

FABRICATION AND ROTATING FREQUENCY TESTS OF ULTRA-THIN ROTORS FOR MARTIAN FLIGHT

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ABSTRACT

This paper describes the fabrication and rotating frequency tests of a unique 4.72-foot diameter composite rotor of 1% thickness-to-chord ratio. The ultra-thin nature of the blade, along with its twist, chord, and material variations, posed several fabrication challenges, such as the control of resin flow during curing and the construction of the root geometry. Once fabricated, the rotor was installed and actuated inside a 10-foot diameter vacuum chamber to measure its rotating frequencies. The measured frequencies matched remarkably well with previous three-dimensional finite element based predictions—at least for the first four modes—confirming the validity of the fabrication process. The test is expected to provide unique data for validation of advanced analysis and insights into rotor dynamics on Mars.

INTRODUCTION

Objective

The University of Maryland and NASA Ames Research Center envision larger, more capable helicopters for the future of Mars exploration after the success of *Ingenuity*. As part of NASA's Rotor Optimization for the Advancement of Mars eXploration (ROAMX) project, 4.72-foot diameter rotor blades of advanced airfoils and radical geometry with 1% thickness-to-chord ratios have been designed, fabricated, and tested at each institution. The unusual design of the blade is meant to generate stable lift under low Reynolds numbers (10,000) and high tip Mach numbers (0.95). The objective of this paper is to describe the fabrication and rotating frequency tests of the ROAMX blades at the University of Maryland.

Background

On the morning of April 19, 2021 at 3:34 am U.S. EDT, the Mars Helicopter *Ingenuity* lifted off the surface of Mars and established the first powered flight outside the living planet (Ref. 1). That flight, and the 72 more that followed (until the last flight on January 18, 2024), covered 10.7 miles of Martian terrain for a total of 128.9 minutes at speeds up to

10 m/s, thereby opening a new era of Mars exploration. The feasibility of a Mars helicopter, which was established on paper two decades ago (Ref. 2), was validated in real life through innovative and intricate engineering (Refs. 3–7).

Ingenuity was a small 1.8 kg-mass helicopter with no payload and was meant only to be a technology demonstrator. Larger and more capable rotorcraft of up to 30 kg are now being envisioned – such rotorcraft could conduct compelling science missions by carrying payloads up to 8 kg (Refs. 8,9). This family of designs are called Mars Science Helicopters (MSH). They use unconventional airfoils and ultra-thin blades to provide high hover efficiency and high blade loading at low Reynolds number (about 10,000) and high Mach number (up to 0.95 at the tip) conditions on Mars. To support the development of this next generation of helicopters, NASA recently launched the Rotor Optimization for the Advancement of Mars eXploration (ROAMX) project to fabricate and test a set of future rotor blades (Ref. 10). These blades are not specific to any particular configuration, but are meant to reproduce the unconventional aerodynamic and structural behavior expected on Mars in a generic manner to advance our understanding of this unusual regime and provide test data for validating analysis. The aerodynamic design was carried out computationally at NASA Ames and reported in Ref. 11. The structural design was carried out computationally at the University of Maryland and reported in Ref. 12. A set of blades were built for NASA by Sensenich Propellers, Inc., and the rotor was recently hover tested at Ames with results reported in a companion paper in Ref. 16.

The unusual design of these blades warranted a close examination of the challenges encountered during the fabrication and testing processes. Thus, a parallel effort was conducted at the University of Maryland with complimentary test plans. The ultra-thin nature of the blade, along with its twist, chord,

