



Paul Schulman²

Department of Electrical and Computer
Engineering,
Michigan State University,
East Lansing, MI 48824
e-mail: schulm14@msu.edu

Samuel-Hunter Berndt

Jet Propulsion Laboratory,
California Institute of Technology,
Pasadena, CA 91109
e-mail: samuel-hunter.berndt@jpl.nasa.gov

Christiahn Roman

Jet Propulsion Laboratory,
California Institute of Technology,
Pasadena, CA 91109
e-mail: christiahn.roman@jpl.nasa.gov

Xiaobo Tan

Department of Electrical and Computer
Engineering,
Michigan State University,
East Lansing, MI 48824
e-mail: xbtan@msu.edu

Computational Fluid Dynamics Modeling Analysis of a Martian Rotorcraft With Individual Blade Control¹

Computational fluid dynamics (CFD) analysis was conducted on a proposed blade root-actuated individual blade control (IBC) system for future Martian rotorcraft. IBC offers many potential benefits to rotary-winged exploration of Mars, including precision control of rotor blade forces. This study seeks to provide an estimate of rotor blade force and system power as a basis for concept feasibility analysis and experimental prototyping. ANSYS FLUENT was used to compute blade pitching moment, lift, and drag under various feathering waveforms, amplitudes, biases, and frequencies. It is determined that the rapid feathering characteristic of IBC has a non-negligible impact on blade forces. It is also found that actuators with power ratings on the order of 10^1 W are likely sufficient for blade actuation on Martian rotorcraft. [DOI: 10.1115/1.4063482]

Keywords: rotorcraft, exploration, Mars, individual blade control, actuators, CFD, aerospace systems, dynamics and control, flight control, modeling, robotics, unmanned vehicles, vibration control

1 Introduction

The Mars Helicopter, Ingenuity, completed the first flight on another planet on April 19, 2021, and has logged over 50 successful flights since. Ingenuity features a pair of two-bladed rotors, each controlled by its own electrically actuated swashplate. The 1.2 m diameter rotors spin at speeds of up to 2800 rpm [1]. Other Martian rotorcraft have also been proposed, including the Mars Sample Recovery Helicopters and Mars Science Helicopter, each having rotor diameters of approximately 1.2 m. This is because larger rotors are limited due to uncontrolled blade flapping modes, which represents a major constraint on Martian rotorcraft.

When a helicopter blade flaps, the up and down motion produces a change in the blade angle of attack (AOA). This change in the angle of attack creates a force opposing the flapping motion of the blade. On Earth, this opposing force is sufficient to dampen the flapping motion. The Martian atmosphere, however, has a density of approximately 1% that of Earth's and does not provide sufficient damping [1]. If the rotor blades are allowed to flap at high amplitudes, structural failure will occur. Currently, control bandwidth must be limited, and blade rigidity and mass must be increased to avoid excessive flapping of the blade. For rotors larger than the current state-of-the-art, acceptable control bandwidth would require a blade mass that is too large, thus presenting an

upper limit on rotor size for Martian rotorcraft. Resolving this problem requires the creation of either stiffer light-weight blade materials to increase the blades' natural frequencies or a blade flap damping system. In this work, we propose a novel solution to dampen blade flaps using individual blade control (IBC).

Helicopters derive their motion through dissymmetry of lift, i.e., different sections of the rotor disk produce different magnitudes of vertical force, resulting in a horizontal component of the net force vector. Dissymmetry of lift is created across the rotor system by pitching, or "feathering," each blade as a function of its position around the disk. Traditional helicopters, including the Mars Helicopter, accomplish this blade pitch actuation with a mechanical swashplate system, shown in Fig. 1. The swashplate is a tilting assembly that transfers orientation from the static frame to the rotating frame and is rigidly attached to the blades, causing them to pitch as they rotate around the rotor disk. Because the swashplate is a rigid, planar disk, blades are limited to a once-per-revolution (1/rev) sinusoidal pitch change and are coupled by phase to the other blades. Unfortunately, this limits the adaptability of blade pitch required for countering aerodynamic perturbations or manipulating transient forces.

