PROPELLER DESIGN, ANALYSIS, AND TESTING FOR THE MARS ELECTRIC REUSABLE FLYER II

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Abstract

NASA's 2021 Ingenuity helicopter demonstrated successful flight on Mars and paved the way for larger flight vehicles carrying scientific payloads with greater range and endurance. NASA Langley is exploring a "tail-sitter" concept, called the Mars Electric Reusable Flyer II (MERF-II). The project aims to optimize propeller geometry for this vehicle to create required lift and thrust in an extremely thin atmosphere, such that the surface of Mars can be efficiently scouted by a small fleet. Although previous research has optimized propeller geometry for Martian cruise flight, a propeller does not yet exist to support hover flight. ODU has developed a wind tunnel test capability for testing Mars propellers at dynamically scaled conditions by operating at very low RPM and tunnel speed. 3D printing technology provides the capability to rapidly prototype and test multiple designs in the same wind tunnel. Initial efforts were devoted to validating the test method, which was accomplished through comparison to several known propeller designs. New MERF-II designs are now being developed and tested, with Particle Image Velocimetry (PIV) being utilized for flow visualization.

Introduction

The Martian atmosphere is harsh. Composed primarily of carbon dioxide and roughly 1% the density of Earth's atmosphere, it does not retain heat well. Surface temperatures can vary from 20°C to -153°C.[1] Weather is also a major concern due to high winds and sandstorms. This makes navigation of the surface quite difficult. Traditionally, surface exploration has been conducted by rovers, but rover exploration is inefficient and heavily restricted by terrain. As of September 2025, the Curiosity rover has traveled a total of 36 km and as of December 2025, Perseverance has traveled a total of 40 km.[2,3] The Martian diameter is roughly 6780 km, meaning the rover-explored sections are minimal in the scale of the planet.

Additionally, the rovers are unable to traverse terrain such as canyons and lava tubes. For this reason, flight vehicles with surface exploration capabilities are highly desired. Ingenuity was the first step in this process, but the craft design was not optimized for the Martian condition. Across 72 missions, Ingenuity traveled about 17 km at a flight speed of 10 m/s.[4] This is a moderate improvement over the rover capabilities because it bypasses terrain constraints, but the range and flight speed leave significant room for improvement. It is for this reason that NASA developed the MERF initiative to optimize a craft that can cover a significant distance at a moderate speed.[5] The objective is to create a rotorcraft that can fly in both hover and cruise. The design goals are to generate 12 N of lift in hover, 6 N of thrust in cruise, and achieve a flight speed of 25 m/s. A small fleet of identical crafts will be developed, each with their own scientific instruments, so as to promote efficient scouting of the Martian surface.

Foundational Work

The MERF initiative was conducted from 2016 to 2018 at NASA Langley, and developed the framework for a high performance craft able to transition between hover and cruise flight. The current initiative aims to revisit the craft prototypes developed in the original MERF initiative. Additionally, researchers at Osaka University, in association with JAXA, developed a propeller model optimized for ultra-low Reynolds number flow.[6] This propeller geometry was used as the baseline testing model in the ODU wind tunnel.

Design Constraints

The Martian atmosphere introduces significant complexity to the proper selection of propeller geometry. Reynolds number, a quantity used to specify flow regimes is defined in Eq. 1 below.

$$Re = \frac{\rho v l}{\mu} \quad (1)$$

In this equation, ρ is the fluid density, v is the velocity, l is the characteristic length being measured, and μ is fluid viscosity. The turbulent transition point for Earth air is typically taken as $5*10^5$. The expected Reynolds numbers on the Martian surface over the proposed craft are on the order of 10^4. To match the Reynolds numbers expected in Martian conditions in a low speed wind tunnel, algebraic scaling can be used across all aerodynamic calculations.

Due to the thin nature of the atmosphere, the speed of sound is significantly lower, at ~240 m/s as compared to Earth's ~340 m/s at sea level. This introduces a size constraint on the propeller, as the tip speed must be constrained to roughly 80% of Mach 1. This rotational constraint limits both the size and speed of the propeller, as approaching Mach 1 introduces significant vibrational effects and leads to large efficiency losses. The full-scale aircraft would have two 1.2 m diameter propellers mounted on it. Dynamically scaled to fit in the ODU wind tunnel, the propellers being analyzed had roughly a 0.5 m diameter and were operated in the 200-300 RPM range.

