Overview and Introduction of the Rotor Optimization for the Advancement of Mars eXploration (ROAMX) Project

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Abstract

Research in pursuit of rotorcraft flight on Mars has been ongoing since the late 1990s at NASA Ames Research Center. Since then, many other organizations have also begun researching rotary-wing flight on Mars. In 2014, the project that led to the first helicopter to fly on Mars began at the Jet Propulsion Laboratory. Ingenuity was developed as a joint effort between JPL, NASA Ames, NASA Langley, and AeroVironment. The Ingenuity Mars Helicopter made history in April 2021 as the first vehicle demonstrating controlled, powered flight on another planet and, in doing so, it has opened a new era of planetary aviation. Future, more capable Mars rotorcraft will be able to fly even further and carry significant science payload. At NASA Ames, through NASA Space Technology Mission Directorate funding, the research necessary to help develop the next generation of Mars rotorcraft has begun with the Rotor Optimization for the Advancement of Mars eXploration (ROAMX) project. The ROAMX project involves computationally and experimentally investigating aerodynamically efficient, compressible, low-Reynolds number airfoils for rotor blades and, further, new high-performance rotor designs. ROAMX is also developing and validating a rotor design methodology to optimize blades given specific mission requirements. The primary experimental effort of the ROAMX project is focused on rotor hover performance, but subsequent airfoil and rotor design advances are anticipated to carry over into improvements in forward flight efficiency. ROAMX is a collaboration between NASA Ames, JPL, the University of Maryland, AeroVironment, and Tohoku University.

Introduction

In April 2021, the Ingenuity Mars Helicopter made history as the first vehicle to demonstrate controlled, powered flight on another planet. In doing so, Ingenuity paved the way for future, more capable helicopters to conduct science and exploration on Mars and other planets. This feat was the culmination of decades of research conducted at NASA Ames Research Center (ARC), Jet Propulsion Laboratory (JPL), Stanford University, Georgia Tech, University of Maryland (UMD), and many others, and has been discussed in detail elsewhere [1,2].

Flying on Mars is no simple task, and though the technical challenges were overcome to successfully fly Ingenuity, many challenges remain to be tackled or improved upon for future flight on Mars. Among the many institutions researching rotorcraft flight on Mars, ARC is continuing Mars rotorcraft aeromechanical analysis and experimentation, aerodynamics analysis and experimentation, dynamics and controls design and analysis, and conceptual design. ARC has conducted studies that helped enable Ingenuity, and ARC partnered with JPL in the design, analysis, and test preparation of Ingenuity. ARC continues to lead research into Mars rotorcraft to advance fundamental knowledge of what it takes to fly on Mars, as well as to support future Mars rotorcraft missions.

The Rotor Optimization for the Advancement of Mars eXploration (ROAMX) project is part of the efforts at ARC to conduct research in support of future rotorcraft on Mars. ROAMX focuses on key aeromechanical topics facing Mars rotorcraft. These topics include airfoil and rotor aerodynamic computational design and analysis specifically for the compressible, low-Reynolds number aerodynamic regime, and experimental validation of computational predictions.

This paper will first discuss previous efforts at ARC that have contributed to Mars rotorcraft research, have been related to the Ingenuity Mars Helicopter, and have laid the groundwork for the research conducted by ROAMX. Next, the background

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of ROAMX and general goals of the project will be discussed, followed by specific computational and experimental ROAMX activities.

Ames

At ARC, experimental, computational, and conceptual design investigations for flight on Mars have been conducted for over three decades. In 1998, Young et al. demonstrated the first ever test of rotors at Mars atmospheric conditions in the Planetary Aeolian Laboratory (PAL), and subsequent Computational Fluid Dynamics (CFD) studies were conducted, as seen in Figure 1 [3,4]. Young also demonstrated the feasibility of many conceptual rotorcraft designs, including a co-axial configuration similar in design to Ingenuity in 2001 [5,6]. These studies began to investigate the conceptual designs that result in best performance for rotorcraft flight on Mars. Additional conceptual designs were investigated and proposed.

Figure 1: First documented hover test of a rotor under Mars-like conditions (left) and first CFD work in support of Mars rotorcraft (right) [3,4].

In 2015, JPL and ARC began working together in support of the development of Ingenuity, as seen in Figure 2. ARC was heavily involved in the flight dynamics and control design, conceptual design and vehicle sizing, and rotorcraft aeromechanics investigations.

Figure 2: Kick off meeting between JPL and ARC in 2015 at ARC. From right to left: Thomas Norman, Dr. Colin Theodore, Dr. Wayne Johnson, Dr. Gloria Yamauchi, Dr. Brian Allan, Dr. Daniel Scharf, Carl Russell, MiMi Aung, Dr. Havard Grip, Susan Gorton, Dr. William Warmbrodt, Larry Young, Dr. J. Bob Balaram, Dr. Alan Wadcock.

Additional hover and forward flight experimental and computational investigations also began on a surrogate-Mars rotor. These experimental and computational studies provided an understanding of how the different conditions present on Mars (and in Earth-based experimental testing) affect experimental and computational methods [7–10]. Using mid-fidelity CFD analysis, correlation was found between analysis and experiment, giving additional confidence to analytical and experimental methods [7,10–13].

