Critical Aerodynamic and Performance Upgrades to Enable Larger Mars Rotorcraft Such as the Chopper Platform

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ABSTRACT

Leveraging lessons learned from NASA's Ingenuity Mars helicopter and concepts such as the Mars Sample Recovery Helicopter, and Mars Science Helicopter has enabled partners at NASA's Jet Propulsion Laboratory (JPL), NASA Ames, and AeroVironment, Inc. to mature a hexacopter vehicle concept (Chopper) with the ability to support a wide range of mission scenarios. This work focuses on the critical aeronautics-related challenges encountered transitioning from an Ingenuity-size vehicle to a much larger vehicle (~15 times the mass) and discusses engineering efforts to address these challenges. Critical upgrades include optimized airfoils, higher solidity blades, and higher fidelity computational models. Because multiple rotors are required to lift the heavier vehicle, increased understanding of the impact of rotor-to-rotor interactions is also necessary. Rotors have been designed that are tailored to more demanding missions and will be validated in a joint test campaign between the partners. While the Chopper concept will be utilized to illustrate these maturation efforts, the lessons learned are applicable to other heavier next generation Mars rotorcraft platforms also.

INTRODUCTION

For decades, Mars exploration and science missions have been accomplished by rovers, landers, and orbiters. From 2021 to 2024, the Ingenuity helicopter carried to Mars by NASA's Mars 2020 mission proved that flight in atmospheres, other than Earth's, is possible with 72 successful flights. These flights suggested the possibility for new mission concepts requiring greater payload capacity, even more challenging environmental/operational conditions, and longer/faster traverse distances. However, at a total mass of 1.8 kg, Ingenuity was not sized to carry the breadth of heavier science instruments required to support these future mission concepts. To realize future science and human exploration missions on Mars utilizing rotorcraft, it is important to understand the aeronautics-related challenges of designing a much larger vehicle. This paper addresses the aerodynamic and other flight performance advances needed to enable larger Mars rotorcraft.

Chopper is a conceptual vehicle design that builds on lessons learned from previous collaborative rotorcraft projects by NASA's JPL, NASA Ames, and AeroVironment Inc.; these projects include proposed vehicles such as the Mars Science Helicopter and the Mars Sample Recovery Helicopter. The Chopper concept is a ~30 kg hexacopter design based on the requirements to travel at least three kilometers per flight while carrying a three-kilogram payload. Such a vehicle platform, "could form the basis for future standalone science missions or be leveraged in a utility capacity—for example, transporting samples in the context of sample return from Mars (Ref. 1)."

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BACKGROUND

The success of Ingenuity has renewed interest in previous Mars aircraft concepts and inspired new designs. Such vehicles could have significant impact to the science (Ref. 2) and human exploration communities. Examples of other, past and present, Mars aerial flyer concepts are detailed in Ref. 3 (which includes designs existing before ~2020). Ref. 4-9, while not comprehensive, are representative of additional vehicle concepts that have been developed from 2020 onward (after Ingenuity launched).

The Chopper concept builds on previous efforts detailed in Refs. 10-12 (Mars Sample Recovery Helicopter and Mars Science Helicopter, Figure 1) and 13-17 (airfoils and ELISA tool from the Rotorcraft Optimization for the Advancement of Mars eXploration, ROAMX, project) that informed the development of the Chopper platform. In Ref. 1, Grip, et al first described the overall Chopper conceptual design effort including design space, mechanical sizing, and power systems. The present work augments Ref. 1 by providing additional focus on the rotor and vehicle flight performance improvements required to facilitate the growth from an Ingenuity-class vehicle to a larger Mars aerial vehicle. The current improvements include rotor optimization, improved wake modeling, and enhanced vehicle performance predictions.

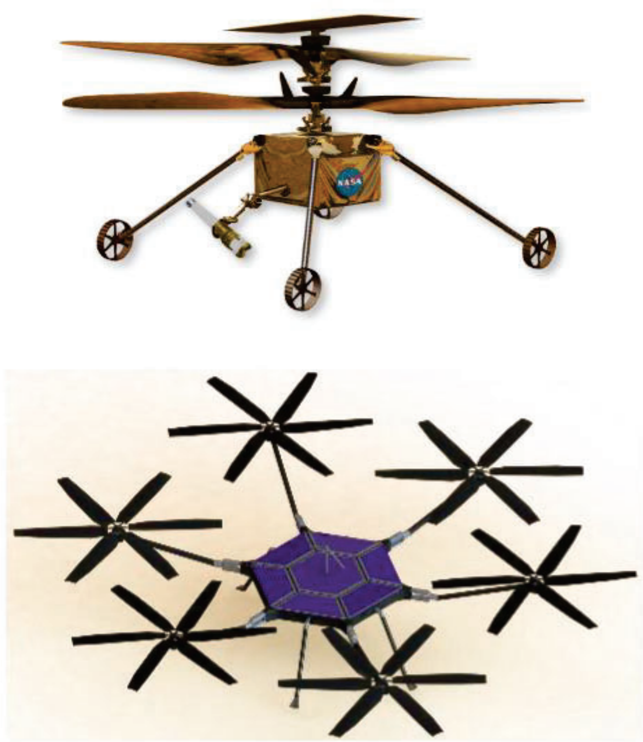

Figure 1. Sample Recovery Helicopter concept (Top) ***Image Credit: NASA JPL/Caltech*****, Mars Science Helicopter concept (Bottom)** ***Image Credit: NASA Ames.***