Experimental Setup

The wind tunnel is operated in NI LabVIEW. Atmospheric measurements are taken using a thermocouple, a barometric pressure sensor, and a dynamic pressure sensor, which are used to compute test section velocity. PID control is implemented to convert velocity into voltage, which is communicated to the tunnel fan. PID control is also used for the motor, in combination with a laser tachometer and reflective tape on the propeller blades. The motor and propeller are mounted on a test stand that can be adjusted between flow-parallel and flow-perpendicular. An ATI load cell is used to measure the forces and moments created as the propeller spins.

Originally, a hub connecting the motor and propeller was used that was quite imprecise. Each propeller featured a circular stub that plugged into the hub, which was then tightened with hose clamps. This meant that the angle of attack of the propeller was determined by taking a protractor and measuring the angle of attack at 70% of the radius. It became quickly apparent that this configuration was not suitable for precise blade adjustment, so a redesign of the hub was conducted. The new design features a propeller hub for each blade and a central motor hub. The propeller is glued into its matching propeller hub, and each propeller hub is attached to the motor hub via screws. The hexagonal stubs allow for rapid calibration between each propeller and its hub to ensure proper angling before gluing. The propeller hubs can be rotated in 5° increments, allowing for a 35° adjustment in angle of attack. The hub design for a 2-blade configuration is shown below in Figure 1. A second iteration of this design was created to accommodate a 4-blade design, although there were no major design differences.

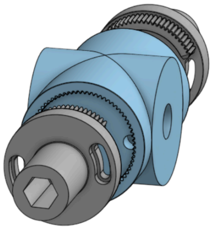


Figure 1 - New hub design

Test Method Validation

To match the scaled velocity conditions, the ODU wind tunnel was pushed to its absolute minimum speeds. The tunnel can be operated up to 52 m/s safely. The typical range tested for the Martian propellers was 0.4 m/s to 4.2 m/s. This ultra-low speed testing is highly unconventional, so the experimental setup was validated prior to Mars propeller testing. To conduct a propeller sweep, the propeller is run at a set RPM starting from static conditions and increasing velocity until the propeller thrust drops to zero. All results with negative thrust are discarded, as they indicate the wind is spinning the propeller more than the motor. Several commercially available APC propellers were tested and compared against available UIUC propeller data.[7] The propellers tested included a 14x10, a 14x12, and a 17x12 propeller. The data gathered matched closely with the tabulated UIUC data, confirming the accuracy of the testing methods.

Propeller Testing

One of the primary advantages exploited by ODU is the capability to verify multiple propellers in the same experimental setup. As such, initial testing was conducted on the 2-blade propeller geometry from the original MERF initiative. The primary criteria being examined are coefficient of thrust C_T (Eq. 2), advance ratio J (Eq. 3), coefficient of torque C_Q (Eq. 4), and efficiency η (Eq. 5).

$$C_T = \frac{T_x}{\rho (RPS)^2 d^4} \tag{2}$$

$$J = \frac{v}{(RPS)d} \tag{3}$$

$$C_Q = \frac{2\pi M_x}{\rho (RPS)^2 d^5} \tag{4}$$

$$\eta = J\frac{C_T}{C_Q} \tag{5}$$

In the above equations, T_x is thrust generated, ρ is air density, RPS is revolutions per second, d is propeller diameter, v is wind speed, and M_x is torque about the x-axis. Shown at right in Figure 2a, the coefficient of thrust C_T for the original MERF propeller had a peak at 0.25 and the useful range of the propeller was found to extend to J = 1.5. The efficiency peak, shown in Figure 2b, was found to be 0.715 at J = 1.07. This indicates a moderately useful propeller, but 71.5% maximum efficiency leaves much to be desired.