This same hardware, depicted in Figure 3, was taken to JPL for "weather testing" in the 25 Ft. Space Simulator [14]. This testing preliminarily demonstrated recirculation of rotor wake flow in this facility. Subsequently, JPL tested a prototype, engineering development model, and the flight model of Ingenuity in the 25 Ft. Space Simulator.

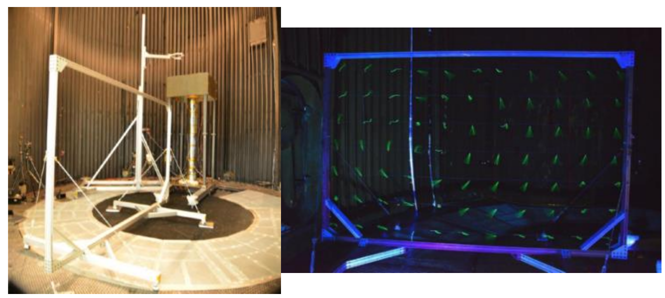

Figure 3: ARC 'Weather Test' hover test stand in JPL 25 Ft. Space Simulator (left) and tufts indicating the flow recirculation (right) [14].

Concurrently, at ARC computational modeling of the Ingenuity rotors and vehicle was ongoing, and computational results can be seen in Figure 4 [15,16]. These efforts led to the initial investigations of optimal airfoil shapes for rotorcraft flight on Mars. First, cambered plates as direct substitutes for the Ingenuity Mars Helicopter airfoils were considered and an improvement in hover performance was seen [17]. Next, selective optimization for different radial stations (with each

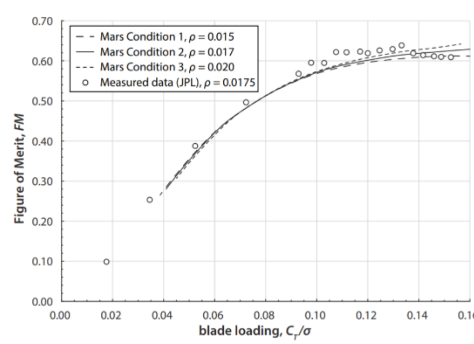

Figure 4: Correlation studies between JPL experiment and comprehensive rotorcraft analysis [16].

widely varying Re and M) was attempted and additional improved efficiencies were observed [18,19].

These compressible, low-Reynolds number airfoil optimization studies have been ongoing for a number of years, and with the launch and success of Ingenuity capturing the world's imagination, these continued airfoil/rotor studies have been the backbone to the computational work of ROAMX.

Airfoil optimization, blade ultralightweight structural design, computational rotor design, vehicle flight dynamics and control investigations, and packaging/stowing design of Mars rotorcraft in entry, descent, and landing (EDL) aeroshells led to the conceptual design of several candidate configurations for future Mars rotorcraft [20,21]. Several additional conceptual design studies have since followed [22–25]. Finally, investigations into possible mid-air deployment of Mars rotorcraft during the final stages of EDL have been ongoing at ARC in partnership with JPL [26,27].

Research continues at ARC in all domains mentioned above, and the aeromechanical investigations being conducted as a part of ROAMX are built upon the heritage established at ARC over the past three decades.

Ingenuity

Several of the previous engineering studies, namely those from the late 1990s and early 2000s, among others (i.e. [28]), aided in the development of the Ingenuity Mars Helicopter, which began at JPL in 2014 [2,29–34].

NASA Ames and NASA Langley became partners with JPL for the Ingenuity Mars Helicopter (shown with the Perseverance rover in Figure 5 [35]). The vehicle was originally meant to demonstrate that flight on Mars is indeed possible. Due to the short amount of time available to design, build, and test the vehicle, heritage and commercial off the shelf components were used wherever possible, including the micro-processor. The rotor blades were based on design heritage stemming from years of AeroVironment experience with propeller-driven high-altitude and long endurance Unmanned Aerial Vehicles (UAVs), though modifications were made [29]. (Note that commercial-off- the-shelf (COTS)

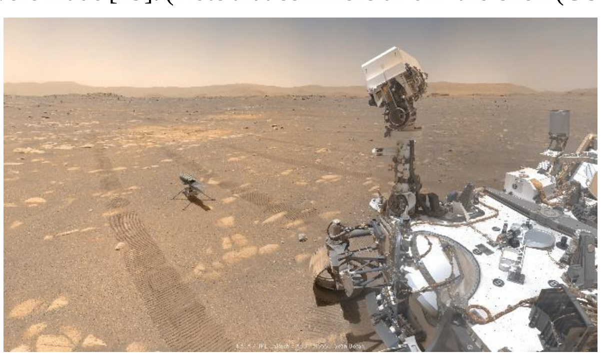

Figure 5: "Selfie" of Perseverance and Ingenuity on Mars [35].

components, as needed, were subjected to Mars-like environmental and radiation testing to qualify them for Ingenuity.)

Testing of Ingenuity on Earth included a 'swinging arm' series of system identification tests (Figure 6) and, further, several tethered flight tests in the JPL 25 Ft. Space Simulator [32]. These flight tests demonstrated that Ingenuity was ready for the harsh environment of Mars.

Figure 6: Ingenuity prototype, engineering development model, and flight model system identification testing on swinging arm and gimbal system [32].