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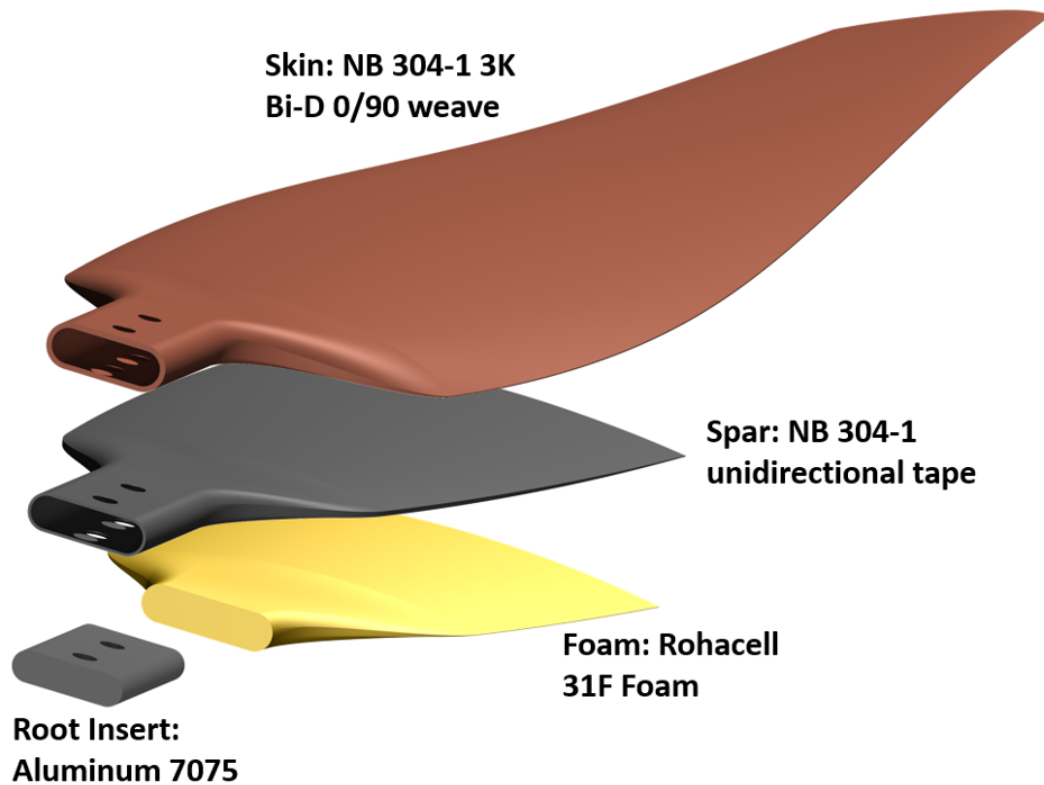


Figure 1. The CAD drawing of the internal structure of the Mars blade showing its unusual spar and materials.

and material variations, posed several fabrication obstacles. These were overcome by implementing an innovative foam core and a layer-wise construction with stencils, respectively. The fabrication process used to make the blades was documented in our recent paper in Ref. 17 along with preliminary non-rotating frequencies. This paper will report frequencies measured in the rotating frame.

Scope of paper

The paper is focused on fabrication and structural dynamic testing. Following this introduction, the first two sections summarize the overall technical approach and the fabrication method. The next two sections describe the non-rotating and rotating frequency tests along with validation of predictions. The conclusion section ends the paper.

TECHNICAL APPROACH

A thickness-to-chord ratio of 1% in the presence of twist and chord variation is difficult to fabricate. Conventional tolerances would change the thickness of such a blade in a way that would significantly compromise its performance. The internal construction is also unconventional, as it contains a cap-like spar structure and multiple ply drop-offs along the radial span. The root structure further complicates the geometry. The internal structure reproduced from Ref. 12 is shown in Fig. 1.

The technical approach was the following:

1. Design the blade mold with very low tolerance,
2. Follow a lay-up strategy of progressive refinement,
3. Strain gage blades for modal testing,
4. Test blades on a two-bladed hingeless hub in a 10-foot-diameter vacuum chamber, and
5. Validate predictions of a 3-D finite element model.

BLADE FABRICATION

The mold was designed in house (Fig. 2) and custom built by Protolabs Network with tight tolerances of ± 0.020 mm (± 0.001 in) to avoid detrimental deviations in blade thickness. The mold is made of Al 5083, an alloy known for its strength and corrosion resistance. The mold is pictured in Fig. 3.

The blade was fabricated in a step-wise manner in order to establish proficiency in the fabrication of each component before attempting to fabricate the full blade. For example, as is customary in typical blade fabrication, the foam core was made first. The shape, thickness, and radial span of the foam were optimized in multiple iterations in an attempt to most accurately reflect the design in Ref. 12. Next, the fabrication of the spar, including the implementation of the root insert, was investigated in a similar manner. Finally, the outer skin and full blade layup were fabricated. Many challenges were encountered at each step—from uneven ply drop-offs, to resin