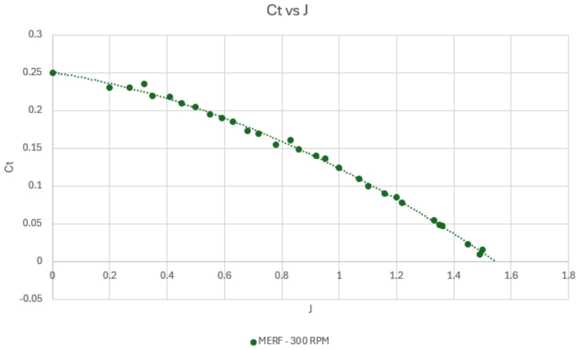


Figure 2a - C_T vs J, MERF propeller, 300 RPM

Figure 2b - η vs J, MERF propeller, 300 RPM

Cruise-Optimized Propeller Geometry

The optimized propeller for low Reynolds number flight conditions developed by Osaka University and JAXA was the primary propeller geometry examined over the course of this testing. From the data provided in [6], it was possible to reconstruct the propeller geometry and fabricate it using SLS 3D printing technology with glass-infused nylon powder. The propeller airfoil and geometry is shown below in Figure 3.

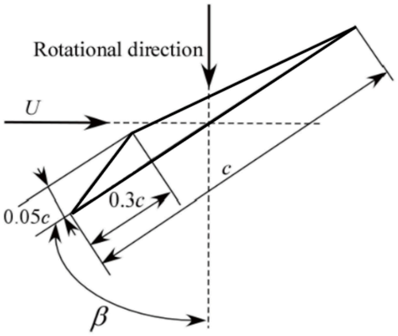


Figure 3 - JAXA propeller specifications

This propeller features a sharp leading and trailing edge, as well as a sharp point at 0.3c. It also features a very aggressive twisting along its length, with the blade root being inclined at 73° from the horizontal and the blade tip being inclined at 32°. While highly unconventional for traditional aerodynamics (although somewhat similar to a marine propeller), this odd geometry minimizes boundary layer separation, which reduces drag and increases efficiency. Additionally, the low aspect ratio, large chord, and aggressive twisting allow for large thrust generation without high rotational speed. The original version of this propeller tested at ODU featured two propeller blades. It was discovered during the testing phase that there was an image in [6] that indicated the testing setup should feature four blades. As such, there is a mix between 2-blade and 4-blade data collected. The 4-blade cruise setup is shown below in Figure 4.