When Ingenuity took off and landed for the first time on Mars (Figure 7 [36]), this accomplishment opened up new possibilities for space exploration by means of aerial vehicles on Mars and beyond. The Mars helicopter performed so well that its five-flight technology demonstration mission was expanded to include, as of the end of 2021, eighteen total flights of increasing difficulty – flying faster, farther, and higher than ever before. The expanded "Ops Demo" mission has allowed the helicopter to also contribute to the science goals of the Mars 2020 Perseverance rover mission, demonstrating the potential of what aerial vehicles can do for planetary science and exploration.

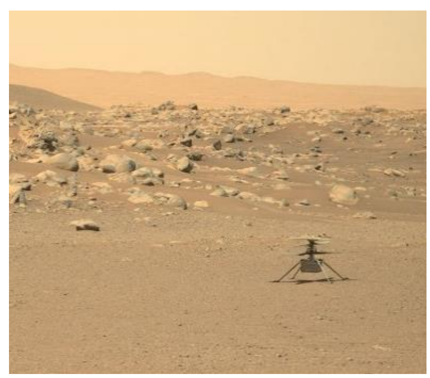

Figure 7: The Ingenuity Mars Helicopter on Mars at Jezero Crater. Picture taken by Perseverance Rover Mast-Cam [36].

Current State of Technology

To enable future Mars aerial vehicles with expanded capabilities, continued research and development efforts are necessary. In many ways, the same technological challenges that existed 3 decades ago still exist today. NASA's ROAMX project seeks to address these challenges, which is the subject of this paper. Through computational and experimental aerodynamic investigations into advanced compressible low-Reynolds number airfoils and optimized rotor performance, ROAMX is helping to enable improved performance of future Mars rotorcraft and expand science and exploration capabilities on Mars.

Efforts are ongoing to improve rotor performance for the low-Reynolds compressible regime, and steady progress has been made. In the early 2000s, a hover figure of merit (FM), or hover efficiency, of 0.40 was achievable. Fifteen years later, Ingenuity was able to achieve FM in the range of 0.50 - 0.60. ROAMX intends to show that FM > 0.60 is achievable, and that a broader range of operating thrust coefficients is possible while maximizing FM.

Likewise, rotor performance in forward flight has been investigated over the past decade. While the ROAMX campaign is only investigating hover performance, the same computational and experimental techniques used to design and validate airfoil and rotor designs are also enabling forward flight investigations, which is the next step in Mars rotorcraft aeromechanical analysis beyond ROAMX.

Ongoing research investigations throughout the aerospace industry into stiff, robust, lightweight materials will enable new rotor/vehicle designs for future Mars rotorcraft. Rotorcraft on Mars also benefit from advances in material investigations, for both fixed and rotating components. Through ROAMX, part of the design and optimization process includes manufacturability investigations and testing of carbon fiber components developed for prototype rotor blades.

One of the key lessons from the Ingenuity development effort, as related to experimentation and system validation testing, is that there are no ideal test facilities that fully meet the needs of Mars rotorcraft development. Accordingly, researchers and developers must be creative in adapting/modifying existing test facilities to use for their efforts. Additionally, novel test stands and test apparatus need to be developed for this purpose. Facility and test hardware development are key to the success of the ROAMX project.

The unique challenges of flight dynamics and control of Mars rotorcraft continue to require research and investigation. Through ROAMX, stiffness of thin rotating components is investigated via blade structural design, manufacturing, and testing. Though not the main objective of ROAMX, the structural capabilities data collected for the aerodynamically optimized design will also inform and influence dynamics and control requirements.

The contributions of ROAMX to Mars rotorcraft research and investigations are essential for providing continued understanding of rotorcraft aeromechanics on Mars and enabling improved future Mars rotorcraft missions.

ROAMX Scope and Goals

ROAMX is a NASA Space Technology Mission Directorate funded project through the Early Career Initiative (ECI) program. ROAMX is part of the ECI class of 2020 and has funding for two years through October 2022.

Need for Improved Future Mission Performance

As mentioned previously, the engineering investigations into the specific airfoil shape and blade shape used for Ingenuity were somewhat limited due to the rapid pace of the Ingenuity prototype development. Consequently, the Ingenuity rotors derived a considerable amount of design heritage from AeroVironment's experience with high-altitude UAVs. These investigations were limited because of the relative lack of knowledge in the research literature of the compressible, low-Reynolds number aerodynamics at Mars flight conditions. The low Reynolds number (Re~10^4) and high subsonic Mach number (> 0.7), which are a consequence of the cold, very thin, and primarily carbon dioxide atmospheric conditions on Mars (Table 1), represent an aerodynamic regime where there is limited computational and experimental investigation. As such, the airfoil chosen for the Ingenuity Mars Helicopter was based on an airfoil optimized for low-Re conditions encountered on Earth [30] – i.e. high-altitude UAVs, with predominantly laminar flow. Experiments and simulations showed that the aerodynamic performance would be sufficient for the helicopter to fly but, because of the significantly reduced Reynolds numbers, the airfoil would yield relatively low lift to drag values, high drag coefficient at zero lift (C_{d0}), and low maximum lift coefficient (C_{Lmax}) as compared to higher Reynolds number airfoil performance [2,11,15,16].