While other configurations were considered at the beginning of the Chopper concept study, the hexacopter form was selected through trade studies, affirming previous design decisions from the Mars Science Helicopter project. Some major differences between the MSH concept and the Chopper concept are below: Chopper is not constrained to the size of a Pathfinder aeroshell, and therefore, did not require the rotor arms to fold to meet geometry constraints, hence reducing complexity. Chopper's blades (0.675 m radius, Ref. 1) are slightly larger than MSH's blades (0.640 m radius, Refs. 11-12). Other notable differences are the movement from the solar panel in the center of the rotorcraft body to six smaller arrays on top of each rotor, improved battery, and a lighter weight structure (Ref. 1). MSH rotors use double-edged plate airfoils (corresponding to roamx-2101 parameterized airfoils, see Ref. 13) opposed to the more traditional thin, teardrop-shaped airfoils utilized by Ingenuity and SRH. The Chopper concept utilizes new airfoils based on ROAMX designs that are modified for improved manufacturability. The rotors are also higher solidity than the MSH design.

CONCEPT VEHICLE DESCRIPTION

While the technology developments described herein likely have implications for next-generation, heavier Mars rotorcraft generally, the impact will be illustrated through application to the Chopper vehicle concept (Figure 2). Environmental assumptions were taken from Jezero Crater on Mars where Ingenuity and Perseverance have operated. The current models assume a 24% unallocated system-level mass margin on top of the PBE (probable best estimate) mass resulting in a maximum system mass of 36.1 kilograms, and growth of payload mass up to 10 kilograms if this margin is otherwise unallocated (Ref. 1). Chopper's landing gear uses heritage designs from Ingenuity. The material upgrades for the composite blades by AeroVironment Inc., enhanced power, and avionics designs are also critical to perform more robust missions. The Chopper rotors were developed following the rotor design process developed under the ROAMX project (Ref. 18) and using the ELISA optimization tool (Ref. 17); both ROAMX and the ELISA tool were developed as an Early Career Initiative project funded by NASA's Science and Technology Mission Directorate. ROAMX focused on aerodynamic optimization. A key advancement in the state-of-the-art under Chopper has been evaluating the manufacturability of such a rotor design through an in-parallel study performed by AeroVironment, Inc. These rotors can be seen in Figure 2 and will be discussed in more detail in the following sections. Tables 1-3 contain environmental assumptions, a summary of key performance parameters, and properties for the Chopper concept vehicle. The rotors will be primarily operated by collective control, versus rotor rpm speed control, and will not have cyclic pitch control inputs (unlike Ingenuity). The rotors will be rigid at the hub/blade attach points with respect to in- and out-of-plane forces and moments.

Figure 2. Chopper platform concept CAD. ***CAD Credit: JPL (Ref. 1), Rotor Credit: NASA Ames (Ref. 17).***

Table 1. Expected Environmental Conditions.

Parameter	Value
Density	0.013 kg/m^3
Speed of sound	235.696 m/s
Viscosity	1.13x10^{-5} kg/m-s
Gravity	3.7114 m/s^2

Table 2. CHOPPER Performance.

Parameter	Value
Range per day	3 km
Ground speed	20 m/s
Flight time of day	0900 LTST
Endurance	207 s
Flight time	150 s
Takeoff/landing and science time	57 s

Table 3. CHOPPER Properties (Ref. 1).

Parameter	Value	Comment
Aircraft mass	36.1 kg	Includes 24% unallocated mass margin
Payload mass	3 kg	
Number of rotors	6	
Blades per rotor	6	
Rotor radius	0.675 m	
Thrust-weighted solidity	0.3	
Rotorcraft diameter	3.75 m	
Landing gear diameter	2.21 m	3 legs
Ground clearance	0.34 m	
Solar array area	1 m^2	
Battery cells	84	28S3P configuration

TECHNOLOGY ADVANCEMENTS

Airfoil Optimization

Airfoils for compressible, low Reynolds number conditions generally optimize towards very thin airfoils with sharp leading edges (Ref. 13). Manufacturability, blade structure (flap frequency), and blade mass, however, generally favor a thicker airfoil. To explore the potential of high-solidity rotors, both the SRH rotor (which was the result of the optimization of Ingenuity's planform and twist, using identical 5% thick airfoils outboard, see Ref. 13) and the ROAMX rotor (fully hover optimized rotor using 1% thick optimized airfoils, see Ref. 13) were used as starting points for the preliminary rotor design and solidity variation. This allowed for a preliminary performance comparison of the optimized airfoils (ROAMX) and Ingenuity airfoils (SRH) while the Chopper conceptual vehicle design was in progress.