Figure 4 - JAXA 4-blade setup

Data and Analysis

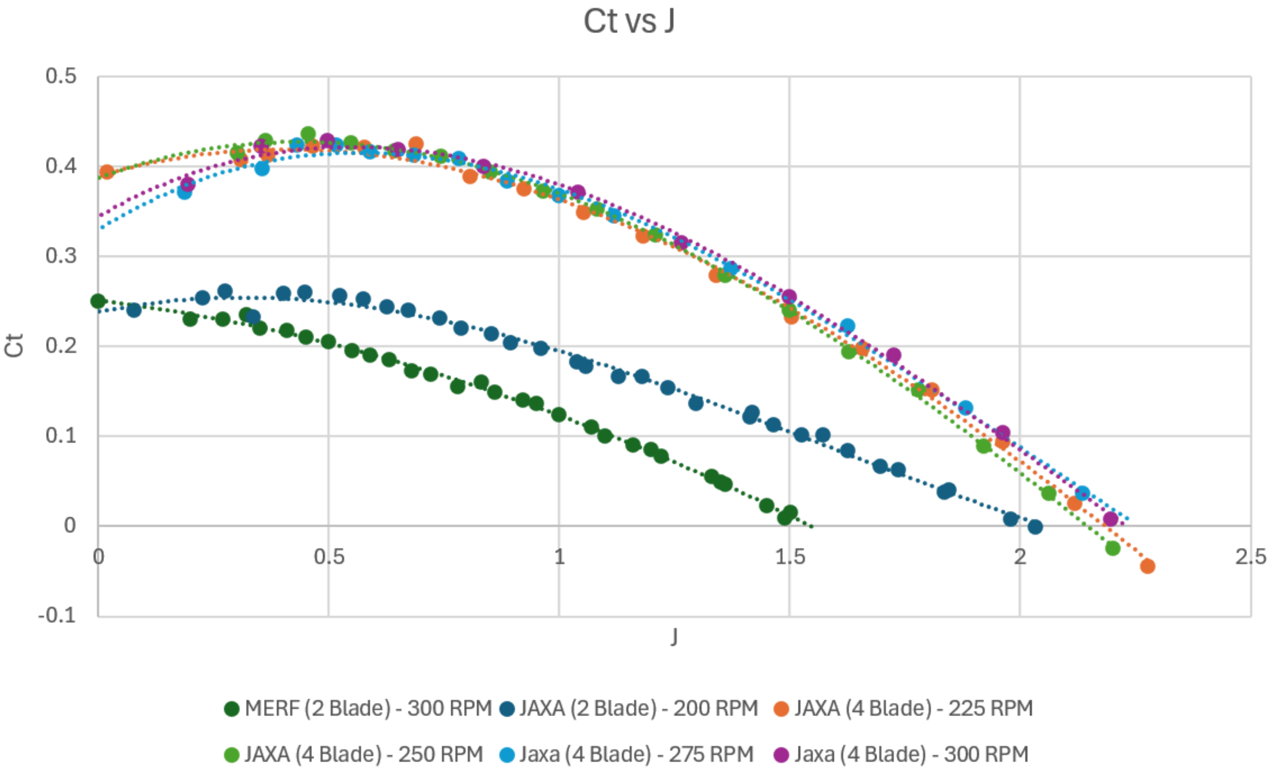
Cruise Flight

All propeller designs in this section were tested in the cruise flight case. The JAXA 2-blade was tested at 200 RPM. The JAXA 4-blade propeller design was tested at 225, 250, 275, and 300 RPM. More points were not collected on the 2-blade JAXA design because it was then noticed the original design called for a 4-blade configuration. The C_T vs J and η vs J curves for all six major trials are shown below in Figures 5a and 5b. It should be noted that the large jump in the C_T data between the JAXA 2-blade and 4-blade setups is due to the difference in blade count. The 4-blade setup has a roughly doubled C_T as compared to the 2-blade setup. The increased blade count also affects the η vs J curves, causing a lower peak efficiency at the expense of higher thrust. Of note is the trend in the efficiency curves for the JAXA design, whereby the lower the RPM, the higher the efficiency peak. This is an interesting trend that will require further experimentation to understand fully.

Comparing the 2-blade JAXA propeller to the MERF propeller, the C_T vs J curve appears nearly identical, but shifted to the right, which indicates a wider range of propeller usefulness. The 2-blade JAXA design has a similar maximum C_T to the MERF design, but the effective range extends out to J = 2, as compared to the MERF cutoff at J = 1.5. The difference between the two designs is far more apparent in the efficiency curves. The MERF design has an efficiency peak of 0.72 at J = 1.07, while the 2-blade JAXA design has an efficiency peak of 0.82 at J = 1.42. This is an enormous improvement over the MERF design.

Comparing the 4-blade cases, all four RPM cases had C_T peaks in the 0.42 - 0.44 range around J = 0.5. The efficiency peaks were lower than the 2-blade case, as discussed previously. Between the 225, 250, 275, and 300 RPM cases, the efficiency peaks were 0.70, 0.68, 0.63, and 0.65 respectively, all occurring around J = 1.7.

For the next phase of testing, all work was and will be conducted on 2-blade designs. It may be discovered after further experimentation that a 4-blade configuration is necessary to generate the target lift and thrust requirements, but presently, data has yet to be collected on most of the novel designs.