In contrast, IBC is a rotor control technique by which each blade's pitch is actuated independently of the others. IBC can independently actuate the blades multiple times per revolution in an arbitrary waveform, thus allowing precise control of transient blade forces. IBC has shown the ability to reduce rotor vibrations, noise, energy consumption, and blade stresses [3], as shown in simulation, wind tunnel testing, and manned flights [4–7]. IBC can also be implemented in many forms, such as morphing blades, active trailing-edge flaps, and blade-root actuation. In

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²Corresponding author.

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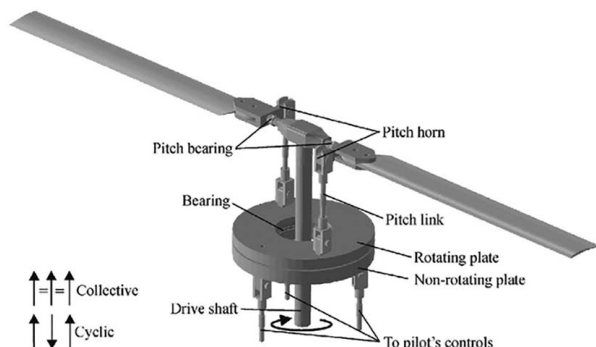


Fig. 1 Diagram of a swashplate [2]

particular, the blade-root actuation method, the focus of this work, places pitch-altering actuators at the root of each blade and eliminates the swashplate.

Despite the aforementioned efforts, there has been little research on blade-root actuation IBC for unmanned aerial vehicles (UAVs) or Martian rotorcraft. A key difference of IBC on the UAV scale is the high-speed, low mass, and compact size of the rotor system, which is conceptualized in Fig. 2. Consequently, implementation of IBC on Martian UAVs requires centimeter-scale high-speed actuators not typically studied in the context of IBC. Saxena and Chopra implemented 10 mm diameter rotating-frame actuators at a frequency of 40 Hz on trailing-edge flap IBC test platforms [8]. However, for the proposed application on Martian rotorcraft, it is expected that actuation frequencies will be upwards of 100 Hz. Furthermore, no information is available on the performance of IBC in the Martian atmosphere, where flight itself is an emerging science.

The thin atmosphere, small blade size (relative to manned rotorcraft), and high rotor speed characteristic of flight on Mars lead to operating conditions with ultra-low Reynolds numbers. Noonan and Bingham reported Reynolds numbers of 3×10^6 to 6×10^6 on manned, terrestrial rotorcraft [9]. The Reynolds numbers for the Mars Helicopter are estimated to be between 1×10^4 and 2.5×10^4 [10]. Comparable flight conditions on Earth are those of insects, small birds, and micro air vehicles, in which Reynolds numbers on the order of 10^4 [11].

The objective of this study is to predict the achievable ranges of blade forces, to estimate hardware performance requirements, and to advise on the design of IBC-enabled blade flap damping systems for Martian rotorcraft. This will be accomplished by exploring the impacts of blade angle of attack, pitching angular velocity, pitching angular acceleration, and pitching waveform on