Preliminary efforts at AeroVironment Inc. indicated that achieving desired mass and structural requirements required increasing airfoil thickness to at least 2.5%. Aerodynamic analyses were performed to assess the performance impact of several methods for adding this thickness to unconventional roamx airfoil parameterizations. As such, the roamx-0202 airfoil parameterization, see Figure 3, constrained to 2.5% thickness was selected for the Chopper rotor, instead of the constant thickness roamx-0201 profiles as used on the ROAMX rotor. Future studies will explore local increases in airfoil thickness, incorporating more complex parameterizations once additional design constraints are known.

While part of the ROAMX rotor's roamx-0201 parameterized airfoils derive their aerodynamic advantage over Ingenuity's clf5605 from reduced thickness at high-subsonic Mach numbers, unconventional airfoils can still significantly enhance rotor hover efficiency without relying on this thickness advantage. Ref. 13 demonstrated the influence of blade thickness on the Pareto-optimal rotor set for ROAMX rotor variants, utilizing roamx-0202 parameterized airfoils with a third thickness objective to filter desired blade thickness distributions from the Pareto-optimal airfoil sets. The results clearly show the influence of blade thickness on attainable rotor figure of merit values for Ingenuity-class rotors. Additionally, it is also shown that even with a constant t/c = 5% outboard (similar to the Ingenuity and SRH rotors), substantial improvements remain achievable with unconventional rotor geometry and airfoils (Figure 4).

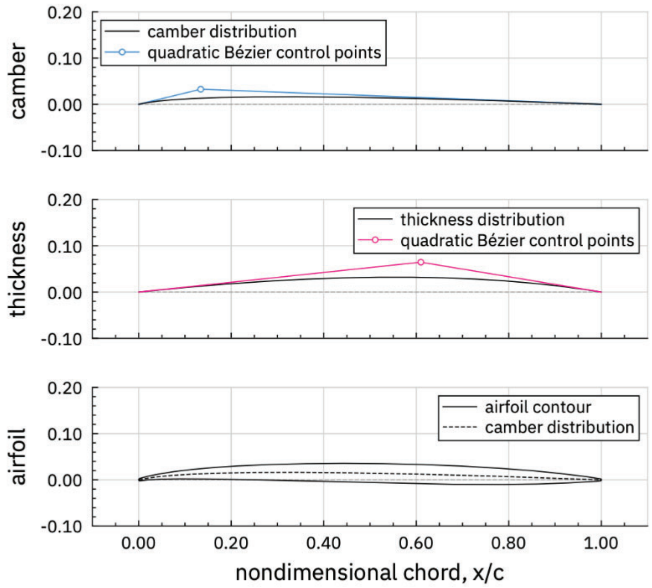

Figure 3. Example roamx-0202 parameterization.

As the vehicle design matures, the authors will continue to iterate on the airfoil/rotor design to tailor it to the final vehicle geometry and mission requirements.

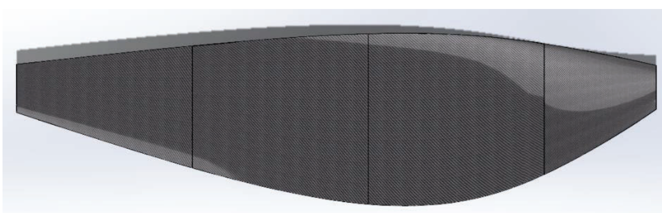

Figure 4. Chopper rotor blade.

Rotor Design and Performance Predictions

Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics II (CAMRAD II), a widely used rotor performance and aeromechanics analysis tool, was used to explore possible design candidates for the Chopper concept vehicle. Prior rotor performance analyses of blades using SRH and ROAMX airfoils were performed using CAMRAD II for various numbers of blades and solidity values. To directly compare the performance, the original blades used for SRH and ROAMX were chord-scaled to achieve desired solidities for the Chopper rotor. It was observed that rotor efficiency, as defined by the figure of merit, is maximized for Chopper in the blade loading operating range of 0.1 to 0.15 and at a solidity range of 0.25 to 0.3 for both SRH and ROAMX airfoils as illustrated in Figures 5 and 6. At the prescribed operating conditions the ROAMX airfoil, an example of next generation optimization practices, was found to produce superior performance compared to the SRH (Ingenuity) airfoil.

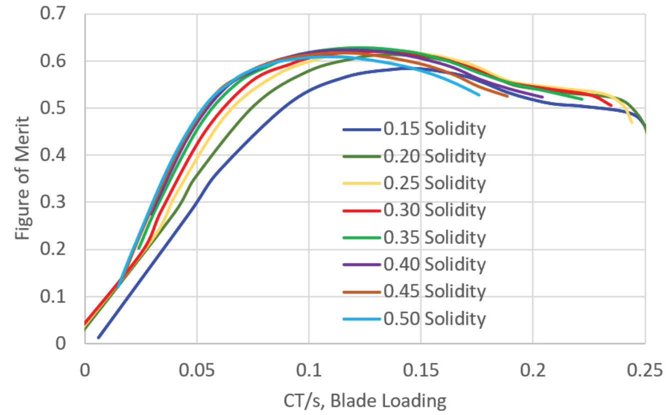

Figure 5. Figure of merit vs blade loading of single rotor SRH 6-bladed configuration at various solidities.

