Mars Sample Recovery Helicopter: Rotorcraft to Retrieve the First Samples from the Martian Surface

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ABSTRACT

The Mars Sample Return Mission (MSR) will carry the next set of Mars helicopters, Sample Recovery Helicopters (SRHs), to the Martian surface. After successfully demonstrating extraterrestrial flight in 2021, Ingenuity has acted as a "scout" for the Perseverance rover while the rover gathers samples of Martian soil. In 2028, the MSR mission will launch a lander and two Ingenuity-sized SRHs to retrieve these samples. These will be the first samples of the Martian surface delivered to Earth. The SRH project will maintain heritage from Ingenuity's design when possible. However, several key changes must be made, including a ground mobility system, a robotic arm for tube manipulation, and the ability to carry the weight of a science payload (the sample tubes). In addition, the onboard software and cameras will be upgraded, and the rotor radius will be increased. Furthermore, new rotor performance and flight dynamics models and thorough characterization of vehicle limits will be required. The new vehicle design will be described, as well as validation and verification efforts to date.

INTRODUCTION

Ingenuity's successful technology demonstration has resulted in the development of two Ingenuity-sized rotorcraft for the Mars Sample Return (MSR) mission. Although it is now an integrated part of the Mars 2020 mission architecture, Ingenuity was originally a technology demonstrator with independent success criteria and milestones from the rest of the MSR mission. For the MSR mission, expected to launch in 2028, the Mars Sample Recovery Helicopter (SRH), if

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The decision to implement Mars Sample Return will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

approved through the National Environmental Policy Act (NEPA) process, will be an integral part of the mission to aid in the retrieval of soil samples from the Martian surface. The two helicopters that comprise SRH will serve as backups to the Perseverance rover and will retrieve the samples if Perseverance is unable to complete an extended mission. The rover or helicopters will be responsible for retrieving the sample deposits, taken as part of the Mars 2020 mission, and transporting the samples to the Sample Retrieval Lander (SRL). The Mars Ascent Vehicle (MAV) will relaunch to deliver the Martian soil samples back to Earth.

The following is informational for the purpose of planning and discussion, and the inclusion of SRH in MSR will not be finalized until completion on the NEPA process.

BACKGROUND

The main objective for the MSR mission is to return Martian soil samples to Earth. Initially, MSR included a new rover designed and funded by the European Space Agency and Italian Space Agency. However, given the success of Ingenuity and the health of Perseverance, it was determined in 2022 that two Ingenuity-sized helicopters would replace the European rover, saving the mission mass and cost.

Ingenuity's Extended Life

Full mission success for Ingenuity was accomplished after the fifth flight of the Technology Demonstration phase. This phase was initially defined as the first five flight which culminated in 499 meters range and ~6.6 minutes of flight time. After completing the Technology Demonstration phase, Ingenuity was authorized to transition to an Operations Demonstration phase, where it has further proved its capability as an aerial scout for the Perseverance rover. At the time of writing, Ingenuity has completed a total of 49 flights for a total distance of 11,224 meters and a flight time of ~86.7 minutes (Ref. 1), thus exceeding the expected distance travelled by ~22.5 times and flight time by ~13.1 times (as initially defined by the full success criteria).

Ingenuity's extended mission confirmed the advantages of having an aerial asset such as a rotorcraft as part of the mission architecture. These advantages had been predicted in aerial literature dating back into the 1990s (Ref. 2). It was projected that rotorcraft would be able to cover large areas quickly and avoid challenging ground terrain, and Ingenuity demonstrated that a rotorcraft can also be relatively fast and inexpensive to build, compared to previous Martian surface assets (landers/rovers). Ingenuity has set the precedent of rotorcraft assistants in future Mars exploration.

Continued Development of Mars Rotorcraft Technology

Conventionally, developing a spacecraft takes many years, making it challenging to accommodate the timeline of a new vehicle within a pre-existing mission architecture. However, even before Ingenuity launched, preparations for a next generation Mars helicopter had begun (Refs. 3-11). The SRH project takes advantage of these latest technology advancements while maintaining heritage principles from Ingenuity to reduce risk.