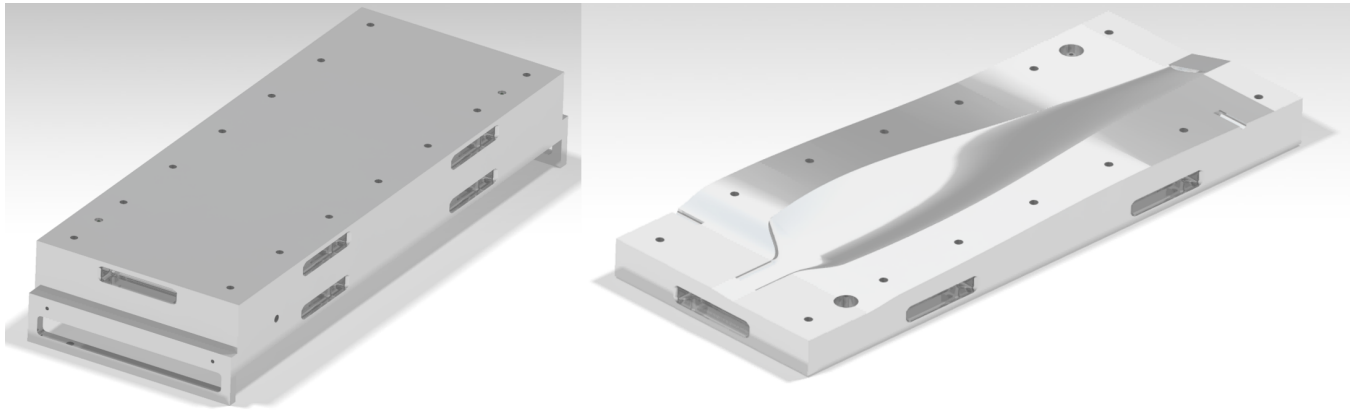


Figure 2. The blade mold (left) and the bottom half of the mold (right).

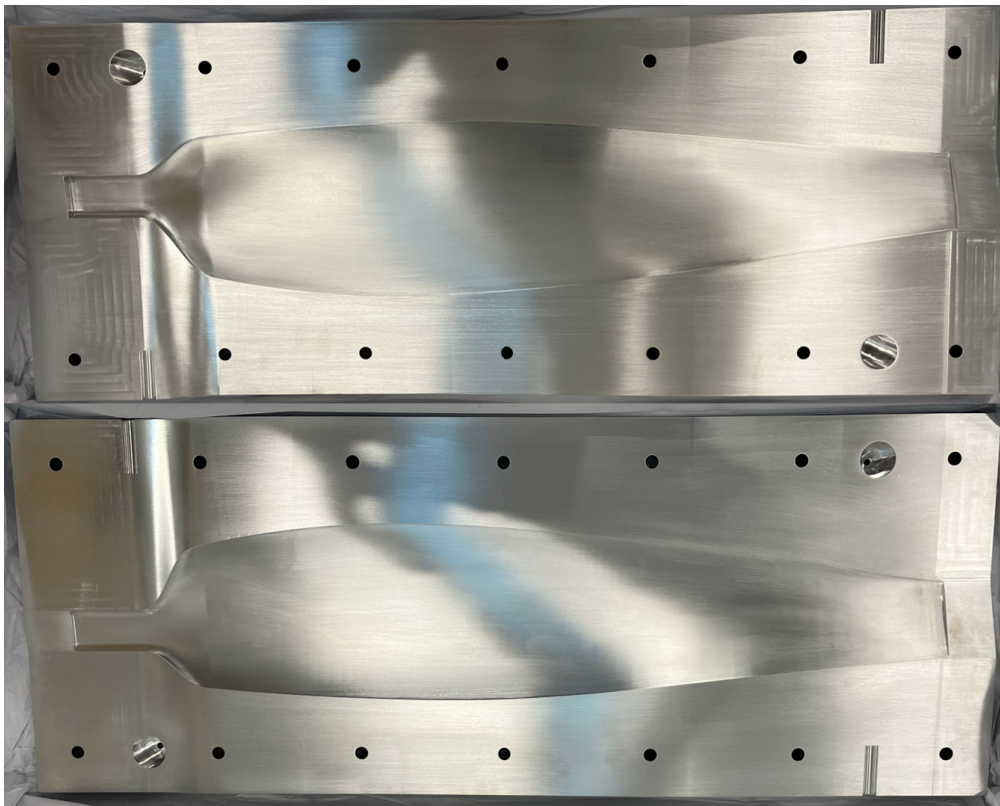


Figure 3. The top and bottom halves of the University of Maryland's ROAMX Mars blade mold procured from Protolabs Network.



Figure 4. Fabricated Blade 1.