Table 1: Comparison of nominal Earth vs. Mars atmospheric and aerodynamic properties.

Parameter	Earth	Mars
Density (kg/m^3)	1.225	0.017
Temperature (C)	15	-50
Air composition	N_2-based	CO_2-based
Sound speed (m/s)	340.3	233.1
Reynolds number (rotorcraft flight)	~10^6	~10^4
Tip Mach number	~0.6	0.7-0.95

While Ingenuity's performance has been outstanding as a technology demonstrator, future rotorcraft with better performance on Mars are of significant interest to the science and engineering communities. Greater understanding of the aerodynamic behavior at reduced Reynolds numbers under compressible flow conditions can lead to advanced rotor designs and allow enhanced exploration of Mars.

Many aspects of vehicle design can enhance performance, and research regarding autonomous navigation, guidance and control, and weight reduction techniques is ongoing. However, current models show that optimized airfoils and blades have the most significant impact on increasing performance, thereby increasing science mission capabilities on Mars.

Little is known about optimal airfoil shapes for flight under the very low Reynolds numbers, high subsonic Mach number aerodynamic regime seen at Mars atmospheric conditions, but animals in nature that experience similar Re during flight (such as the dragonfly and pigeon, Figure 8) exhibit thin, unconventional airfoil shapes for this regime [19,37]. Precursor work [11-13] has shown that with thin, unconventional airfoil shapes, enhanced airfoil performance is possible. These thin airfoil shapes, optimized for low Reynolds numbers, could also be used in terrestrial applications such as high-altitude flight and micro aerial vehicles. Airfoils that are optimized for flight under the compressible Reynolds number flow experienced on Mars can lead to more efficient, optimized blades, which in turn can increase payload capability for rotorcraft on Mars.

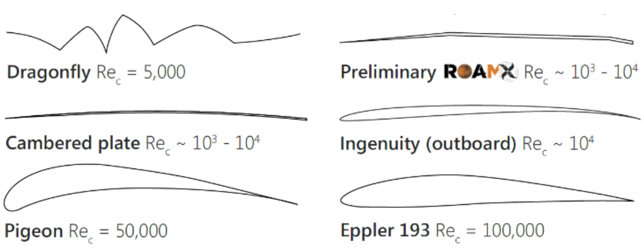

Figure 8: Airfoil shapes relevant for various Reynolds number ranges [19,37].

With increased payload capability, a rotorcraft could carry significant science instruments such as spectrometers, magnetometers, environment sensors, and cameras, as seen in Table 2. With these types of instruments, science that could be conducted on Mars includes mapping, polar science, atmospheric science, and subsurface geophysics [31].

Table 2: Examples of science instruments that could be carried by a rotorcraft on Mars.

Examples of Science Instruments	Weight (g)
VNIR spectrometer	500
Tunable spectrometer	300
Magnetometer	20
Environment sensors (temp, humidity, wind, etc)	100
Camera for imaging	250
Soil sensors	100

Improved rotorcraft performance on Mars could dramatically open up the science and exploration possibilities on the Red Planet, as has been detailed elsewhere [22,25]. As mentioned above, optimization of blade design can have a monumental impact on rotorcraft capabilities. Whether paired with a rover or on a standalone mission, a rotorcraft can traverse Mars with freedom that rovers do not have. Figure 9 illustrates what an advanced helicopter on Mars can do, compared with the Perseverance science mission.

Figure 9: Advanced Mars rotorcraft sortie range compared to Perseverance science missions.

To date, significant advances in compressible low-Reynolds airfoil optimization, using genetic algorithms guiding two-dimensional unsteady Reynolds-Averaged Navier-Stokes flow solvers, have been demonstrated. Additionally, a separate set of rotor optimization algorithms have been devised to guide the comprehensive rotorcraft analysis code CAMRAD II [38] to define new rotor designs, using the novel low-Reynolds number airfoils, for Martian operating conditions.

ROAMX is seeking to enhance the exploration capability of rotorcraft on Mars specifically through continued aerodynamic investigation and optimization of airfoil and blade planforms designed specifically for operation under Mars flight conditions. This is accomplished through computational optimization and experimental validation.

Computational and experimental work of ROAMX primarily focuses on hover performance, culminating in an experimental demonstration of improved rotor performance in an advanced, four-bladed, single rotor compared to a baseline rotor blade set based on Ingenuity's rotor blade. This work will also produce a validated design methodology for rotor blades in hover operating under Mars flight conditions. Efforts in ROAMX are also taken to investigate the structural design of rotor blades with thin airfoils such that experimental testing can be conducted on Earth under relevant Mars flight conditions. Experimental testing of thin, unconventional airfoils will also be conducted to validate computational predictions.

Given a mission and operating location on Mars, next-generation rotors can be quickly and efficiently designed using these methodologies that are being developed as a part of ROAMX. Finally, the project seeks to mitigate risk and further the Technology Readiness Level (TRL) of key technologies in anticipation of future rotorcraft-centric science mission proposals. Preliminary results show that significant performance increases are possible for an Ingenuity-sized rotorcraft using optimized blades (Advanced Rotorcraft Design in Figure 10 [20]). The performance increase allows for the vehicle to use a bigger battery and allows the vehicle to carry a significant science payload.