MISSION OVERVIEW

There are three mission scenarios to return the Mars 2020 soil samples to Earth. Scenario 1 assumes that the Perseverance rover is fully functional. If Perseverance is "healthy" ~9 months prior to SRL's arrival, SRL will land near Perseverance, and the SRHs would not be used for sample collection. However, if Perseverance were to run into complications, Scenario 2 would be employed. In this scenario, SRL would be sent to the Three Forks landing site and the SRHs would recover the pre-dropped (dropped in late 2022) sample tubes and deliver them to the SRL. Scenario 2 ensures that the opportunity exists to collect and return the samples regardless of the status of an aging Perseverance rover. Scenario 3 assumes that the Perseverance rover has started to show signs of degradation, but in a slow and predictable manner. In this case, the mission team will evaluate if Perseverance should travel to a to-be-determined site within the range of SRH in order to create a second depot of the samples gathered outside of Three Forks landing site.

Figure 1. Artist rendering of SRH vehicle. Credit: NASA Mars Sample Return Mission.

Since the sample tubes have already been dropped in the Three Forks landing site (December 2022), the current MSR mission requirements are primarily derived from Scenario 2. The only additional requirement derived from Scenario 3 is the ability to fly at higher altitudes, requiring SRH to operate in reduced atmospheric density conditions. In this case, the range and number of flights would be adjusted to account for changes in performance with lower density. In the Three Forks landing site, a worst-case, four-sol cadence returns all the samples to the lander (assuming only one helicopter is used at a time) with sufficient time to launch before the onset of increased dust storms during the Martian fall.

A high-level Concept of Operations (CONOPS) for SRH is as follows: SRH will deploy from the deck of the SRL (unlike Ingenuity which was deployed from the ground). During the Operations phase, SRH will fly from the lander location to a designated spot near the sample tube. Using a new ground navigation system, SRH will position itself, drive up to, and collect the sample tube. Next, SRH will fly back towards SRL and land at a fixed distance from SRL. Finally, SRH will drive up to SRL and transfer the sample tube. The entire sequence of SRH maneuvers will require a higher level of autonomy than Ingenuity, but human judgment will also be employed for critical milestones (Figure 2). Reference 12 provides additional information about the goals and components of the MSR mission in a broader context.

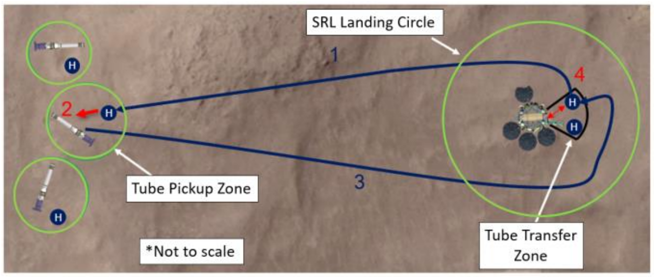

Figure 2. CONOPS for Three Forks location. Credit: Jet Propulsion Laboratory (JPL).

VEHICLE DESCRIPTION

The two helicopters that comprise the SRH set are identical and provide redundancy. The two helicopters will maintain Ingenuity design heritage when possible to reduce risk and cost in the relatively short development time available. It is not possible with the coaxial configuration to provide sufficient redundancy to meet mission requirements as a single rotorcraft. This is because a coaxial design, by nature, has a single failure point. Unlike a multirotor helicopter, if any of the hardware in the rotor system were to fail, the coaxial rotorcraft could likely no longer fly. Therefore, in order to meet the appropriate mission redundancy requirements for MSR, the second helicopter provides redundancy to the first. Ingenuity was not subject to the same redundancy requirements because it was a technology demonstrator. For simplicity, the term ‘SRH’ will be used throughout the rest of the paper, instead of individually referring to the two rotorcraft, since they are identical.

For SRH, the coaxial configuration also allows the rotorcraft to fit within existing compact pockets of the SRL for accommodation. The major components with similar designs to Ingenuity include two counter-rotating rotors between 0.6 m and 0.7 m in radii (range to be discussed in Optimized Rotor Section), a solar panel for charging after the helicopter has separated from the lander, cameras for navigation and imaging, a carbon fiber mast and minimal payload frame, and carbon fiber legs with heritage leg suspension and deployment hinges (Figure 3).