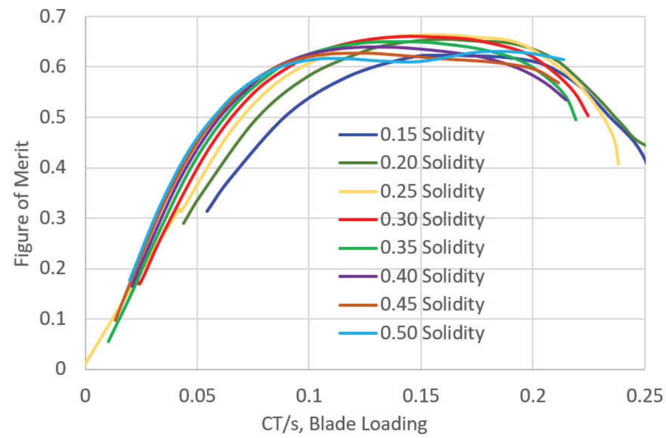

Figure 6. Figure of merit vs blade loading of single rotor ROAMX 6-bladed configuration at various solidities.

Figure 7 shows the effect of both blade number and solidity on figure of merit of the ROAMX rotor. While increasing the number of blades improves rotor hover performance (increasing solidity increases thrust), it also adds additional mechanical complexity. Thus, higher number of blades (8+) was not considered feasible. The study resulted in the selection of the 6-bladed configuration with a solidity ratio of 0.30. Higher solidities also consistently had challenges with blade overlap and reduced FM. Figure 8 shows solidity versus thrust for the 6-bladed configuration.

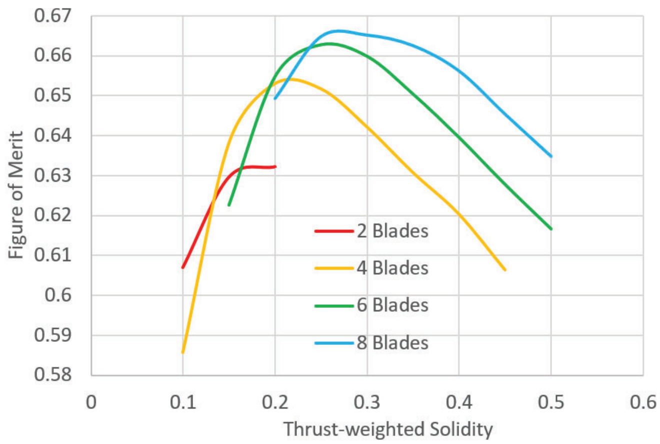

Figure 7. Figure of merit vs thrust-weighted solidity for ROAMX airfoils with varying number of blades.

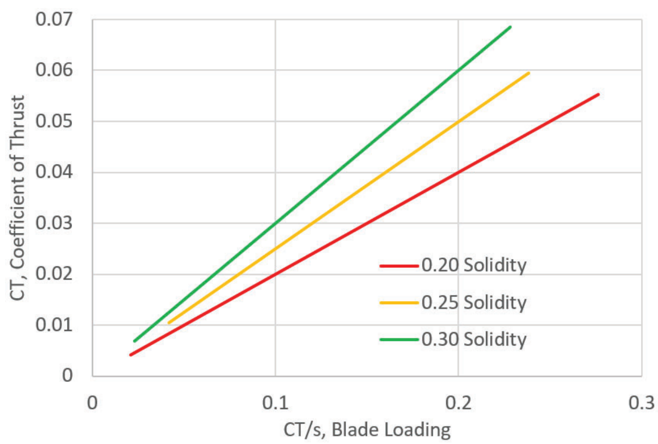

Figure 8. Coefficient of thrust vs blade loading for ROAMX 6-bladed configuration with varying solidity.

Wake Modeling

An additional area that required maturation to transition from the Ingenuity coaxial configuration to the Chopper hexacopter was rotor wake modeling. Flight dynamics models of the Ingenuity Mars Helicopter utilized a three-state dynamic inflow model, similar to that of Pitt and Peters (Ref. 19). However, while dynamic inflow formulations readily lend themselves to flight dynamics prediction, they do not consider rotor-rotor interference a-priori. Yet, rotor-rotor interference effects inevitably influence both structural and flight dynamics, making their accurate modeling essential for effective control design. This holds particularly true for complex multirotor applications with rotors operating in close relative proximity to each other. For Ingenuity, coaxial rotor interference effects were accounted for through empirical tuning parameters correlated with experimental data (Ref. 20). For the larger, multirotor Chopper configuration targeting much increased forward flight speeds, appropriately modeling rotor wake and rotor-rotor interactions was determined to be critical for accurate flight dynamics predictions. A schematic of the Chopper rotor layout is presented in Figure 9, where rotors with odd indices (1, 3, 5) are positioned approximately 0.15R above those with even indices (2, 4, 6), illustrated using solid and dashed lines, respectively. Furthermore, the rotor disks partially overlap with a maximum radial disk overlap of 0.11R, as also seen in Fig.9 (not to scale). Since the Chopper vehicle size and baselined flight envelope exceeds current testing capabilities, model-based analysis becomes increasingly important, driving the need for higher-fidelity solutions to calibrate reduced-order inflow models.