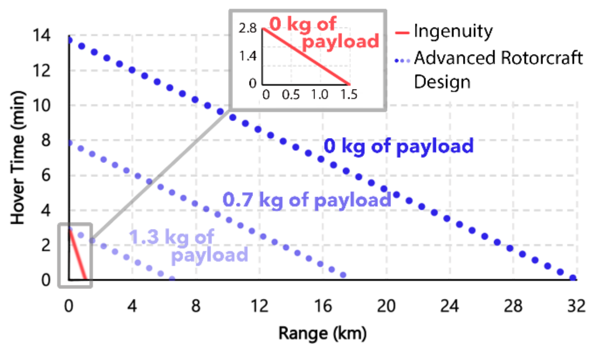

Figure 10: Comparison between Ingenuity and advanced rotorcraft design using optimized blades [20].

Previous Research

The research that ROAMX intends to conduct builds upon a foundation of aerodynamics research conducted in the community.

As mentioned previously, ROAMX is examining the aerodynamics of low-Reynolds, high subsonic Mach number flow to better design rotor blades for Mars rotorcraft flight. This aerodynamic regime is not well understood, and airfoils operating under compressible flow at low-Reynolds numbers have previously been investigated to only a limited extent. Kroo et al. focused on Earth-based mesicopters that operate under low-Reynolds numbers and conducted a significant amount of airfoil computational work. Anyoji et al. also conducted two-dimensional airfoil experiments at relevant Mars flight conditions [39,40]. Other substantial work at Mars flight and low-Reynolds number conditions has been conducted [41–46].

Beyond airfoil design considerations, efforts to consider blade chord and twist distribution designs date back to the early 2000s when rotors were developed and tested at ARC [3,47]. Performance of rotors designed for Mars rotorcraft flight was correlated through the Computational Fluid Dynamics (CFD) code OVERFLOW by Corfeld et al. [4,6]. These rotors used the low-Reynolds number Eppler 387 airfoil, as it is a well-known and well-documented low-Reynolds number airfoil.

Several different test campaigns of rotors at Mars flight conditions have previously been conducted at ARC starting in the early 2000s and continuing to the present. The Planetary Aeolian Laboratory (PAL), a large, low-pressure chamber at ARC, can be evacuated and reach densities which are comparable to the atmosphere of Mars. The facility has been utilized to conduct both hover and forward flight testing at Mars flight conditions, Earth atmospheric conditions, and at densities between the two [3,7,10,12,13,48].

As mentioned previously, many of these efforts contributed to the success of Ingenuity. However, greater exploration of Mars is possible, and further engineering work is required to bridge the gap between concept and reality by validating the technology required to enable future rotorcraft missions. This is the focus of ROAMX: to further airfoil and blade optimization with structural and dynamic considerations in mind followed by experimental verification of the blade and airfoil performance models, leading to a validated airfoil and rotor design methodology for future Mars rotorcraft, discussed below. Flight in this regime is relatively novel, and only experimental validation can give assurance that predicted performance increases are possible. The results obtained by ROAMX will validate the expected performance of the designs of next-generation Mars rotorcraft and will enable future exciting and scientifically enlightening Mars missions previously reserved for science fiction novels.

Computational Efforts of ROAMX Project

To bring expanded exploration of Mars via rotorcraft to reality, ROAMX computational work seeks to optimize blades and airfoils for operation in the low-Reynolds number, high subsonic Mach number regime. In addition, work is being done to further understand the fluid flow in this regime. Finally, in partnership with the University of Maryland, structural design and analysis of rotor blades is necessary to ensure blades operate safely under expected loading conditions.Airfoil and Rotor Design Methodology

Recently, Koning et al. have been investigating unconventional airfoil shapes featuring sharp leading edges (Figure 11) and have found that for the low- Reynolds numbers, high subsonic Mach number regime, these airfoils

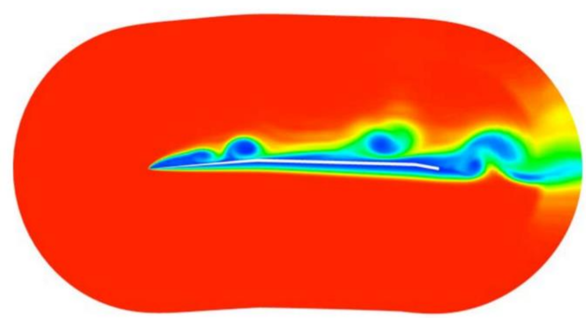

Figure 11: Precursor unconventional airfoil optimization CFD work [19].

exhibit promising performance results [17–19]. Computational efforts under ROAMX are expanding upon these results and continue research on unconventional airfoil shapes and the underlying unsteady aerodynamics that govern airfoil performance in this regime.

Previously demonstrated airfoil optimization techniques [17–19] are built upon in ROAMX to develop additional airfoil shapes that perform better than the clf5605 (Ingenuity outboard airfoil) baseline at same operating conditions. Additions include:

- The ability to implement a third objective in the form of a structural metric in the optimization such that lift is maximized, drag is minimized, and the structural metric (thickness, or second moment of area, for example) is maximized. This contributes to the ability to design for manufacturability, structure, and dynamics and control.
- The optimization architecture is set up to allow post-optimization selection of the desired structural metric (when running in 3-objective mode), allowing the aerodynamic optimization to be decoupled from the structural optimization, which is of particular importance in the inboard region of the blade.
- Manufacturability constraints for carbon-fiber type applications (such as minimum thicknesses and minimum radii) are built into the airfoil geometry routines.
- Airfoil geometry can now be specified as a combination of nodes and linear, quadratic, or cubic sections in between the leading edge, nodes, and trailing edge. This can be done for both camber and thickness without the need to adjust any code for the genetic algorithm, greatly speeding up the capability of evaluating a wide range of unconventional geometries, as well as classic airfoils (NACA 0012, clf5605, etc.) in the design space.