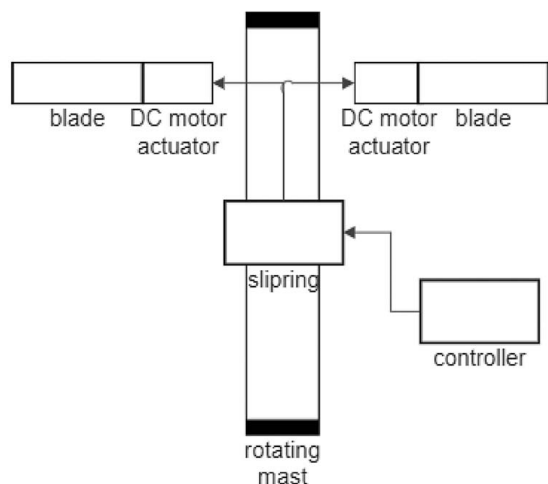


Fig. 2 Illustration of a simple blade root-actuated IBC rotor

power requirements for blade-root actuators and rotor-drive motors during rapid IBC feathering in the Martian atmosphere. The achievable ranges of blade forces will define the system's ability to dampen the blade flap. In this work, a computational fluid dynamics study is conducted in ANSYS FLUENT to estimate blade forces under various feathering frequencies, amplitudes, pitch biases (known as "collective," or the average angle of attack), and waveforms. These blade forces are used to estimate the maximum transient power of the IBC actuators and the time-averaged power consumption of the IBC and rotor drive systems.

2 Approach

2.1 Blade Geometry and Mesh. A rotor blade with properties like those of the Mars Helicopter was modeled and is shown in Fig. 3. A low-Reynolds number airfoil, CH 10-48-13, was used from root to tip, excluding blending zones and the cylindrical root. The blade's pitching axis (z-axis) is coincident with the longitudinal centerline of the cylindrical root. The blade planform matches that of the Mars Helicopter [12], though no longitudinal twist is applied. The moment of inertia about the pitching axis is $1.73 \times 10^{-5} \text{ kg} \cdot \text{m}^2$. The blade is encased in a 4.2 m by 2.8 m by 1.0 m rectangular fluid environment, with the blade feathering axis located 0.7 m from the flow inlet. The mesh is made of 1,087,191 tetrahedron elements. The maximum face size is $8.88 \times 10^{-3} \text{ m}^2$, the minimum face size is $1.02 \times 10^{-8} \text{ m}^2$, and the minimum edge length is $1.86 \times 10^{-4} \text{ m}$.

2.2 FLUENT Setup. Inlet flow was set as a linear gradient from 2 m/s at the blade root to 177 m/s at the tip. The fluid was matched to the Mars atmospheric conditions: density of 0.017 kg/m^3 , dynamic viscosity of $1.130 \times 10^{-5} \text{ N} \cdot \text{s/m}^2$, and temperature of 223 K. Blade feathering was achieved with a user-defined function for rigid body motion. A viscous $k-\omega$ SST model with low Reynolds number corrections was used. Validation of simulation results was conducted by varying simulation models and variables and observing the behavior of the results. First, three viscous models were tested, including the $k-\epsilon$, Spalart-Allmaras, and $k-\omega$ SST models. No significant change was observed in the results, indicating a stable setup. Next, the time-step was varied from larger to smaller. It was noticed that below a certain time-step, the results did not change. Below an even smaller time-step, the

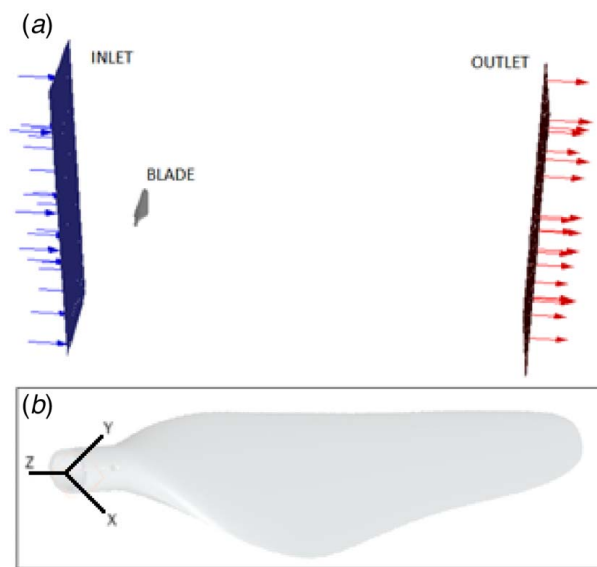


Fig. 3 (a) The inlet, outlet, and blade position, and (b) the blade geometry, datum, and axes

results exhibited discontinuities expected when a time-step is too small. Suitable time-steps were chosen within this range.