Figure 5. Fabricated Blade 2.

bubbling, to edge damage and fiber tear; each obstacle was addressed one by one.

Two major challenges emerged during the fabrication process: 1) resin pooling and bubbling that led to uneven surface finish outboard of 0.35R and 2) geometric complexity at the root that led to surface deformities and internal damage. As described in Ref. 17, these obstacles were remedied by 1) implementing a full span foam core that extended beyond the original 0.35R design so that the resin was absorbed internally and did not bubble on the surface, and 2) using a thicker foam core to provide an adequate distribution of foam density across the blade, thereby eliminating deformities near the complex root geometry, respectively. Furthermore, laser-cut stencils were fabricated in-house and implemented for each carbon fiber wrapping step, which helped to keep the mass nearly identical between blades over each iteration.

Five blades were fabricated in a repeatable manner. The mass breakdown for these blades is shown in Table 1. The error is within 1% for total cured mass. The total final mass is the mass of the cured blade after being post-processed and instrumented. To post-process the blade, all excess resin and material outflow is trimmed off. After it is post processed, gages, wires, and protective epoxy are used to instrument the blade. The first row shows component masses from the CAD model from Ref. 12. The fabricated blade has more mass than the CAD model because it has epoxy adhesive and blade instrumentation, components that are essential for blade fabrication and testing, respectively, but not part of the original CAD. Two blades have been tested thus far—blades 1 and 2. They are shown in Figs. 4 and 5, respectively.

NON-ROTATING FREQUENCIES

The non-rotating frequencies were reported in our previous paper in Ref. 17, but they are repeated here for completeness. They were close to predictions made in Ref. 12. The predicted fan plot is shown in Figure 6 along with the non-rotating frequencies. The blades were cantilevered and shake-tested. The same shaker would later be used in the vacuum chamber. Normally, the first frequency (in this case, flap) can also be picked from a simple impulse response. This test was carried out to verify the first frequency. The shake-test picked up six frequencies. Blade 1 and 2 frequencies were within 5% of each other. The first four were within 10% of predictions. Only the fifth and sixth frequencies deviated significantly from predictions.

ROTATING FREQUENCIES

In preparation for rotation, the blades and blade grips were first statically balanced to ensure equivalent mass and center of gravity. They were then attached to a hingeless hub, which was installed inside the University of Maryland 10-foot diameter vacuum chamber. The vacuum chamber is shown in Fig. 7, and the blades installed inside are shown in Fig. 8.

The hub and the excitation system is a refined version of what was developed for this facility in Ref. 14. The hub attaches to a 64-channel slip ring, which allows the transfer of data from the non-rotating frame to the rotating frame. The strain sensors were wired first to a PCB terminal on the side of the hub, then to the slip ring wires running vertically through a shaft