In ROAMX, the optimization framework is being used to generate airfoils that perform at Ingenuity's operating conditions (Table 3), but at a higher tip speed of Mtip = 0.80. ROAMX, through analysis and experimental campaign, is validating the optimization framework such that future optimal airfoils can be generated for any given operating condition on Mars (or any low-Re compressible flow regime).

Table 3: Ingenuity operating conditions.

Radius (m)	Chord (m)	Speed of sound (m/s)	Temperature (K)	γ	R ($m^2/s^2/K$)	μ (Ns/m^2)
0.605	0.09	233.13	223.2	1.289	188.9	1.13E-05

Recent work has also investigated rotor blade planform geometries specifically tailored for flight on Mars using unconventional airfoil cross-sections [20]. The ROAMX project is expanding upon this work and is also investigating optimal chord and twist distributions for Mars flight conditions. These chord and twist distribution investigations are being conducted using CAMRAD II computational analysis [38]. Both piecewise linear, quadratic and cubic twist and chord distributions are currently explored. The ROAMX efforts will be constrained to rotors with a thrust-weighted solidity of 0.25, to allow for fair comparison between different rotor designs with varying airfoils, planform, and twist.

As with the airfoil optimization framework, in ROAMX the chord and twist framework is being used to generate rotor planforms that perform at Ingenuity's operating conditions; however, through ROAMX the framework will be validated and future rotor planforms can be generated for any given operating condition on Mars (or any low-Re compressible flow regime).

Aeromechanics, Structural, and Mechanical Rotor Design

Because of the improved performance seen by employing thin unconventional cross-section airfoils for the outboard portion of Mars rotor blades, structural considerations are crucial to the design of these optimized rotor blades. It is also important to consider manufacturability of these blades.

AeroVironment, Inc. designed and built much of the rotating and nonrotating structural components of the Ingenuity Mars Helicopter, including the rotor hubs, blades, and collective/cyclic control system (and the custom electric motors driving the rotors) [29,30]. The blade fabrication lessons learned from AeroVironment have allowed ROAMX to define design requirements such as minimum acceptable leading-edge thickness for manufacturability. ROAMX is consulting AeroVironment regarding the manufacturability of ROAMX optimized blades.

The University of Maryland (UMD) has been investigating conceptual Mars vehicles and the aeromechanics of flying on Mars since the mid-2000s and is designing the internal blade structure of the ROAMX optimized blades [28,49–55]. Using the outer mold line and airfoil shapes designed by ROAMX, UMD will design the internal structure of the blades such that they can withstand the expected aerodynamic loads during testing. To analyze the internal structural design, UMD is using their in-house analysis code X3D, depicted in Figure 12 [54]. Analysis includes static and rotating structural analysis, as well as stability analysis.

Experimental Efforts of ROAMX Project

Computationally based performance improvements, obtained by employing unconventional airfoils in the low-Reynolds number, high subsonic Mach number regime, are quite

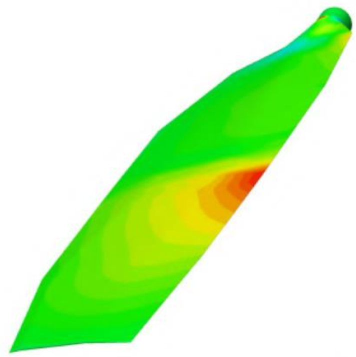

Figure 12: UMD rotating structural analysis of concept Mars hexacopter blade [54].

encouraging. However, experimental validation of these results is needed to provide confidence in the predictions and enable future Mars rotorcraft to utilize such designs. Thus, ROAMX intends to manufacture and experimentally test optimized blades discussed above to validate prediction models. In addition, in partnership with Tohoku University, airfoil testing of unconventional airfoils is planned.

Blade Manufacture and Testing

To aid in risk-reduction, ROAMX is manufacturing previously designed blades (Advanced Mars Helicopter Double-Edge Plate blades – Figure 13) [20] to ensure manufacturability, repeatability of manufacturing, and to validate internal structural design. These risk-reduction blades will be subjected to sectional property measurements.

To assess the risk of centrifugal failure before spinning, static tensile testing will be performed to simulate centrifugal loading. Due to reduced thrust in the thin Martian atmosphere, the main failure mode of concern is centrifugal (tensile) failure, especially at the higher speeds necessary to obtain desired thrust and tip Mach number.