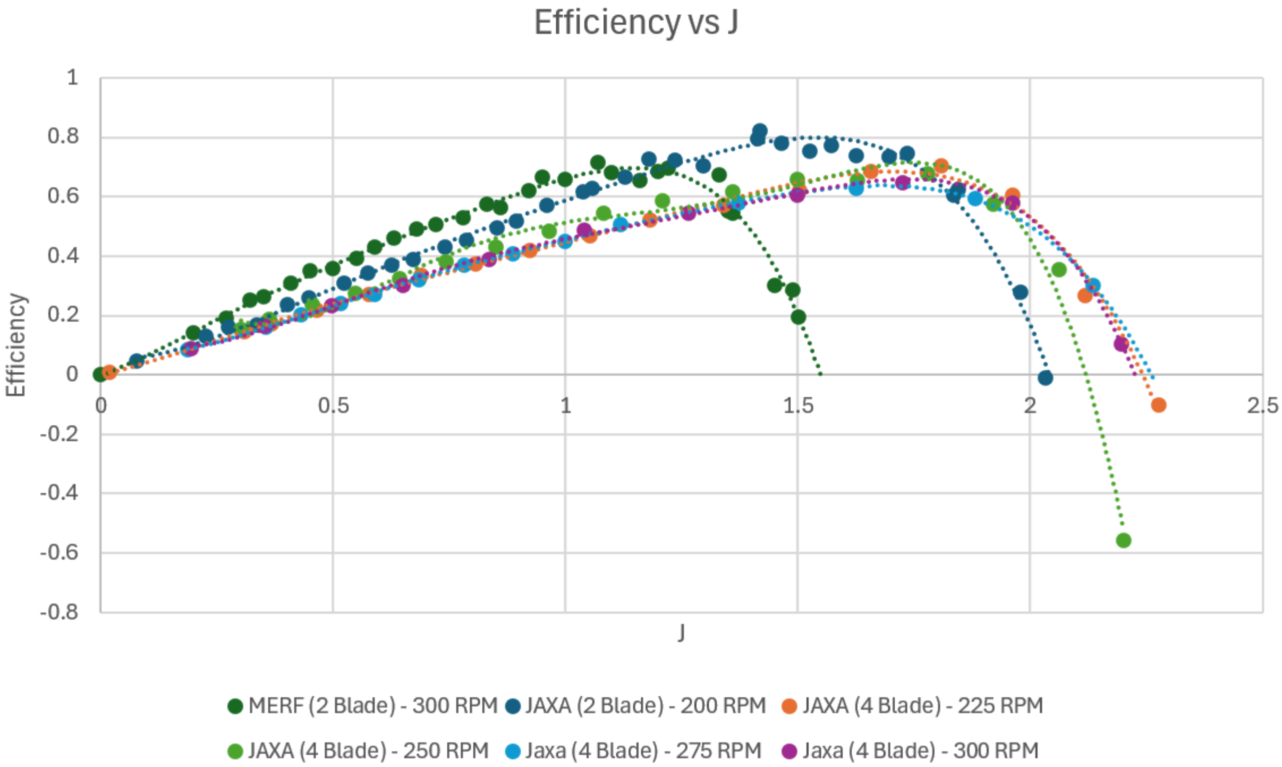


Figure 5a (top) - C_T vs J Figure 5b (bottom) - Efficiency vs J

Hover Flight

Current hover data has been obtained solely in the propeller analysis software QBlade. The η vs J curves of the JAXA 2-blade propeller at 200 RPM and the JAXA 4-blade propeller at 250 RPM in cruise are shown below in Figure 6 in orange and green respectively. The blue curve is the QBlade prediction for the JAXA 2-blade propeller at 250 RPM, and notably has an efficiency peak extremely far from the cruise peaks. This indicates the propeller is not suitable for both flight cases because the efficiency peaks cannot both be achieved in the rapid transitions between cruise and hover.

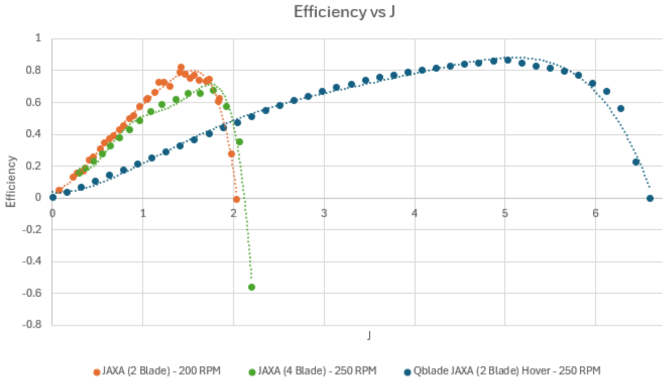


Figure 6 - η vs J comparing hover and cruise

Geometry Optimization

Due to significant discrepancies between the advance ratios of the efficiency peaks of the hover and cruise flight cases for the JAXA propeller design, it was clear that the geometry would need to be adjusted to bring the efficiency peaks in closer alignment.