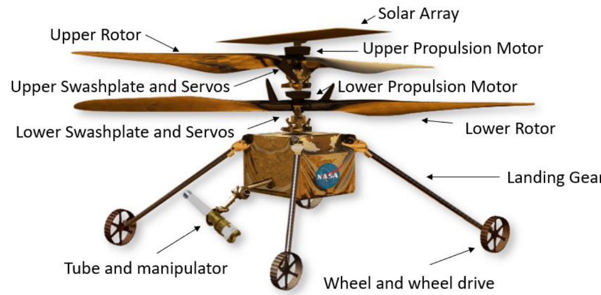

Figure 3. Labeled SRH diagram. Credit: Mars Sample Return Program.

Key Changes from Ingenuity

Some of Ingenuity’s hardware and software either do not meet SRH requirements or are no longer available. Primary hardware that is no longer available (in the condition and quantity required) includes Ingenuity’s SiFlex radio and the 801 Snapdragon processor.

Major hardware changes to accommodate SRH mission requirements include the addition of a ground mobility and sample manipulation system, rotor radius increase and optimization, high-capacity batteries, a larger solar array, eight additional servos, an additional camera, and updated software. Updates to the software extend SRH’s capabilities to include in-flight absolute localization and ground-based operations on existing hardware.

SRH will have an improved radio based on the SiFlex design and will use a newer model for the Snapdragon primary flight computer. The added ground mobility system will allow precise approach and capture of the sample tubes and precise approach and delivery to the SRL. SRH has a tank-like steering system with four light weight metal/composite wheels. The sample manipulation arm is one of the most novel aspects of the design, requiring high precision capabilities for grabbing onto sample tubes (up to 150 g each) while weighing as little as possible itself (target <100 g). This will be the smallest robotic arm used on Mars. The manipulation arm will offer SRH rover-like abilities to interact with its environment, instead of being a passive observer like its predecessor Ingenuity. Compactly fitting a highly maneuverable and precise robotic arm into a small package requires a creative engineering solution, such as potentially deriving the arm servos from the rotor servos. Additionally, the manipulation arm and controls system must be robust and capable of handling shadowing from the rotors, variation in the terrain, lightning, dust, and other unpredictable environmental factors. Low mass designs are key for Mars rotorcraft success, so new, lighter materials developed at AeroVironment will also be utilized for the carbon fiber shell of the blades. The total mass of SRH is expected to be ~2.5 kg, compared to Ingenuity’s 1.8 kg total mass.

As previously mentioned, accommodation also differs. The two helicopters will be placed on and deployed from the top of the SRL (Figure 4). Ingenuity deployed from the underside of Perseverance, allowing check outs and take off directly from the ground. Due to the additional complexity of taking off from the lander, additional analysis and testing will be required. This analysis and testing will characterize the wake interactions and recirculation which might degrade take-off conditions. Preliminary mid-fidelity CFD (RotCFD) results for the rotor outwash interaction between the rotorcraft and lander are shown below (Figure 5). If this outwash is allowed to build for too long, it has the potential to alter flight dynamics and reduce the clean air available to the rotor to function optimally. Additionally, it must be shown that the helicopter blades will not strike the lander at any point during the take-off sequence. The computational results are discussed in more detail below.

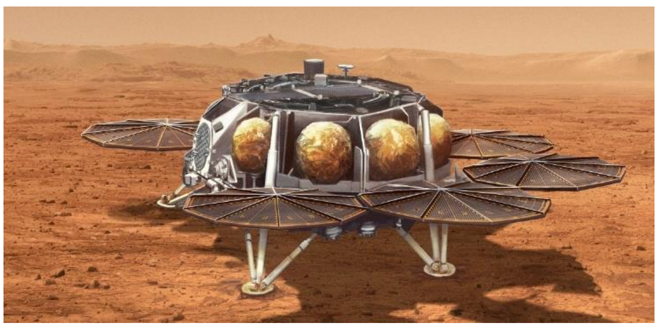

Figure 4. Mars Sample Retrieval Lander (SRL).

RotCFD is a mid-fidelity computational fluid dynamics tool (Refs. 13 and 14) that can represent rotors as either actuator disks or rotor blades (as lifting lines) through distributed momentum sources. The rotor blade sectional airfoil coefficients were developed/documented in Ref. 15. In the results presented in Figure 5, all SRH outwash predictions over the Lift-off Adapter and Inverted Retention (LAIR) box were performed using actuator disks for the coaxial rotors. RotCFD was used extensively throughout the Ingenuity development effort from early prototype development, through the engineering model development and testing, and the final performance and flight dynamics testing of the Ingenuity flight model. Reference 16 represents a recent example of continued use of RotCFD to refine forward-flight performance estimates of Ingenuity. In this regard, Figure 5 results represent a continuation/transition of the use of RotCFD from Ingenuity to the SRH vehicles.