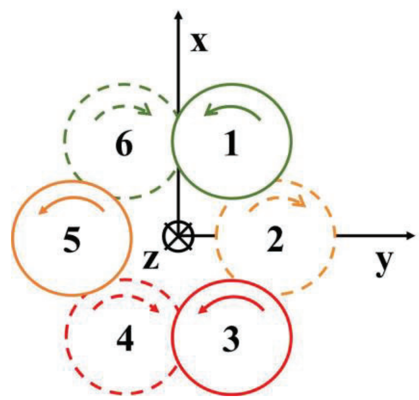

Figure 9. Planform view schematic of Chopper rotor layout configuration (Ref. 23).

The Viscous Vortex Particle Method (VVPM) is a mid-fidelity, first-principles approach to rotor wake modeling based on a Lagrangian formulation of the incompressible Navier-Stokes equations in vorticity-velocity form. It is a grid-free method that represents the vorticity field using a vortex particle ensemble. Compared to traditional CFD methods, VVPM reduces numerical artificial dissipation, allowing for more efficient retention of vorticity intensity over time. The rotorcraft comprehensive analysis tool FLIGHTLAB features a VVPM implementation (Ref. 21,22) that was validated for Mars applications in Ref. 23, where experimental coaxial rotor performance data for Ingenuity-type rotors was seen to correlate well with simulation around the design blade loading. However, in Ref. 23, predictions beyond the nominal flight envelope of Ingenuity were seen to deviate using the calibrated dynamic inflow model when correlated against system identification flight data from Mars (Ref. 24). To accommodate the identified gap in analysis capabilities for the larger-scale Mars vehicle platforms, VVPM was utilized to assess the effects of rotor-to-rotor interference on the Chopper concept vehicle. Dominant effects on rotor wake structures, trim and induced inflow distributions, focusing on the extremes of the flight envelope, were studied. The complexity of the rotor wakes can be appreciated in Fig. 10, showing the planform and side view of an iso-surface based on vorticity magnitude for Chopper, in ascending forward flight while subjected to a crosswind.

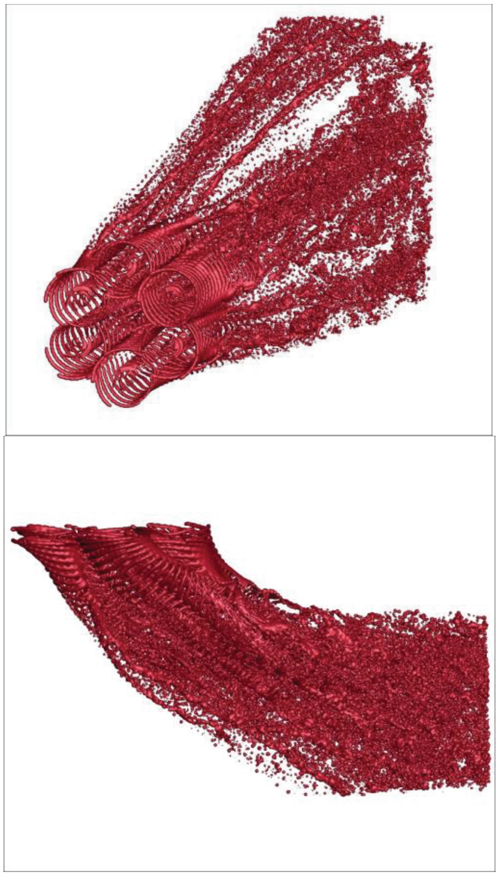

Figure 10. Vorticity magnitude iso-surface for Chopper concept in ascending forward flight with lateral wind.

The inflow from interfering rotors alters the effective angle of attack on the blades, directly affecting the control effort needed to achieve a given thrust and trim condition. In Figure 11, the trim collective variations with increasing longitudinal airspeed are shown for all six rotors when including the VVPM wake. Accounting for rotor-rotor interference reveals differences in trim collective features that an interference-agnostic model would fail to capture; notably, the collective differences between the two horizontal rotor planes.

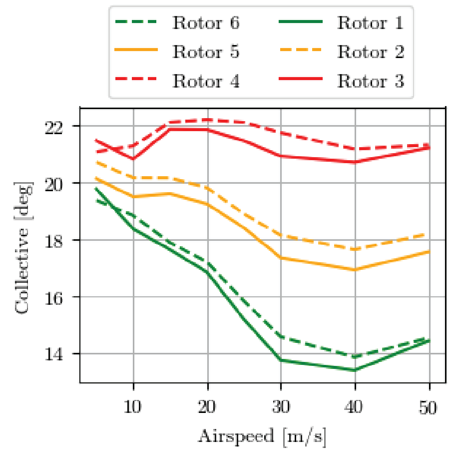

Figure 11. Trim collective control with VVPM for increasing longitudinal forward flight speed (Ref. 23).

In Figure 12, let λ denote the rotor induced velocity normalized with tip-speed, where λ is defined positive downward. The polar induced inflow distributions for a longitudinal airspeed of 30 m/s, advance ratio $\mu = 0.167$ are visualized in Figure 12, contrasting self-induced inflow against the inclusion of rotor-rotor interference.