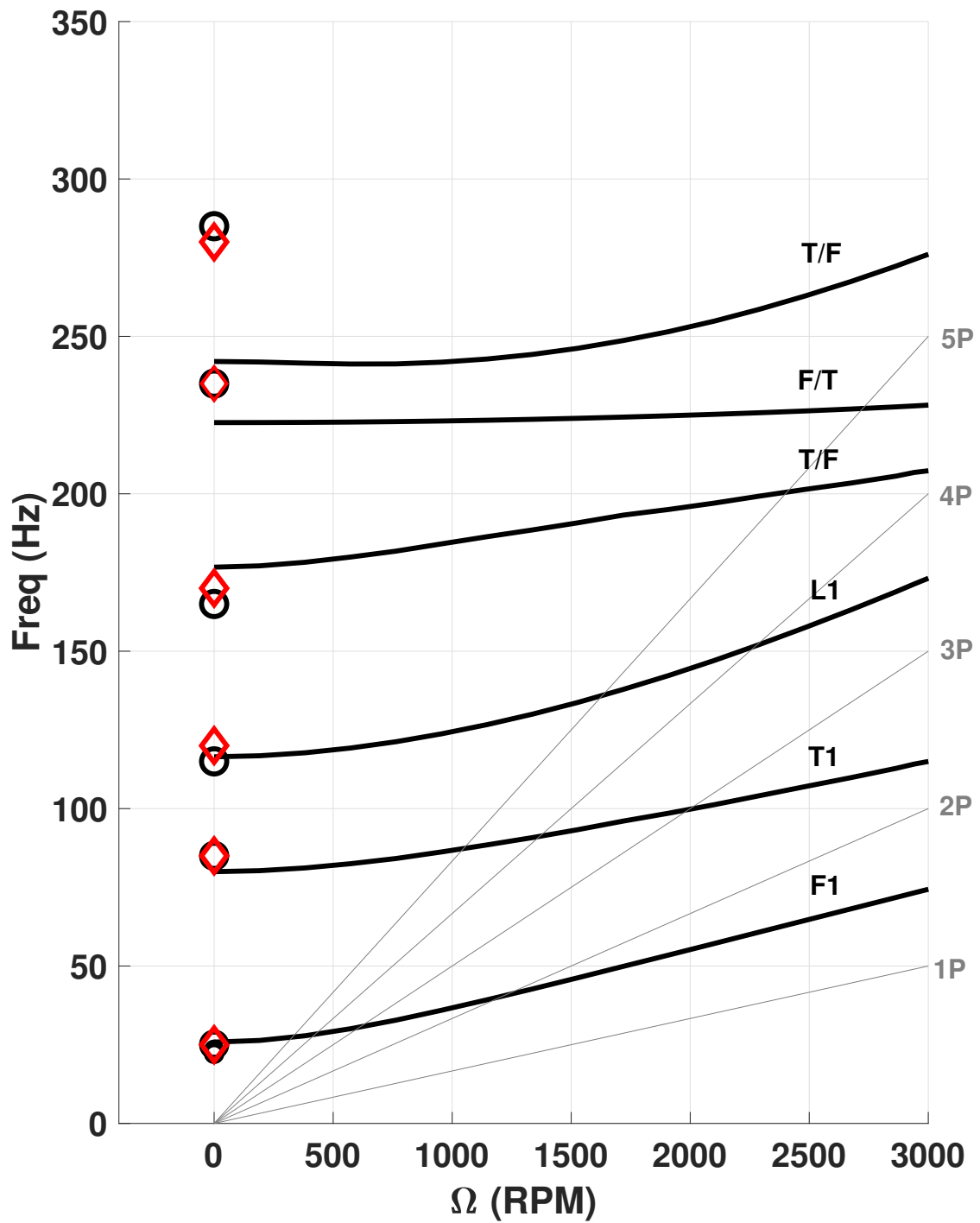


Figure 6. Fan plot. Lines are predictions. Symbols are data. F: flap, L: lag, and T: torsion. Blade 1: $\circ$, Blade 2: $\diamond$.

Table 1. Measured mass of each component in grams.

Blade	Root insert	Foam	Adhesive	Spar	Skin	Total cured	Total final
CAD	24	0.68		37.7	105.6		167.98
1	23.89	20.11	22.00	44.88	145.07	255.22	193.89
2	24.13	19.55	21.72	45.10	144.97	254.61	193.87
3	24.08	19.61	20.70	44.93	144.88	253.58	
4	24.15	19.65	20.14	44.63	144.28	252.41	
5	24.12	19.59	20.37	44.69	144.94	253.21	

in the center of the vacuum chamber. On the non-rotating side, the slip ring wires were connected to a DAQ to obtain data. The shaker was wired in a similar manner on the rotating side. On the non-rotating side, the shaker slip ring wires were connected to a function generator. The function generator provided voltage and excitation frequency to the shaker.

Non-rotating tests were repeated inside the vacuum chamber to verify the setup and confirm that the same bench-top frequencies could be recovered. First, an impulse test was carried out to measure the first frequency. This measurement matched with bench-top tests. Over six trials, the chamber average for blade 1 was 22.26 Hz whereas the bench-top average was 22.65 Hz, and the chamber average for blade 2 was 23.20 Hz whereas the bench-top average was 21.67 Hz. This level of difference was deemed acceptable. Next, a shake-test was carried out to measure the higher frequencies. This revealed Electromagnetic Interference when exciting the blades at high frequencies, above about 150 Hz. The frequency response of the strain gage signal showed a linear variation with excitation frequency. The cause of this linear variation was traced to the proximity of the shaker wires to the strain gage wires inside the slip ring. It was speculated that the shaker wires induced a voltage on the strain gage wires. For example, if the sinusoidal current produced by the function generator powering the shaker is

$$I = I_m \sin(2\pi ft) \quad (1)$$

where f is the frequency of current from the function generator, I_m is the maximum current, and t is time, then the voltage induced is

$$\varepsilon = -M \frac{dI}{dt} = -MI_m 2\pi f \cos(2\pi ft) \quad (2)$$

where M is a mutual inductance. The voltage clearly varies linearly with frequency, which causes a linear increase in the FFT content produced from the strain gage signals, even though the blade is not resonating at these frequencies. The wires exiting the slip ring on both the non-rotating and rotating sides were shielded in an attempt to mitigate this effect as much as possible.