Extensive testing and iteration was conducted in QBlade with variations in the propeller twist and chord length. Several viable models have been selected, all of which take the baseline JAXA design and depitch the twist. Wind tunnel testing has not been able to be performed yet to experimentally verify these models, but will be completed shortly after the publishing of this paper.

New Geometry Data

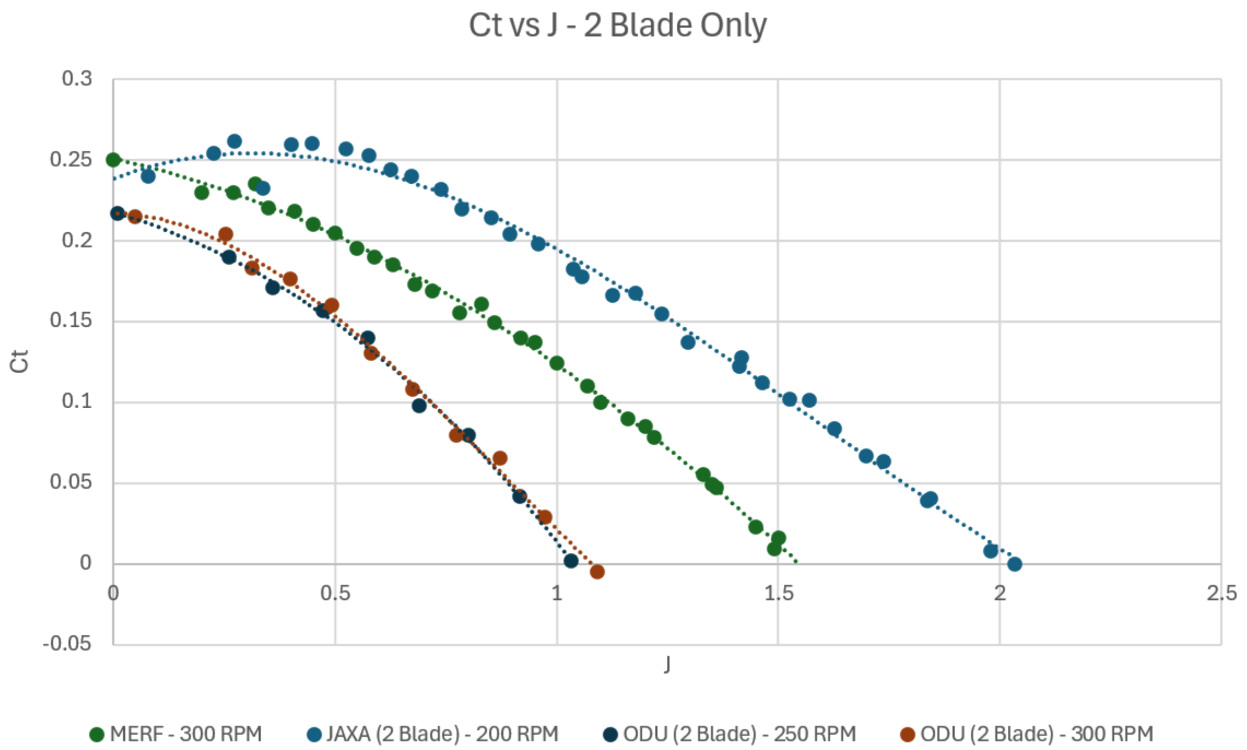
One propeller with modified geometry has been fabricated thus far. The new geometry developed has currently been tested in cruise at 250 and 300 RPM, with more tests planned. The data comparing all 2-blade geometries is shown below in Figures 7a and 7b.

Analysis of the ODU Propeller in Cruise

The ODU modifications to the JAXA propeller geometry demonstrate significantly lower C_T and efficiency peaks. Notably, the ODU propeller's efficiency peaks are at a much lower advance ratio, aligning with the objective to lower the necessary advance ratio to achieve peak efficiency, and bringing the hover and cruise peaks into closer alignment. The 250 and 300 RPM cases both saw a max C_T of 0.22. The efficiency peaks were 0.68 and 0.73 between the 250 and 300 RPM cases respectively, both occurring around $J = 0.85$. It is then clear that in the effort to optimize a propeller geometry for multiple flight cases, thrust and efficiency both suffer greatly. However, while the ODU design performs notably worse than the JAXA design in cruise flight, computational simulations show a significant increase in hover thrust and efficiency.