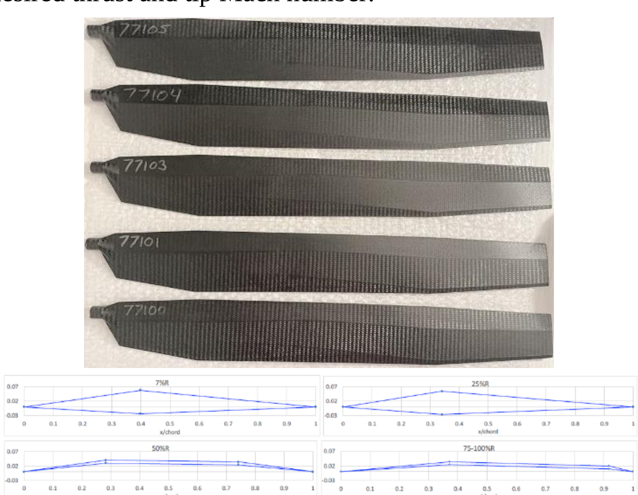

Figure 13: Manufactured risk-reduction blades and blade cross-sections [20] to ensure repeatability of manufacturing and validate design.

After the internal structural design of the ROAMX blades is completed, the blades will be manufactured for experimental testing. Like the risk-reduction blades, these ROAMX blades will be subjected to modulus of elasticity measurements and static tensile testing of magnitude equal to 110% of centrifugal force load expected during testing. These tests are done to ensure manufacturing repeatability, to validate internal structural design, and to ensure safety during testing.

Facility Considerations

Experimental testing for ROAMX will be conducted in the NASA Ames Research Center Planetary Aeolian Laboratory (PAL – Figure 14). The PAL is connected to the ARC Thermophysics Facilities Branch, Steam Vacuum System (SVS) and, thus, has the capability to connect to robust vacuum source and evacuate the test chamber (PAL tower) to a minimum of 5.5 millibars. Because of this, the PAL has been used for Mars-related testing for the past three decades. Historically, the PAL was built to test rockets and thus boasts a ceiling height of 30 meters and an internal volume of 4000 cubic meters [56]. The Mars Surface Wind Tunnel (MARSWIT) that is housed in the PAL was used for previous experimental rotor testing at ARC, see Figure 15 [7,10], and Young et al. used the PAL for rotor hover testing in the early 2000s [3].

Figure 14: External view of PAL tower.

Because of the knowledge gained from prior experience of rotor testing in the PAL at Mars densities (Figure 16), several additional sensors and systems have been procured and are being implemented into the PAL by ROAMX and the Thermophysics Facilities Branch at ARC. This includes an MKS 627 absolute pressure transducer that can accurately read pressure (0.12% of reading) experienced at Earth's atmosphere all the way to Mars atmospheric pressures.

Another system that is being implemented into the facility is improved pressure control. Previously, adjusting and maintaining the vacuum level in the PAL test chamber (tower) was a rather slow, labor-intensive, manual process performed by the Facility Operator. The new, automated, system will

Figure 15: Experimental testing in the PAL.

allow the facility to reach the desired test condition more quickly and maintain a more constant pressure. This, in turn, maximizes the dedicated time the facility has connected to the source of vacuum, by minimizing the time it takes to regulate to a steady pressure.

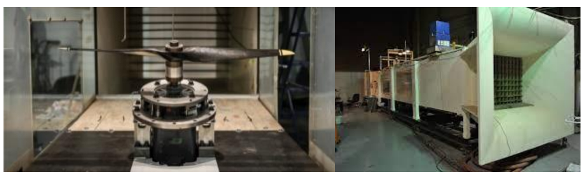

Figure 16: Previous ARC rotor testing (left) in the PAL MARSWIT (right).

Hover Testing

To validate the performance of the optimized airfoils and blades, experimental testing is needed. Hover testing at relevant Mars flight conditions will be conducted in the PAL for the ROAMX project. A 4-bladed rotor will be tested and average performance data (collective, rpm, thrust, and power) will be collected. In addition, Ingenuity rotors in an identical testing configuration will be tested as a baseline to compare against ROAMX performance data. Single rotor configuration was chosen over a co-axial configuration for simplicity and for broader applicability of experimental results.

To match the Reynolds number experienced under Mars flight conditions, the density of air in the facility will be varied. To match tip Mach number experienced under Mars flight conditions, RPM will be varied, allowing independent control of the primary conditions of interest. Because the speed of sound is lower on Mars than on Earth, the RPM needed to achieve equivalent tip Mach number on Earth is approximately 20% higher.

To conduct hover testing, complete experimental design is necessary. This includes design and structural analysis of the test stand. Components of the test stand must be vacuum-rated to ensure that nothing will fail during testing. To control the pitch and RPM, control systems are also required for the experiment.

Airfoil Testing

ARC and Tohoku University have recently implemented a Space Act Agreement so that airfoil testing of Mars airfoils in the Mars Wind Tunnel (Figure 17) at Tohoku can be conducted with the ROAMX project [40]. Logistics of the airfoil testing at Tohoku University are currently being discussed.

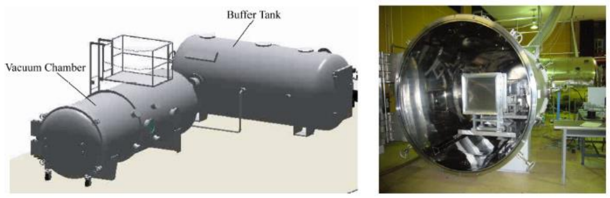

Figure 17: Tohoku University Mars Wind Tunnel [40] (compressible, low Reynolds number airfoil wind tunnel) where joint research under a Space Act Agreement will be conducted in support of ROAMX and future Mars rotorcraft.