2.3 Static Tests. Tests were completed without blade feathering in order to determine the aerodynamic properties of the blade and to establish a baseline case in which feathering plays no role in blade performance. For the static case, 250 time-steps of 0.001 s were executed for a total of 0.25 s, which allowed sufficient time for a steady solution to develop. Pitching moment, lift, and drag data were produced at each angle of attack. The center of pressure on the xz -plane intersecting with the pitching axis was determined. Data were gathered for each angle of attack between 0 deg and 20 deg inclusive for a total of 21 simulation runs.

2.4 Dynamic Tests. The main efforts of the study were the tests implementing blade motion. For the dynamic cases, 5000 steps of 5×10^{-5} s were executed for a total of 0.25 s, which allowed sufficient time for a repeating transient solution to develop. Five test sets were carried out, each imparting a different pitching motion on the blade. Each test set included tests at pitching frequencies of 1, 2, 4, 6, and 8/rev. The five test sets are as follows, described by waveform, peak-to-peak amplitude, and bias (collective):

- (1) Sinusoidal waveform, 10 deg amplitude, 5 deg bias.
- (2) Sinusoidal waveform, 2 deg amplitude, 1 deg bias.
- (3) Sinusoidal waveform, 2 deg amplitude, 5 deg bias.
- (4) Skewed sinusoidal waveform, 2 deg amplitude, 5 deg bias.
- (5) Quadratic waveform, 2 deg amplitude, 5 deg bias.

Figure 4 illustrates the three waveforms studied in this work. The sinusoidal waveform, which also describes traditional swashplate systems at a 1/rev frequency, is defined by

$$\text{AOA}(t) = -\frac{\theta_{\text{IBC}}}{2} \cdot \cos(n \cdot \omega_{\text{rotor}} \cdot t) \quad (1)$$

where AOA is the blade angle of attack in radians, t is the time in seconds, θ_{IBC} is the blade pitching amplitude in radians, n is the pitching frequency per rotor revolution (1/rev), and ω_{rotor} is the rotor speed in rad/s.

The skewed sinusoidal waveform is approximated by

$$\text{AOA}(t) = \frac{0.494708}{-0.25} \tan^{-1} \left(-0.25 \frac{\sin(f)}{1 - c \cdot \cos(f)} \right) \quad (2)$$

where f is defined as

$$f = \omega_{\text{rotor}} \left(t - \frac{0.006219}{n} \right) \quad (3)$$

This waveform was considered after it was observed during testing that symmetric upward and downward pitching produced asymmetric results, with the upward pitching motion producing

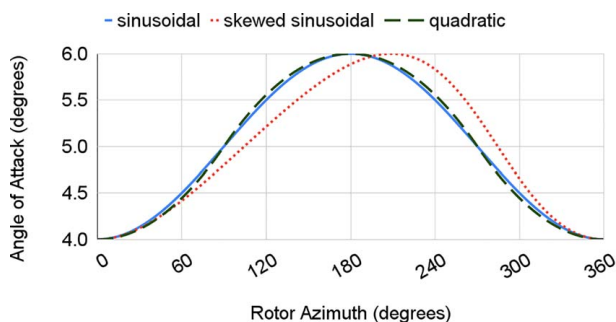


Fig. 4 Blade angle of attack as a function of rotor azimuth at a frequency of 1/rev, amplitude of 2 deg, and bias (collective) of 5 deg, for three different waveforms

higher forces than the downward pitching motion. In an effort to minimize the maximum transient torque, the waveform was skewed by a factor of 25% toward the down pitch, leading to a faster down-pitch and slower up-pitch than the unskewed waveform.