Figure 5 illustrates preliminary outwash flow visualization results stemming from a rapid ramp-up in rotor collective above the LAIR box, simulating initial takeoff from LAIR. Shown are the box and SRH vehicle surface pressures highlighted from low pressure (green) to high pressure (yellow, orange, and red). Rotor wake velocity magnitude isosurfaces are also shown as transparent gray. The objective of these RotCFD outwash predictions is to assess any potential interactional aerodynamic complications that might result during takeoff of the SRH from the LAIR storage box during initial deployment from the sample return lander.

Additional computational fluid dynamics work, coupled with the recent experimental testing in the JPL 25Ft. Space Simulator, will be used for further assessment of takeoff flight dynamics during SRH deployment from the lander.

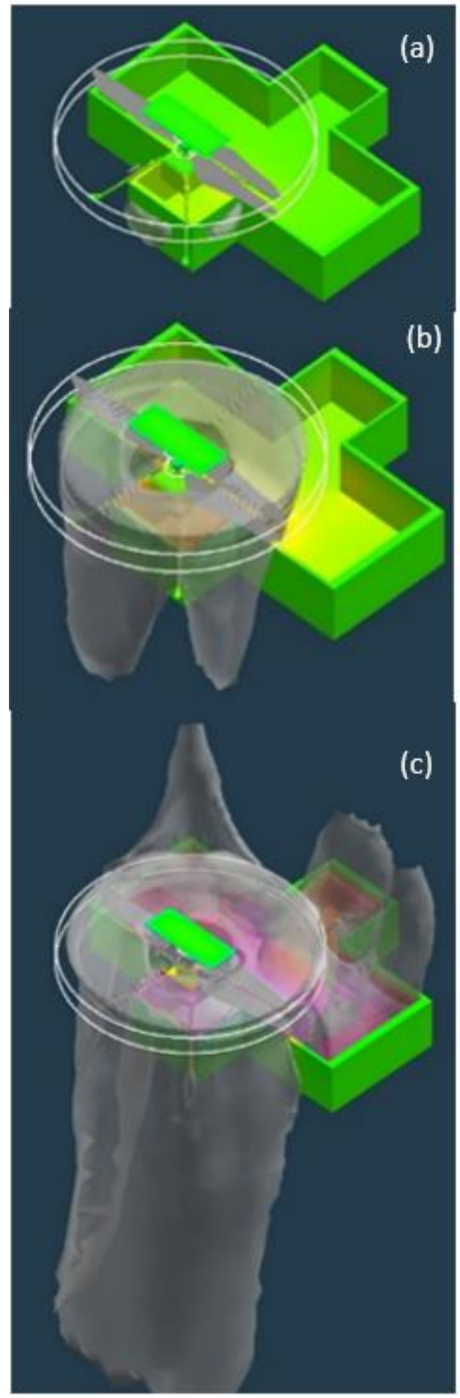

Figure 5. RotCFD- 15 m/s outwash building with time and interacting with LAIR (accommodation box). Time =8 (a), 12 (b), and 20 (c) seconds from top to bottom.

Although vehicle development involves many other systems (communications, avionics, power system design, navigation, etc.), this paper is intended to focus on the aeromechanics aspects of the design, and, thus, the remainder will focus on the SRH rotor.

VERIFICATION AND VALIDATION (V&V)

As noted in the previous section, SRH's mass is much larger than Ingenuity's (a ~40% increase from 1.8 kg to 2.5 kg). However, there are growth limitations due to lander accommodations and to maintain design heritage. SRH's greater mass requires increased power and likely higher blade loading and tip speeds (assuming fixed rotor area). There are currently three areas of design exploration for increasing the performance capability within a similar accommodation volume. These include higher blade solidity, faster tip Mach numbers, and optimizing the rotor (planform and twist). Independent of the design process, CONOPS will also be designed to account for environmental factors, such as flight time of day and season, to aid performance.