Before every test, the blades were inspected root to tip for any physical damage. All connections on the hub were inspected

and tightened as needed, from the four shoulder bolts securing the hub to the vacuum chamber shaft, to all blade-blade grip-hub connections, to the PCB terminal screws holding each wire in place. A multimeter was used to check the connectivity of all wires between the rotating and non-rotating sides. The multimeter was also used to check for electrical shorts and to measure blade strain gage and shaker resistances. The rotating side slip ring wires and strain gage wires were secured in place with aluminum tape.

The entry port to the vacuum chamber was sealed using a cast-iron steel panel and several steel bolts. The pump was turned on and a gage was used to measure the internal pressure in the vacuum chamber until 0.3 inch Hg (greater than or equal to 99% vacuum) was reached. This process took about 45 minutes. After near-vacuum was achieved, data from tare tests were recorded. The 60 Hz supply frequency and its integer multiples were identified and excluded from frequency identification.

The desired rotor RPM was set using the motor controller. The RPM was monitored using a sensor and Arduino connected to the DAQ. At each RPM, tare data from the baseline with no shaker actuation was taken. Then, a frequency sweep was performed from 5 to 350 Hz at a resolution of 5 Hz. Five different RPM values were tested—250, 450, 700, 950, and 1200. Note that the present chamber motor is limited to this top speed.

For representative results, the frequency response at 250 and 700 RPM are shown in Figs. 9 and 10, respectively. The linear relationship between induced voltage and frequency discussed earlier shows up in these results. However, the relative scale between data points is consistent, so peaks are still visible and frequencies can be identified. The severity of this effect did vary between data sets, at times making higher modes difficult to identify. In such cases, higher frequency modes were omitted from the fan plot. The electrical supply frequency noise at 60 Hz and its integer multiples are easily discernible and can be discarded. The most significant challenge arises when the structural frequencies are near these values. For example, this is the case for the first lag mode, which is expected to lie around 120 Hz up to 1000 RPM. The data in this range is saturated with supply frequency noise. A finer frequency resolution will be needed to identify the modes. The clearly identifiable modes are shown in the same fan plot in Fig. 11.



Figure 7. The University of Maryland's 10-foot diameter vacuum chamber.



Figure 8. The University of Maryland's 10-foot diameter vacuum chamber.