Airframe

The airframe for the MERF-II craft is being developed by NASA Langley in parallel with ODU's propeller testing efforts. The craft is a flying-wing tail-sitter with an intended span of 6 m and an aspect ratio of 4.8. The wing will bear a NACA 15106 airfoil across the span, constructed of carbon-fiber wrapped foam core. The craft will take off laying flat, which will cause a cruise-to-hover transition at low speed. Once airborne in hover flight, the motors will push to higher RPM. The camber of the airfoil will generate a moment that will force the craft to transition from



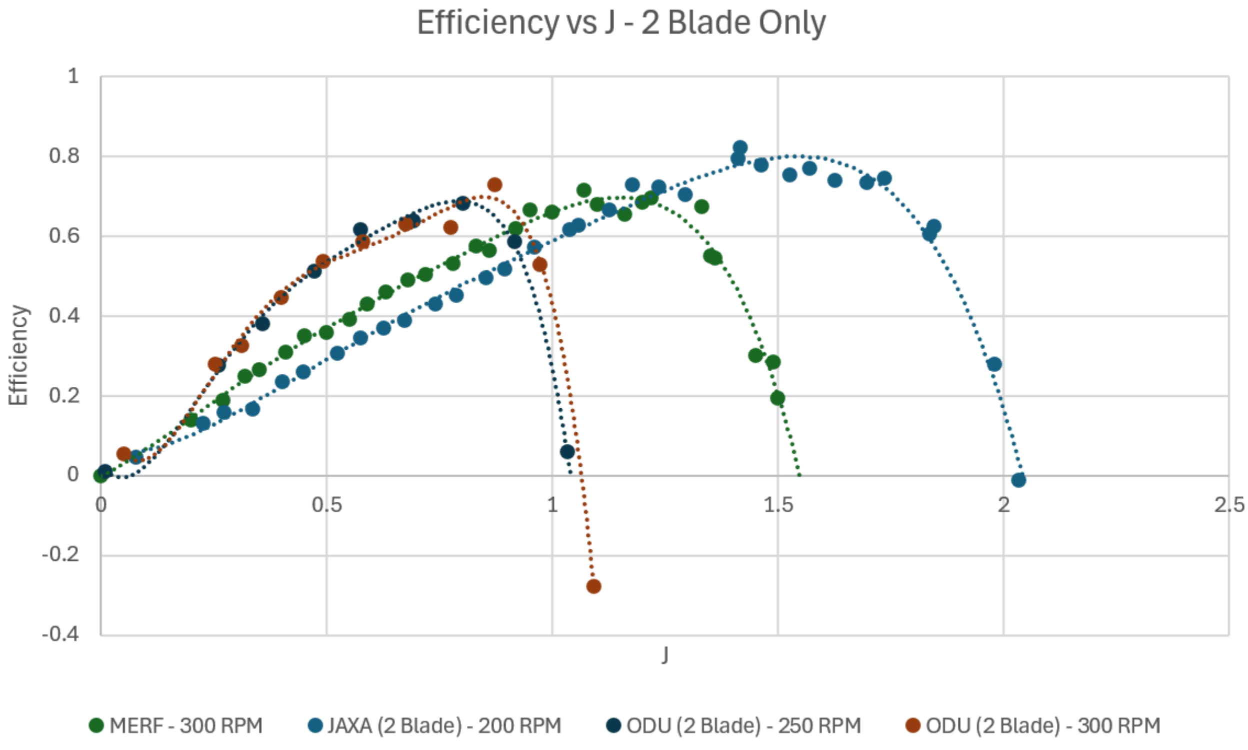


Figure 7a (top) - Cruise C_T vs J, all 2-blade propellers

Figure 7b (bottom) - Cruise η vs J, all 2-blade propellers hover into cruise flight. For transport of the airframe to the Martian surface, the design will feature multiple hinged panels. Figure 7 below shows Version 2.3 of the MERF-II airframe. The design has since been updated to fold into sevenths, so as to be more compact. More details regarding the current and previous iterations of the MERF-II craft can be found at [8]. At the bottom of [8] is a link to the FY25 presentation, which summarizes all of the available data before the propeller geometry efforts were conducted, although most of that information is beyond the scope of this paper.