Increased Blade Loading

Before any rotor optimization was attempted, it was necessary to determine the performance limitations of Ingenuity's rotor. Ingenuity's Engineering Design Model (EDM-1) was used to explore blade loading limitations. From October to November of 2022, Ingenuity's EDM-1 was placed in JPL's 25-ft. simulator (Figure 6), with part two of the test campaign resuming in February of 2023. Modifications were made to Ingenuity's EDM-1 hub to allow the collective range to be increased from 20 to 23 degrees. Initially, the density and Reynolds number (Re) were lowered to avoid high power draw. These restrictions were removed for later tests, but power draw remained in a manageable range. In the second entry, the density and Re were closer to the expected operating conditions for SRH. Preliminary results from these tests (EDM-1) can be found in the Rotor Testing Summary section.

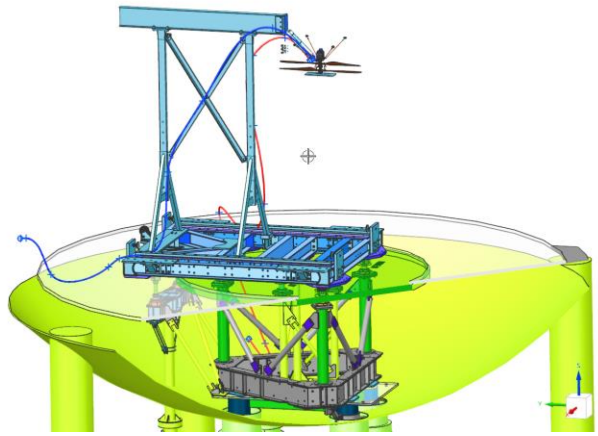

Figure 6. CAD of Ingenuity EDM-1 Test Set Up. Credit: JPL.

Faster Rotor Speed

Rotor speed was also explored further to determine if higher performance could be achieved. Ingenuity's rotors currently do not exceed ~0.7 Mach tip speed. Computational models suggested that the rotor could potentially be pushed further into the transonic range. The challenge with this approach is to take advantage of any additional performance while not stalling the rotor (from adverse compressibility effects) or requiring more power than could be supported.

A new single rotor test stand was developed by AeroVironment to further characterize the rotor up to 0.9 Mach tip speed. EDM-1's test set up could not be utilized because of load and power limitations. Preliminary test results for the Transonic Rotor Test can be found below in the Rotor Testing Summary section.

Optimized Rotor

SRH requires a rotor that can lift the aircraft with high confidence (low risk) at minimum power. Increases in aircraft mass required to perform the SRH mission lead to increased thrust and power demands which reduce margins for rotor performance and control. Thus, a series of simulations and optimization exercises were used to reduce risk through rotor optimization.

Several aerodynamic studies were performed, using CAMRAD II (Ref. 17), investigating the rotor size (blade chord or radius increase) and rotor shape (planform and twist), while keeping the airfoils of the heritage Ingenuity design. As airfoil design is nontrivial in the compressible low-Reynolds number regime, this design freedom allows the heritage airfoils to be kept and will allow for a similar rotor structural design as relative thicknesses are unchanged.

The Evolutionary Algorithm for Iterative Studies of Aeromechanics (ELISA, Ref.6), developed at NASA Ames, was used to optimize aerodynamic rotor hover performance of Ingenuity's rotor planform and twist, while keeping the Ingenuity heritage airfoils and their distribution over the blade. Several solidities were investigated and separately used as constraints for the rotor planform during the optimization cycles. The optimizations simultaneously optimize thrust and power, resulting in a Pareto-optimal sets of rotors with the minimum-power design for each attainable blade loading, for each chosen solidity.

The described investigation culminated in an SRH risk-reduction rotor design with an increase in blade radius and similar dimensional chord, an updated blade planform, and a very similar blade twist distribution to Ingenuity (maintaining heritage processes). The increase in radius results in reduced power requirements at a given thrust, and the increased blade area permits operation at reduced tip speeds and/or lower blade loading compared to using Ingenuity's rotor design to generate equivalent lift. The reduction in rotational speed reduces centrifugal forces and, in turn, can also result in a lighter hub. Increasing the blade radius while keeping chord identical maintains the Reynolds number for efficiency and minimizes the weight needed to achieve required flap stiffness. Chord and twist versus radius for the larger SRH blade (0.7 m radius, 0.128 solidity, thrust-weighted chord) compared to Ingenuity can be found in Figure 7.