Blade-vortex interactions (BVI) from upper rotor vortices striking the lower rotors contributes to a significant non-uniform induced velocity distributions at the rotor disks, with a sharp gradient at the azimuth of likely BVIs. As expected, the advancing and retreating sides exhibit a pronounced lateral gradient in forward flight, however, this effect is further compounded by interference from upstream rotors due to the altering rotational directions of the rotors. Downwash, implying an adverse effect on rotor efficiency, is observed on the middle (2,5) and aft (3,4) rotor pairs owing to the front rotor wakes being convected rearward in forward flight. In addition, side-by-side pairs (1,6) and (3,4) are predicted to benefit from a mutual upwash effect, dominantly on the retreating sides. These snapshots highlight the additional complexity in interference patterns of a multirotor (hexacopter) configuration, where "conflicting" interference effects are compounded into net effects that are difficult to predict a-priori without conducting an analysis such as was done in the present study.

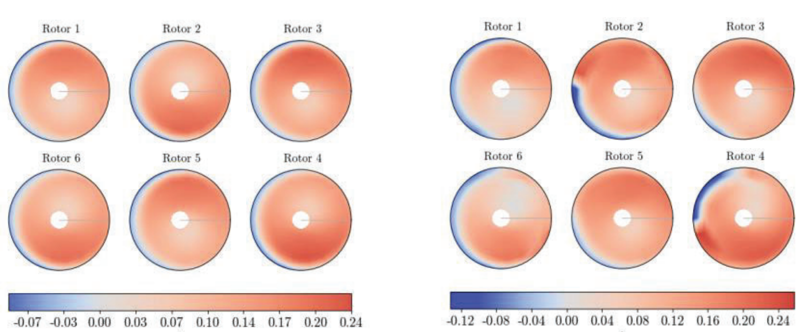

Figure 12. Rotor inflow distributions in forward flight. Left: Self-induced. Right: With rotor-rotor interference.

VVPM's relative computational efficiency enables extensive offline analysis across various flight conditions. However, it remains unsuitable for real-time simulation and lacks straightforward linearization. Current work seeks to bridge this gap by establishing an approach that captures the higher-fidelity VVPM data within a reduced-order framework, thereby making it compatible with conventional dynamic inflow models. The preliminary approach shares a similar vein to that developed and validated in Ref. 25, but it is extended to allow for pair-wise interaction for the full hexacopter configuration. A detailed account of the developed methodology is given in Ref. 23. At the highest level, interference effects are assumed linear and pairwise independent, implying they can be superimposed to the self-induced velocity. For this study, only a uniform interference was considered, but the framework can be generalized to truncation at higher order states as outlined in Ref. 23. The interference states are related to the aerodynamic loads of the rotors imparting interference through a gain matrix. Under the current effort, interference data was generated across the nominal flight envelope of Chopper, allowing the gain matrices to be derived and interpolated with advance ratio. Upon implementation, the interference module can be queried at any given flight condition within the domain within which the interference data was generated. With the gain interference matrices derived, the capability to include first-order effects in applicable flight dynamic tools have been established. Current work is on-going to quantify the impacts to the flight stability of the vehicle and, ultimately, control system design.

In addition to more mature wake modeling methods being integral into the assessment of rotor-to-rotor interaction, the propagation and shape of the rotor wakes may have additional CONOPS implications. Higher thrust requirements to enable a heavier vehicle (compared to Ingenuity) result in higher predicted outwash. Figure 13 illustrates the higher thrust produced by the Chopper rotor utilizing the roamx-series airfoils as compared to Ingenuity. Preliminary calculations following methodology from Ferguson's Rotorwash Analysis Handbook (Ref. 26), showed the radial velocities (outwash) have peak values near the ground. Some dust "kick up" was observed from images of Ingenuity's landings also (Ref. 27). The stronger outwash could impact the sample area if it is immediately around the landing zone.