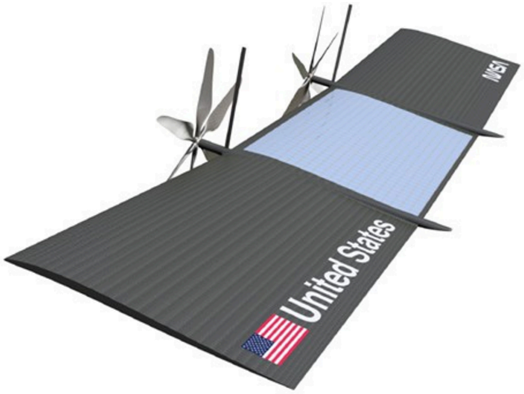


Figure 8 - MERF 2.3 airframe

QBlade and XFLR5 were used for the computational data for the propellers and airframe respectively. Utilizing the data currently available, the 5 kg airframe will be able to support a 0.5 kg payload and will be flying in a Reynolds number regime around $3.9*10^4$. The propellers will operate at roughly 65% total efficiency, with the tips spinning at roughly 70% of Mach 1. The craft can achieve a lift-to-drag ratio of 10.5, and under optimal conditions, can achieve a range of 84 km with an endurance of 54 minutes. As compared to the range and endurance of Ingenuity discussed previously, this is a phenomenal improvement. These computational results will be validated by wind tunnel testing as soon as propeller geometry optimization has concluded and models have been fabricated.

Future Efforts

PIV Testing

Particle Image Velocimetry (PIV) is a flow visualization technique involving a smoke screen, laser sheet, and RPM-synchronized camera. The objective of this method is to take a picture of the same propeller blade at the same point in its rotation and create a time-averaged picture of the vector fields present in the air passing over the blade. A PIV test was conducted on the ODU propeller, but the images captured were imperfect due to significant scratching on the plastic panel of the wind tunnel test section. A glass panel has been constructed to replace its plastic counterpart and testing will begin soon on the currently fabricated ODU propeller and several other altered-geometry prototypes.

Hover Flight

All hover data is currently computational. Testing has not yet been conducted on any of the propellers in a hover configuration. Once PIV testing has concluded, all fabricated propellers will be tested in a hover configuration to verify the geometry alterations. If the efficiency peaks between hover and cruise are in moderate alignment, the propeller geometry will be considered a success.

Transition Flight Cases

With hover and cruise flight validated individually, the final step in developing a viable prototype is to test a variable pitch case. The testing setup does not currently exist to test a propeller that changes flow inclination during the test. A test could currently be conducted with discrete angle adjustments in roughly 10° increments, but continuous transition data is desired. The design of a variable test setup will be one of the final challenges faced on the ODU half of the project.

Airframe

The mission scope has slightly adjusted for the airframe since its design and testing at NASA Langley. The original craft was designed to fold in thirds, intended to be its own mission and thus having little spatial constraints. The new concept would have the craft as a "ride-along" on a larger mission, which would require much smaller packaging. The craft has tentatively been redesigned by ODU to fold in sevenths, so as to fit in roughly a 1.3 m x 1.25 m x 0.5 m box. This design is highly subject to change and has yet to be reviewed by personnel at NASA. Due to the unpolished nature of this design iteration in its current state, the author does not feel it fit to include in this paper.

Conclusion

ODU has developed an experimental test method that is highly useful for testing multiple propeller designs in an unpressurized environment. This economical nature of testing and ability to rapidly design and fabricate propellers has allowed for significant advancement towards a propeller design that can propel a high-performance fleet of aircraft scouting the Martian surface. Current testing results indicate a high degree of success in the efforts to optimize each craft's range, endurance, speed, and payload capacity. If future testing yields results of similar caliber to existing test data, the design(s) will be delivered to NASA Langley and integrated into the finalized airframe.

Acknowledgements

Special thanks to **Dr. Colin Britcher** for his advising and directing of the project.
Kevin Ramai for theoretical analyses and CAD design work.
Virginia Space Grant Consortium for their sponsorship via their Undergraduate STEM Research Scholarship.

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