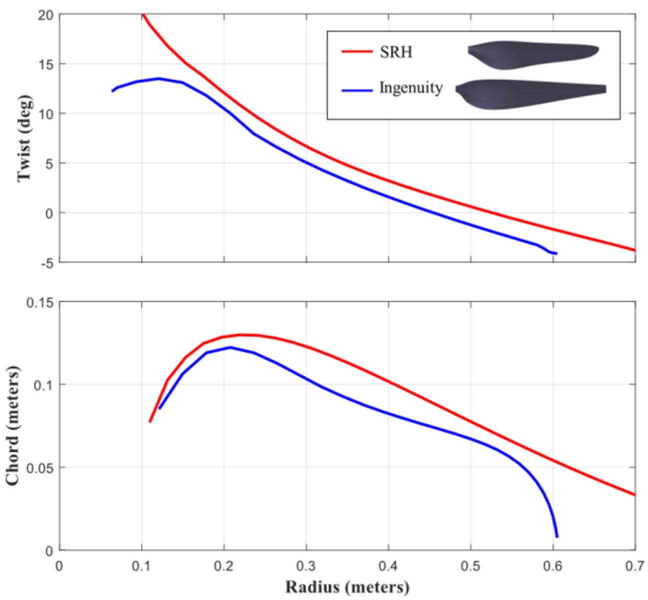

Figure 7. Twist (deg, top) and chord (m, bottom) for SRH (red) and Ingenuity blade (blue).

A slightly larger rotor (~0.7 m, constrained by accommodation space in lander) is low risk from a fundamental physics perspective compared to designing a blade from scratch and reduces power required for a given thrust. This leads to smaller motors and battery capacity required for a given flight which reduces mass.

Rotor Testing Summary

Performance results from the Engineering Design Model 1 (EDM-1) Test (Figure 8) and Transonic Rotor Test (TRT) (Figure 9), experimental tests performed at JPL in the 25-ft Space Simulator (SS), are provided in the form of figure of merit (FM) against blade loading (C_T/σ). Figure of merit is used to gauge the efficiency of a rotor and is defined as the ratio between the ideal and actual power of the rotor. The FM calculation presented uses the estimated power from the efficiency of the motor, also known as mechanical power.

Testing of the EDM-1 rotor was performed for various Reynolds numbers ranging from 5,200 to 14,500, with minimal RPM variation (2043 - 2500) but a sizable density variation (0.01 and 0.03 kg/m^3). Figure 8 shows the performance of EDM-1 via FM versus blade loading. Results show an increasing FM with Reynolds number between a blading loading of 0.12 and 0.14. The increase in FM is attributed to the increase in Reynolds number (due to either increased density or increase rotor speed), which reduces the airfoil section drag.

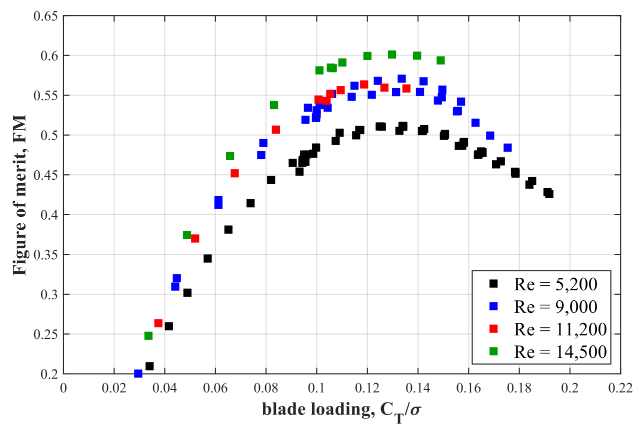

Figure 8. Figure of merit versus blade loading for EDM-1 in the JPL 25-ft. Space Simulator.