The quadratic waveform is defined by

$$\text{AOA}(t) = \left(\frac{\theta_{\text{IBC}}}{2} \right) + \left(\frac{4\theta_{\text{IBC}}}{\pi^2} \right) \cdot \text{sgn}(\cos(n \cdot \omega_{\text{rotor}} \cdot t)) \cdot \left(\frac{\sin^{-1}(\sin(n \cdot \omega_{\text{rotor}} \cdot t))^2}{2} - \frac{\pi^2}{64} \right) \quad (4)$$

This waveform was considered after it was observed that the inertial moment during rapid pitching of the blade was much larger than the aerodynamic moment. Thus, a waveform that minimized maximum angular acceleration was sought. This was achieved by using a waveform that produced constant alternating angular acceleration with no peaks or valleys, at the consequence of having an infinite angular jerk.

2.5 Post-Processing. The primary considerations for actuator performance are maximum torque, maximum angular velocity, maximum power, and time-averaged power. The torque about the pitching axis is computed as the sum of the blade's propeller moment, inertial moment, and aerodynamic moment. The propeller moment is the tendency of the blade's center of gravity to align with the plane of rotation and is computed by

$$M_{\text{propeller}} = I_{\text{total}} \cdot \omega_{\text{rotor}}^2 \cdot \text{AOA}(t) \quad (5)$$

where $M_{\text{propeller}}$ is the propeller moment in N-m, and I_{total} is the total moment of inertia in kg-m^2 . Moment of inertia is taken as the sum of the blade inertia, $1.73 \times 10^{-5} \text{ kg-m}^2$, and the actuator rotor inertia, $1.08 \times 10^{-7} \text{ kg-m}^2$, about the blade's pitching axis. The inertial moment is the blade's tendency to resist the pitching motion and is computed by

$$M_{\text{inertial}} = I_{\text{total}} \cdot \alpha(t) \quad (6)$$

where M_{inertial} is the inertial moment and α is the pitching angular acceleration in rad/s^2 . The aerodynamic moment is the result of air flow over the blade and is determined by simulation. Blade actuator power is determined by multiplying the blade's feathering (angular) velocity by the sum of moments acting on it. Per-blade rotor drive power is determined by multiplying the rotor velocity by its torque, where the torque is determined by multiplying the transient blade drag by the average center of pressure as measured in the negative direction from the blade root.

3 Results

Figure 5 shows the blade lift at different fixed angles of attack. The blade center of pressure moves from 0.007 m at 0 deg angle of attack to 0.000 m at 10 deg angle of attack in the x direction from the pitching axis. The center of pressure is near constant in the z direction at about 0.414 m from the blade root. It can be observed that the lift remains within an order of magnitude of the Mars Helicopter blade of approximately 1 N per blade at a hover. Furthermore, the lift is observed to increase at a near-constant rate between 0 deg and 10 deg angle of attack, the maximum feathering range tested in the dynamic cases.

Figure 6 shows that the peak pitching moment and lift increase with feathering frequency and that peaks occur at shifted angles of attack. This indicates that the blade center of pressure moves as a function of the pitching condition. Furthermore, this demonstrates that feathering frequency is an important factor in determining blade forces. In fact, under 2 deg, 4/rev actuation, peak moment and lift increased by 32% and 7% respectively over the values calculated from the static data.