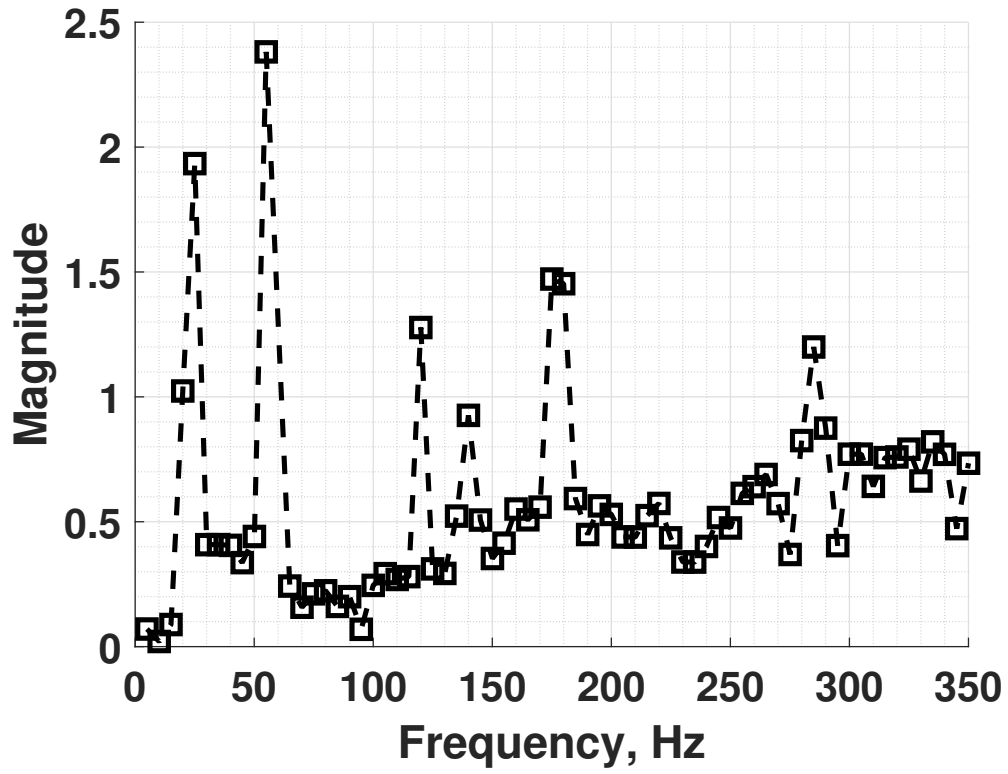


Figure 9. A representative plot from a frequency sweep from 5 to 350 Hz at 250 RPM.

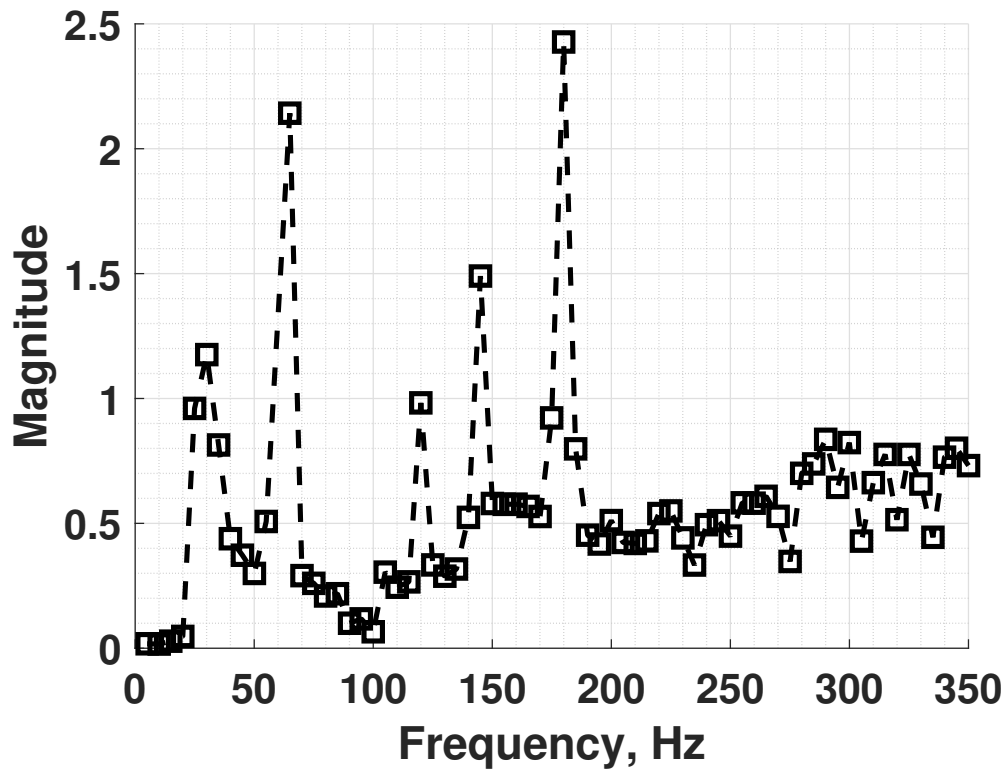


Figure 10. A representative plot from a frequency sweep from 5 to 350 Hz at 700 RPM.

