in ground frame.

The simulation includes horizontal wind disturbances derived from data measured by Perseverance’s MEDA instrument (Ref. 39) in absence of other data from Mars, although it is unlikely to be representative of a wall traverse in Valles Marineras. A scale factor of 1.5 was applied to the speed to account for the difference between the MEDA altitude above ground level (AGL) and the flight altitude AGL. The MEDA instrument only measures horizontal wind; the vertical wind speed was estimated for the purpose of the demonstration simulation. A vertical wind disturbance was taken as a low-frequency sinusoidal with amplitude 2 m/s. The resulting true airspeed expressed in the body frame experienced over the course of the flight is shown in Figure 21 with x and z velocities, (v_x , v_z), on the left and right vertical axis, respectively. The bounds of the rotor-rotor interference database was generated based on a-priori estimated flight profiles. To ensure that the simulated trajectory, including wind perturbations during the wall climb, remains within the limits of the interpolation, Figure 22 illustrates the database boundary in red dashed lines. The simulated flight trajectory, expressed in body-frame airspeeds, is drawn in blue. For the majority of the simulated flight, the interference queries remain within the bounds of the convex hull of the interference data. At

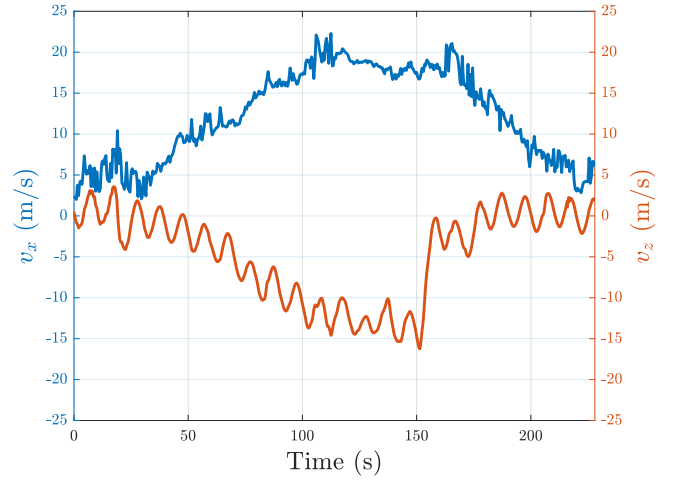


Figure 21. Airspeeds in helicopter bodyframe during Wall Traverse.

the highest descent rates, the trajectory briefly exceeds the database boundary, though this excursion is small and unlikely to significantly affect the interpolation results.

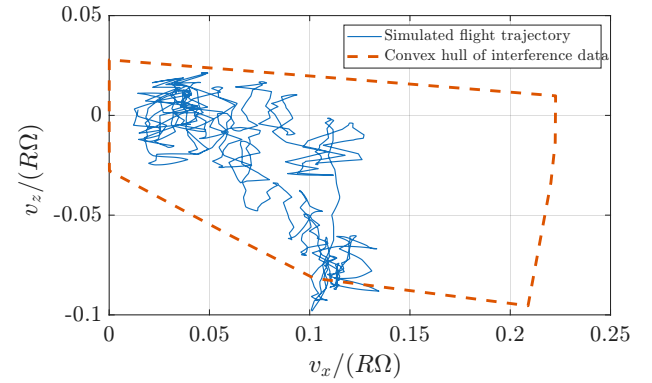


Figure 22. Check of model interpolation bounds.

The change in total inflow at the rotor disks due to interference affects rotor power. The relative impact on mechanical rotor shaft power, computed as $(P_{\text{intf}} - P_{\text{nointf}})/P_{\text{nointf}}$, when including interference in the simulated wall climb is shown in Figure 23. The power readings are filtered through a low-pass filter, but the low-frequency content induced by vertical wind perturbations remains discernible.

A net increase in inflow due to downwash generally reduces rotor efficiency, thus increasing power, which is captured in the reduced-order model and observed for the aftmost downstream rotors (red) in Figure 23. Conversely, mutual side-by-side upwash can have a favorable effect, as seen for the front rotors (green). This effect diminishes at the highest climb velocities and forward flight speeds and is most pronounced during leveled longitudinal deceleration. Nevertheless, the relative impact remains below 5% for a single rotor: the largest effect is net positive, while adverse effects are limited to roughly 3% at the highest forward-flight speed.

Overall, rotor-rotor interference exerts a small but measurable influence on rotor power during the wall-climb, and the model

predicts both beneficial and adverse contributions from the six rotors that vary with the instantaneous flight condition.

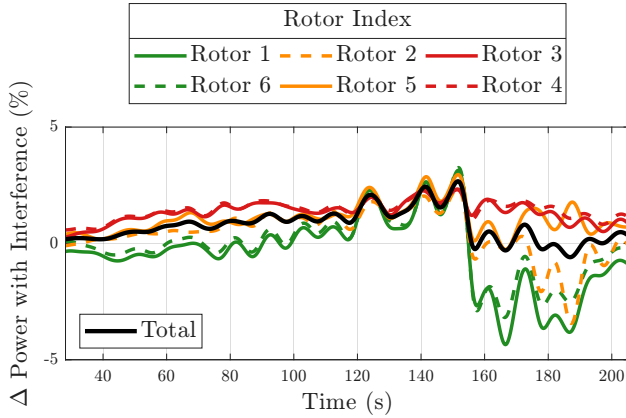


Figure 23. Impact of rotor–rotor interference on mechanical shaft power during wall climb.

CONCLUSIONS

This paper presented the derivation of a real-time capable, linearizable rotor–rotor interactions aerodynamics model for a Mars hexacopter concept, extracted from a mid-fidelity VVPM wake database covering the full flight envelope. The prediction capability of interference at unseen flight conditions was investigated. The reduced-order interference model was implemented into a flight dynamics simulation environment, and the impact on trim, linearized dynamics and closed-loop characteristics were evaluated. The following conclusions were supported by the results:

1. The proposed interference model accurately captures compound interaction effects experienced in multirotor systems, such as mutual upwash in side-by-side configurations counteracting the downwash from upstream to downstream rotors.
2. The model was seen to extend well to non-nominal blade loading conditions. Variations in atmospheric density had a measurable effect on interference velocities, underscoring the need to account for wake skew angle in the model parametrization when flying in varying atmospheric densities. Gaussian Process Regression reduced the interpolation error across flight speeds by up to 20% compared with linear interpolation, although its scalability may limit its suitability for real-time simulation.
3. The applicability of the model at flight conditions characterized by global wake structures was found limited, such as forward flight at high descent rate, as the assumption of pair-wise interference decomposition is violated.
4. Observed impact of rotor–rotor interaction for the Chopper hexacopter concept on trim and linear response in hover was small, yet an increased attitude damping was

observed. In forward flight, on-axis bare airframe responses exhibited attenuation at the lower frequencies due to interference, as well and increased sensitivity of the pitch response to vertical perturbations in cruise.

5. Predicted total increase in mechanical shaft power due to multirotor wake interactions remained below 5% throughout a flight trajectory representative of a hypothetical science mission for the Chopper concept.

FUTURE WORK

Model improvements to address current limitations are in progress. These enhancements include implementing a linear variation of interference across the rotor disks, introducing time delays to capture first-order wake dynamic effects, and expanding the database to incorporate out-of-trim states. Future efforts will also compare the linearized model dynamics results using the rotor-level parametrization that accounts for wake skew. Finally, further exploration of the flight envelope is required to identify the most critical points of stability degradation due to rotor–rotor interference, and subsequent evaluation in a closed-loop setting to assess impact on flying quality.

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