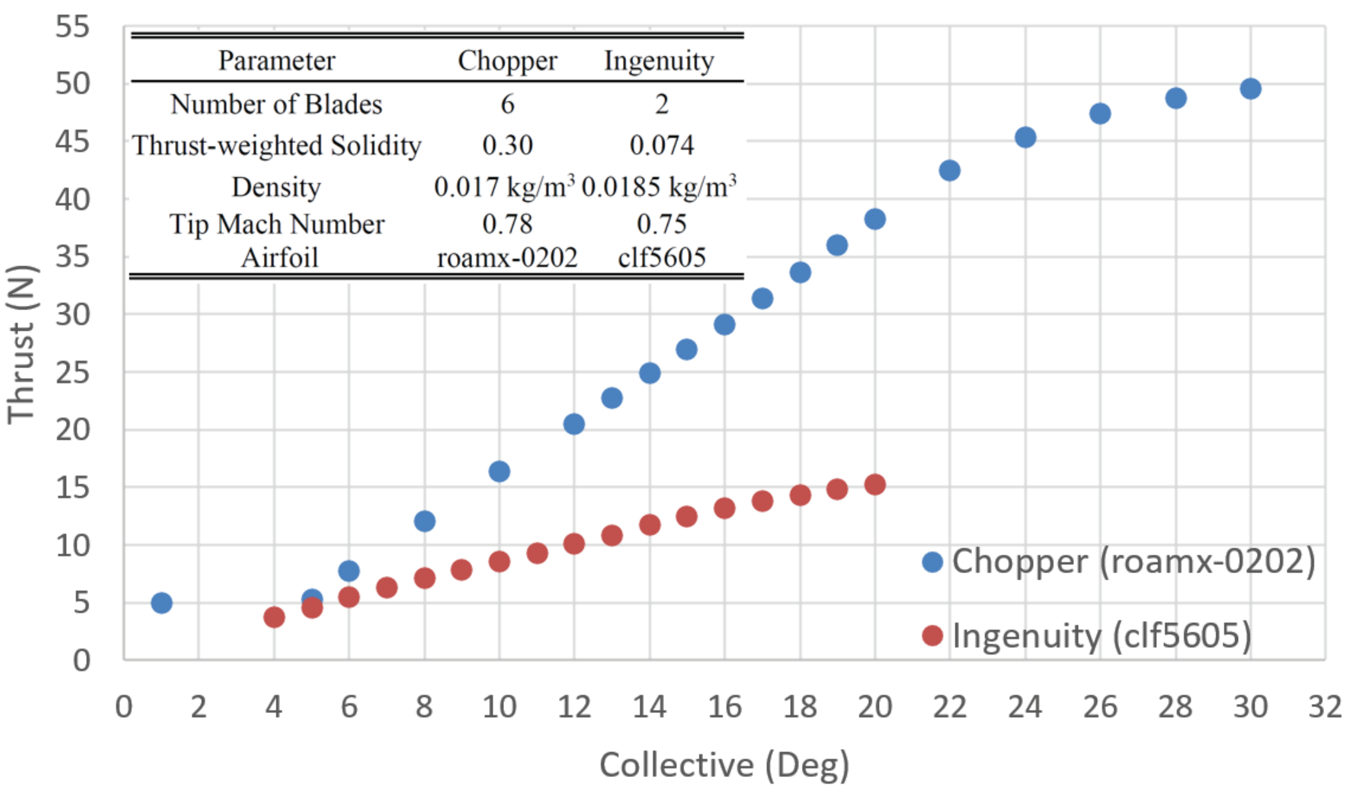

Figure 13. Comparison of single rotor thrust produced by Chopper (using roamx-series airfoils) and Ingenuity.

Predictions and testing have not been matured at this time to confirm if these forces are significant enough to warrant design or CONOPS adaptations. However, a short preliminary experimental campaign tested a scaled version of Ferguson predictions of outwash velocities on mockup Mars sample return tubes. Three tubes were tested in the JPL Marsyard sandlot, one full scale and two subscale, to investigate the effect at a variety of Reynolds numbers. Table 4 indicates the velocities that are equivalent to the Chopper outwash (~60m/s) for different experiment scales; here, the ratio of dynamic pressure and area against the tube weight was matched (0.19 for all cases). Sample tubes were noted to shift position in most cases at or below this equivalent velocity unless the tubes were slightly buried in sediment or their path blocked by pebbles. These effects should be further quantified as modeling efforts mature, as this relevant experiment was unable to eliminate the concern of outwash effects on the tube workspace.

Table 4. Tube Rolling Results.

Parameter	Mars Case	Tube 1: Full scale	Tube 2: Subscale	Tube 3: Subscale
Scale	1	1	0.135	0.135
Diameter	19.2 cm	19.2 mm	2.6 mm	2.6 mm
Length	184 mm	184 mm	25 mm	25 mm
Weight	0.44 N(Mars)	0.39 N	0.0033 N	0.0012 N
Outwash Velocity	60 m/s	--	--	--
Equivalent Velocity	--	5.9 m/s	4 m/s	2.4 m/s
Dynamic pressure	23.4 Pa	21.3 Pa	9.8 Pa	3.5 Pa
Pressure x Area / Weight Ratio	0.19	0.19	0.19	0.19
Tube Diameter Reynolds Number	1300	7600	700	420
Trial 1		6 m/s	2.5 m/s	0.9 m/s
Trial 2		5.2 m/s	1.9 m/s	1.9 m/s
Trial 3		5.2 m/s	5.2 m/s (slightly buried)	5.2 m/s (slight buried)
Trial 4		5.8 m/s (slightly buried)		
Trial 5		6 m/s (pebble behind tube)		
Trial 6		4.8 m/s		
Trial 7		2.2 m/s (placed on rock)		

Aerodynamic Interactions During Egress and Landing

The current Chopper concept utilizes the Entry, Descent, and Flyaway (EDF, formerly known as MAHD) for landing (Figure 14, Ref. 28). EDF is an entry, descent, and landing (EDL) concept that allows the larger Mars hexacopters to use their own landing gear and reduces the cost and mass associated with a dedicated lander. Additionally, this EDL method is a candidate for landing altitudes that are too high for traditional landers.