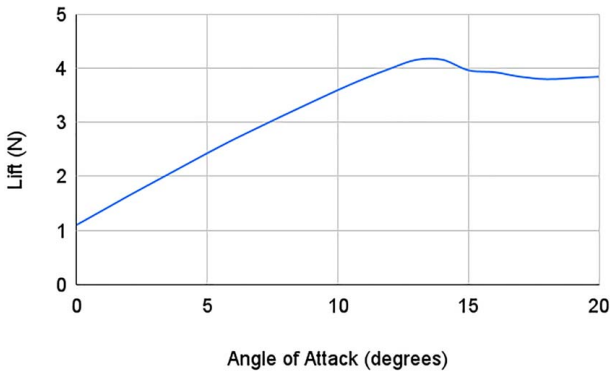


Fig. 5 Blade lift at fixed angles of attack

Figure 7 shows the average power draw of the blade-root actuators and rotor drive motor per blade. It can be observed that actuator power and rotor drive power scale similarly for all actuation conditions, reaffirming that blade pitching moment and drag are coupled. The drastic difference between average and peak actuator power can be attributed to regeneration of power due to the inertia of the blade as it slows and begins to pitch in the opposite direction. Real-world energy losses would likely increase the average power draw.

Figure 8 gives the maximum transient power requirement of the blade-root actuators under the various test cases. It can be observed that sinusoidal actuation requires the lowest actuator power rating of the tested waveforms when actuation amplitude is held constant. While the quadratic waveform reduces the inertial moment, the sharper change in angular velocity produces a higher aerodynamic moment, canceling out any benefit hoped to be gained. It can also be

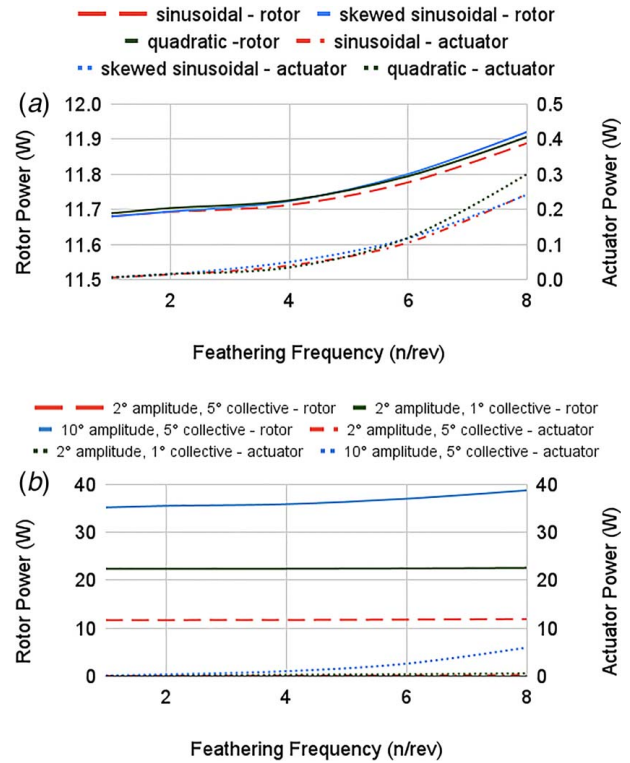


Fig. 7 Average power consumption of blade-root actuators and rotor drive motor calculated per blade, at (a) a 2 deg amplitude and 5 deg bias with varying waveforms and (b) a sinusoidal waveform with varying amplitudes and bias