Beyond ROAMX: The Future of Mars Rotorcraft Aeromechanics

The computational and experimental work conducted as a part of ROAMX will help to advance knowledge about the aeromechanics and aerodynamics of rotorcraft flight on Mars. There is, however, much more aeromechanical, and aerodynamic analysis to be conducted and researched beyond ROAMX. As mentioned previously, forward flight rotor testing is a natural follow-on to the ROAMX effort. Including stability and control measurements as a part of forward flight testing would be greatly beneficial to lay the groundwork for future tests and for fully qualifying blade performance. Further investigation into lightweight structures and analysis of those structures is also needed. Further manufacturability analysis is needed as well.

As noted, an outcome of the ROAMX computational work is an optimization framework that can be used to optimize airfoils and blades for any location on Mars (for compressible low-Reynolds flow) and for any mission flight requirements. Correspondingly, an outcome of the ROAMX experimental work is a new rotor hover test capability at ARC, and the ability to continue rotor testing under Mars-like conditions in the PAL facility. The test facilities, test stand, and overall test apparatus are not just intended to enable ROAMX hover testing, but also to prepare the path forward for future Mars rotorcraft aeromechanics investigations.

As interest in rotorcraft as extra-terrestrial explorers on Mars and other planetary bodies continues to grow (such as [57]) , key technical challenges in addition to those tackled in ROAMX need to be addressed (as detailed by Young et al [22]). Those challenges include:

- Assessing and implementing lessons learned from the design, manufacture, and flight of Ingenuity.
- Forward flight rotor testing of rotors that incorporate unconventional thin airfoils in the outboard sections.
- Tool development for structural and dynamic analysis, specifically for low-Reynolds compressible flow airfoils.
- New control system designs and mechanisms that can compensate for the lack of aerodynamic damping on Mars.
- Technical challenges involved with future generation planetary aerial vehicles, with robotic science missions incorporating multiple flying vehicles, and with robotic assistants to human exploration

In parallel to the ROAMX effort, work is also ongoing at ARC to develop a new low-Reynolds number wind tunnel with a 2-by 2-meter test section, which is larger than the existing MARSWIT wind tunnel (utilized previously in [7–10]). This new wind tunnel, as seen in Figure 18 for use in the PAL, will be used to test larger rotors than the approximately Ingenuity-sized rotors previously tested in the PAL, thus providing another test capability for future Mars rotorcraft applications at the appropriate atmospheric densities.

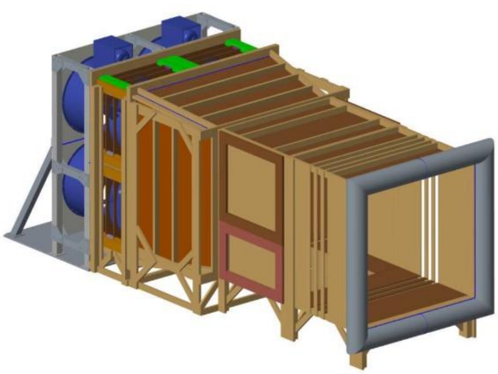

Figure 18: RAPTOR wind tunnel currently under construction at ARC which will be used for forward flight Mars rotor testing.

CFD and comprehensive rotor analysis work is also ongoing at ARC, as seen in Figure 19, to continue investigations into various conceptual rotorcraft designs for Mars applications.

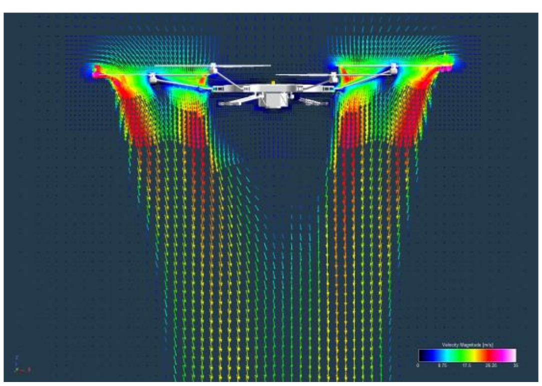

Figure 19: Hover condition Mars Science Helicopter CFD analysis conducted at ARC.

This new generation of wind tunnel data, in conjunction with past experimental work, and supplemented by Ingenuity 'wind wall' and flight data, will allow the refining of critical analysis tools [58] for future Mars rotorcraft.

Concluding Remarks

ROAMX is seeking to further the understanding of aerodynamics experienced under compressible low-Reynolds number flow experienced with rotorcraft flight on Mars. ROAMX intends to:

- Computationally optimize airfoils and rotor blades for efficient performance under Mars flight conditions.
- Experimentally validate computational performance predictions through experimental testing of airfoils in a wind tunnel and rotor blades in the hover configuration under relevant Mars flight conditions.
- Investigate structural design and analysis of rotor blades with thin airfoils for testing under relevant Mars flight conditions on Earth (i.e. Mach number and Reynolds number experienced with flight on Mars, with standard Earth air composition and temperature).
- Develop and validate a design framework and methodology such that, given Mars mission requirements, optimized airfoils and blades for operation under those conditions can be rapidly generated.

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