The Transonic Rotor Test (TRT) experiment was conducted to understand the performance behavior of a single rotor using the Mars helicopter (Ingenuity) blade geometry at what is considered high rotor speeds (M_{tip} = 0.65 - 0.85). Performance results from the TRT are shown in Figure 9 for FM versus blade loading along with assosiated color curve fitted lines to aid in distinguishing between each of the tip Mach number speeds. Results indicate a reduced hovering rotor efficiency for a tip Mach number greater than 0.75. A peak FM of 0.48 is observed at M_{tip} = 0.7 at a blade loading of 0.13, which is an indication of the onset of blade loading stall. The abrupt drop in FM could be due to the airfoil design lacking efficiency at higher blade loading.

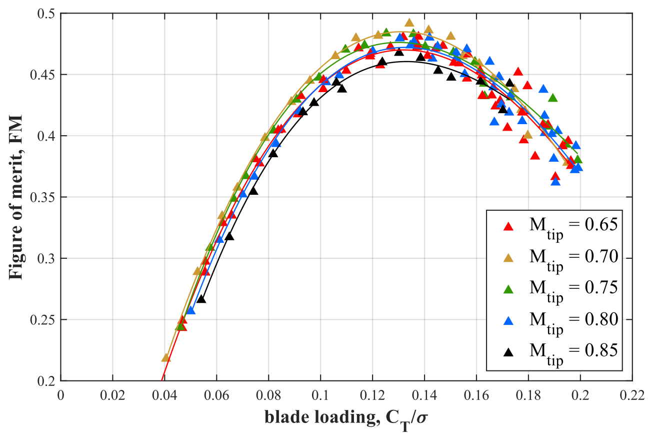

Figure 9. Figure of merit versus blade loading for TRT in the JPL SS.

After analysis of the results obtained via the EDM-1 and TRT tests, it was determined the lowest risk path forward would be to update the baseline rotor from the 0.6 m radius Ingenuity rotor design to the 0.7 m radius rotor optimized through the study described in the Optimized Rotor section (March 2023). This new baseline design will allow increased performance capability and control margins at lower power than the 0.6 m rotor. While rotor speeds and blade loading may still have slight alterations as the design is finalized, it will also allow SRH to stay closer to Ingenuity rotor speeds and blade loading, maintaining heritage design principles.

NEXT STEPS

Next steps begin with thoroughly analyzing the rotor testing data and documenting it (likely as a future NASA Technical Memorandum, NASA TM). Additionally, computational models (CAMRAD II and OVERFLOW) must be correlated with EDM-1 and TRT test data. If 2D airfoil test data is available from the ROAMX (Ref. 7) project, it will also be used for correlation. Results from the testing with LAIR will be replicated in HeliCAT, supported by 3D CFD if required. Once it is demonstrated that the test data can be reproduced in simulation, performance calculations (CAMRAD II and 3D CFD) will be adjusted and used to predict an expanded flight envelope. Lastly, doublet runs taken throughout testing will help to check flight dynamics models which will inform test plan definition for a future vehicle system identification test campaign.

Long-term, a series of surrogate vehicles will be built, such as a flight prototype, a ground-based prototype (for ground mobility and manipulation testing) and a SRH Engineering Design Model. These surrogates will be used to further verify the SRH design, resulting in a validated flight article. SRH is expected to launch as part of the Mars Sample Return Mission in 2028.

CONCLUDING REMARKS

The Mars Sample Recovery Helicopter will be the second generation of Mars rotorcraft, expected to launch in 2028. The primary objective of SRH is to capture and transport Mars soil sample tubes to SRL for return to Earth via the MAV. SRH is heavily based on the heritage designs of Ingenuity, but some major alterations must be made to increase the performance capability. One of the key changes is ground mobility and manipulation capability which allows SRH to better navigate and have access to its immediate surroundings. This capability increases the mass of the vehicle compared to Ingenuity. In order to increase the performance accordingly, the rotor can have higher blade loading, spin faster, or be made larger with an optimized twist and chord. A series of rotor test campaigns and analytical studies from October 2022 to March 2023 explored the limits of each of these approaches. Through testing, it was determined that the lowest risk method of increasing performance was to increase the rotor radius from 0.6 m to 0.7 m while maintaining the original Ingenuity airfoil design and chord. A larger rotor means SRH operates at similar rotor speeds, and therefore a similar Mach tip regime, as Ingenuity. This maintains heritage in the design process and increases control margins compared to maintaining Ingenuity's rotor radius. Lastly, this method maintains the option for additional performance growth through increased blade loading and rotor speed if needed later in the mission design process.

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