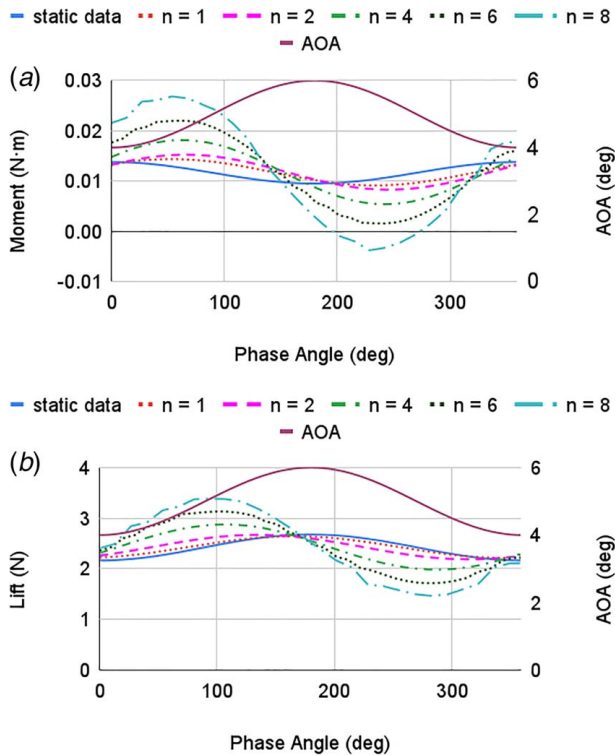


Fig. 6 (a) Blade pitching moment and (b) lift over a single actuation cycle under a sinusoidal waveform with 2 deg amplitude, 5 deg bias, and various frequencies

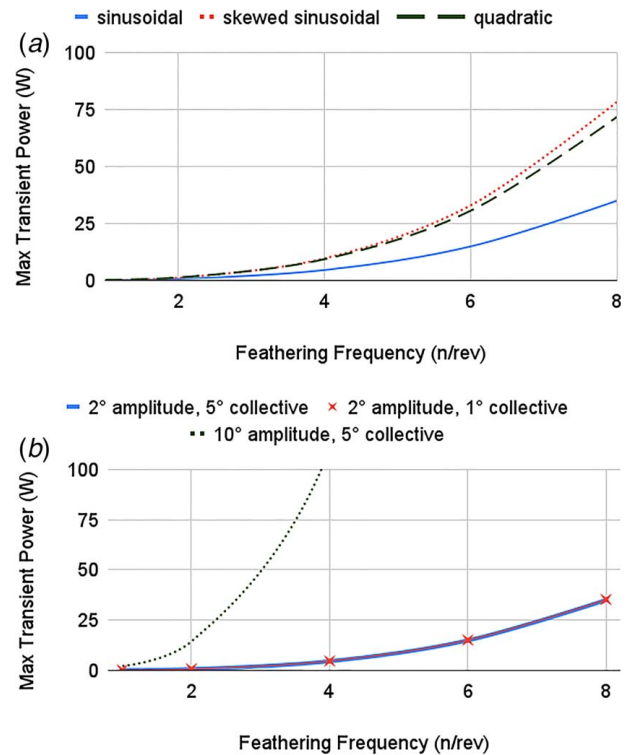


Fig. 8 Maximum power draw of blade-root actuators at (a) a 2 deg amplitude and 5 deg bias with varying waveforms and (b) a sinusoidal waveform with varying amplitudes and bias

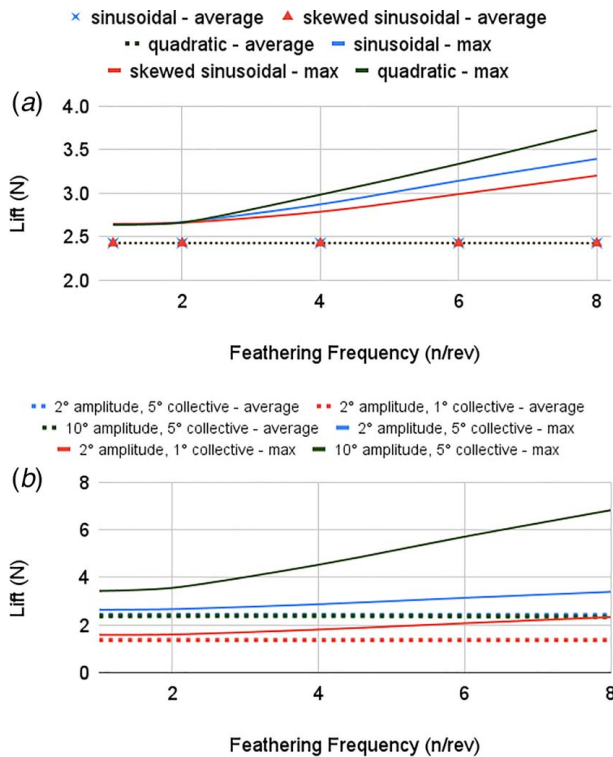


Fig. 9 Average and maximum lift per blade at (a) a 2 deg amplitude and 5 deg bias with varying waveforms and (b) a sinusoidal waveform with varying amplitudes and bias

observed that pitch bias has little effect on the maximum transient power. Finally, it can be observed that, when 2 deg pitching amplitudes are applied at an up to 8/rev frequency, or 10 deg amplitudes at a traditional cyclic frequency of 1/rev, actuator power requirements remain on the order of 10^1 W.