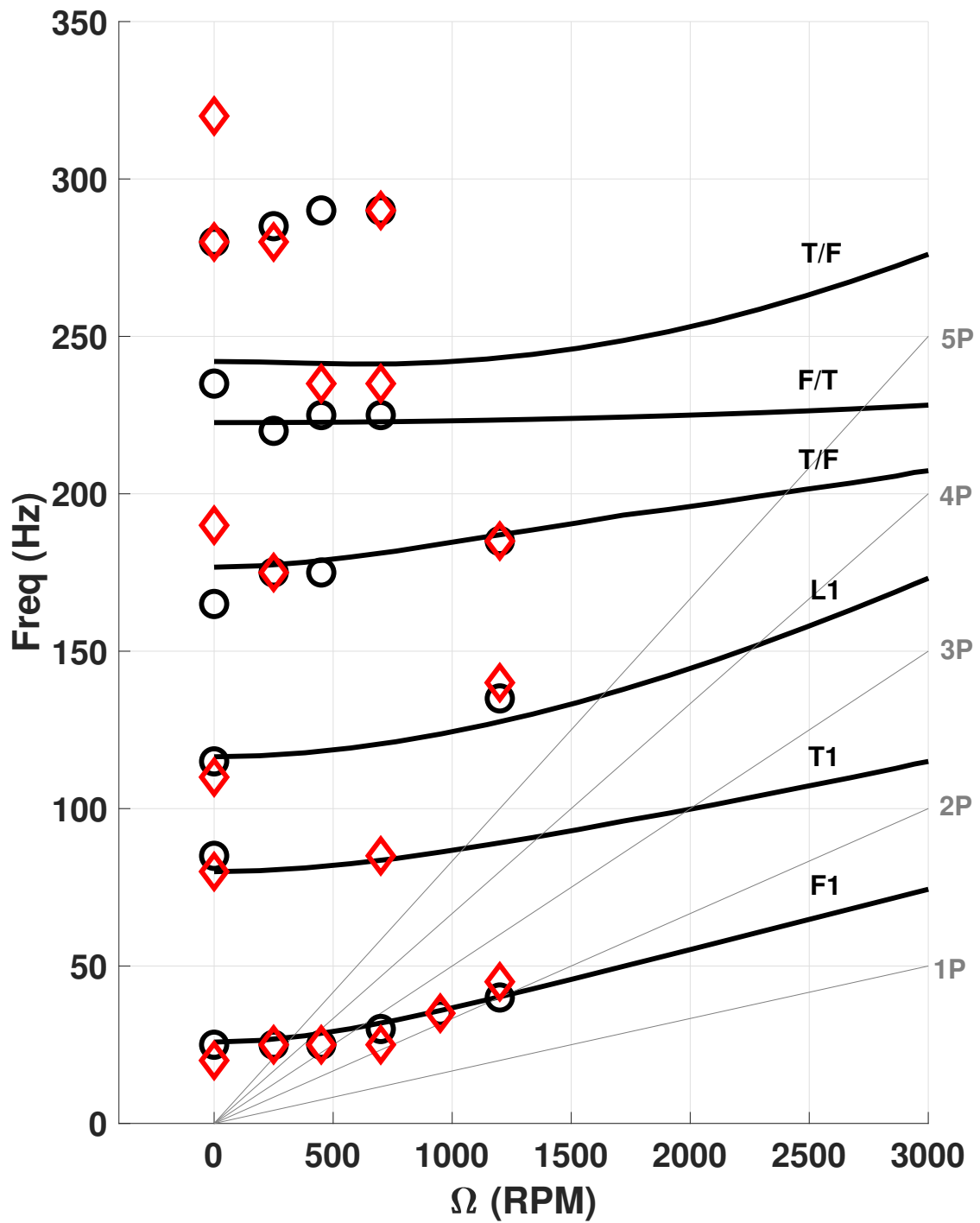


Figure 11. Fan plot. Lines are predictions. Symbols are data. F: flap, L: lag, and T: torsion. Blade 1: $\circ$, Blade 2: $\diamond$.

The trends are evident. The frequencies match well with the pre-test design predictions, and they are consistent with the non-rotating frequencies shown earlier. Blade 1 and 2 frequencies remain close. The first four frequencies fall within 5% of predictions. The fifth and sixth frequencies deviate significantly. Even though these higher modes are not expected to be excited during flight, it would be important to trace the source of these discrepancies and refine the structural model.

CONCLUSIONS

This paper described the fabrication and rotating frequency tests of a unique 4.72-foot diameter composite rotor of 1% thickness-to-chord. The ultra-thin nature of the blade, along with its twist, chord, and material variations, posed several fabrication challenges, such as the control of resin flow during curing and the construction of the root geometry. Once fabricated, the rotor was installed and actuated inside a 10-foot diameter vacuum chamber to measure its rotating frequencies. The key conclusions are that composite rotor blades of radical geometry and 1% ultra-thin airfoils can indeed be fabricated and their structural dynamic behavior predicted within reasonable errors—less than 5%—for the first four modes. The fifth and sixth frequencies deviated significantly. This deviation was consistent between the bench-top and vacuum chamber tests. Slip ring wires need to be shielded to mitigate Electromagnetic Interference above about 150 Hz so that higher frequency modes are clearly discernible in all test cases.

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