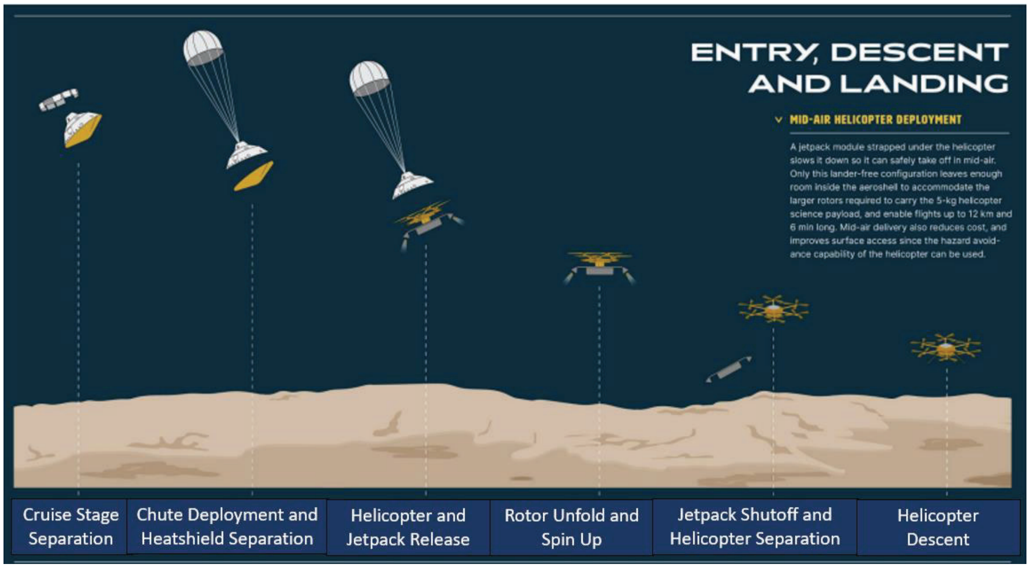

Figure 14. EDF CONOPS (Adapted from Ref. 28).

Reference 29 describes the complexity of the aerodynamic interaction between the rotorcraft, jetpack, and wind. Reference 29 also details an experimental effort to explore this interaction in Earth's atmosphere. Under Chopper, a single jet and rotor were tested in the Planetary Aeolian Laboratory at Mars density, to further advance the technology readiness level (TRL) of the concept (Figure 14). The proof-of-concept effort was successful. The full results of this effort will be described in a future work, as the test was only recently completed (March 2025). To achieve TRL 5, the team plans to next test the combined rotor and jet in the presence of wind at relevant Mars densities.

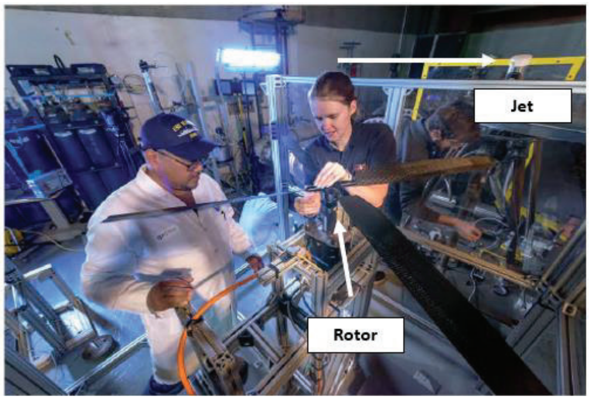

Figure 14. Team members installing rotor next to single jet in Planetary Aeolian Lab.

NEXT STEPS

The Chopper concept will continue to be adapted to fit additional mission requirements driven by the science/payload team. Rotor designs will be verified by experimental efforts which will, in turn, be used to improve rotor performance predictions. The wake modeling impact on flight dynamics and mission CONOPS will continue to be explored, and vehicle design adaptations will be made as necessary.

NASA's Mars Exploration Program has funded a joint proposal from the JPL, Ames, and AeroVironment, Inc. teams for a high solidity, high Mach number (>0.95 Mach tip speed) rotor test, currently scheduled for Fall 2025. This test will provide a data set to calibrate performance predictions and confirm the predicted advantages to the higher solidity rotor designs. Additionally, the team plans to attempt to push the tip speeds of the blades past Mach 1.0 since previous testing during the SRH project did not reveal definitive divergent behavior due to compressibility (Ref. 30).

CONCLUSIONS

Technology gaps were identified in airfoil and rotor design and rotor wake modeling that were key to enabling larger, next-generation Mars rotorcraft mission concepts. Balancing optimization of airfoil shapes with a focus on rotor/blade aerodynamics and manufacturability was studied. The impact of higher solidity rotor designs was explored, and results will be validated in an upcoming test campaign. These advancements were applied to the Chopper vehicle concept to improve vehicle performance. The baseline Chopper configuration is a hexacopter with six blades per rotor. Higher fidelity wake modeling was implemented to address concerns regarding rotor-rotor interactions. These improvements have implications for flight dynamics and control of the vehicle and are also crucial to understanding how the wakes interact with the vehicle's surrounding environment which may inform CONOPS. Additionally, advancements were made in the TRL process of the Entry, Descent, and Flyaway (EDF) concept which would enable the larger rotorcraft to access more diverse landing sites for less cost. These efforts have resulted in a more refined hexacopter candidate for next-generation Mars rotorcraft missions.

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