Figure 9 shows the lift produced for each test case. It can be observed that the average lift changes only as a result of bias (collective) and does not change as a result of amplitude or waveform. It can also be observed that waveform, amplitude, bias, and frequency affect the maximum transient lift, with the quadratic waveform producing the highest maximum lift when other factors are held constant.

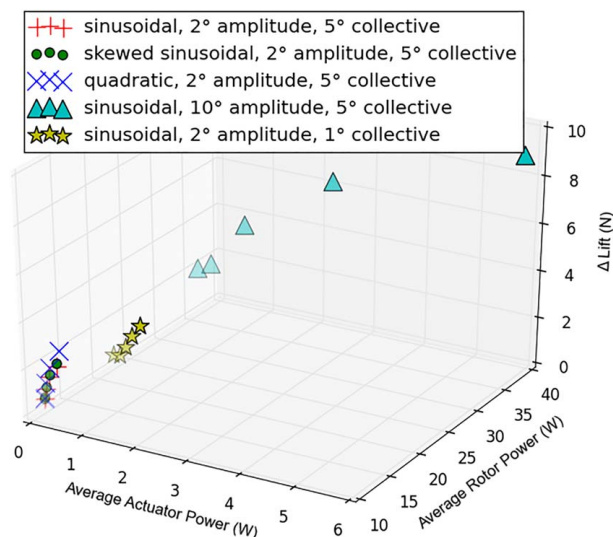


Fig. 10 Change in lift per actuation for each test case plotted against system power draw. A darker shade indicates a higher frequency, with data displayed at 1/rev, 2/rev, 4/rev, 6/rev, and 8/rev for each test set.

Figure 10 shows the ability of each pitching condition to generate a change in vertical force (maximum transient lift minus minimum transient lift) as a function of the system power draw. For the 2 deg amplitude cases, it can be observed that a higher pitching frequency leads to a larger change in vertical force with a minimal increase in power draw. A 10 deg pitching amplitude produces higher changes in lift but does so at much higher power draws. Finally, it can be observed that these results vary relatively little across the tested waveforms.

4 Conclusions and Future Work

This work investigated rotor blade forces and system power of a theoretical individual blade control Martian rotorcraft. We found that sinusoidal actuation performed better than the other tested waveforms in regard to transient blade actuator power. Under such a condition, it was predicted that a 25 W actuator was capable of 1/rev cyclic input at 10 deg and up to 6/rev IBC input at 2 deg. Time-averaged blade actuator and rotor drive power were found to vary little with feathering frequency, but greatly with feathering amplitude. It was also predicted that per-blade peak-to-peak lift changes of 2 N are achievable. Furthermore, it was found that peak transient actuator power and center of pressure varied with feathering frequency. These results indicate that the proposed IBC system may be within the capabilities of current hardware, that a useful force gradient can be developed, and that the aerodynamic effects of IBC actuation waveforms will necessitate additional analysis when compared to traditional swashplate systems.

Future work will focus on the inclusion of transient inlet flow and rotor blade deformation in order to capture aerodynamic perturbations and blade flapping modes which are limitations of the present work. We also plan to conduct experiments to validate the blade properties in ultra-low Reynolds number flow and to investigate the real-world performance and losses of commercial off-the-shelf actuators in order to overcome the accuracy limitations associated with computer modeling.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

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