Hydro Hawk: Hydrogen-Powered eVTOL

Zero-Emission Future

Sustainable aviation is growing rapidly with the rise of electric vertical take-off and landing (eVTOL) vehicles.

Hydrogen's high specific energy density makes it an attractive option toward advancing a zero-emission aviation future.

The race for hydrogen-powered eVTOLs is on, driven by new innovations in hydrogen storage, fuel cell cooling, and weight management.

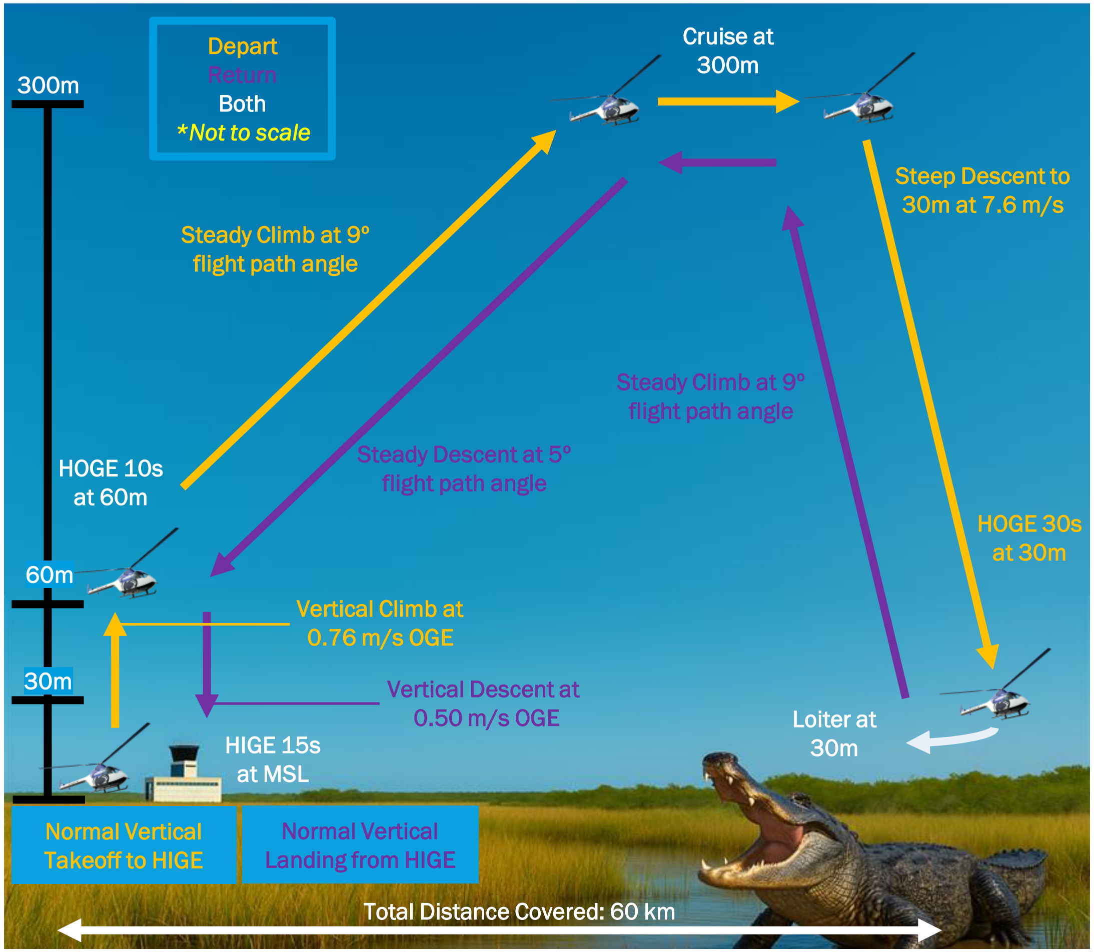
Design & Capabilities

Hydro Hawk is a conventional main rotor helicopter with a NOTAR anti-torque design, making it safer and quieter for low altitude loiter and observation.

Using a team-built integrated software, dynamic design adjustments are made to maximize the configuration for endurance throughout the detailed design process.

Designed for light transport and a small environmental footprint, Hydro Hawk can deliver a payload up to **185 kg** and can fly for at least **1 .7 hours** using a Proton-Exchange Membrane hydrogen fuel cell (PEMFC) as a power source.

Mission Profile CONOPS & RFP Requirements



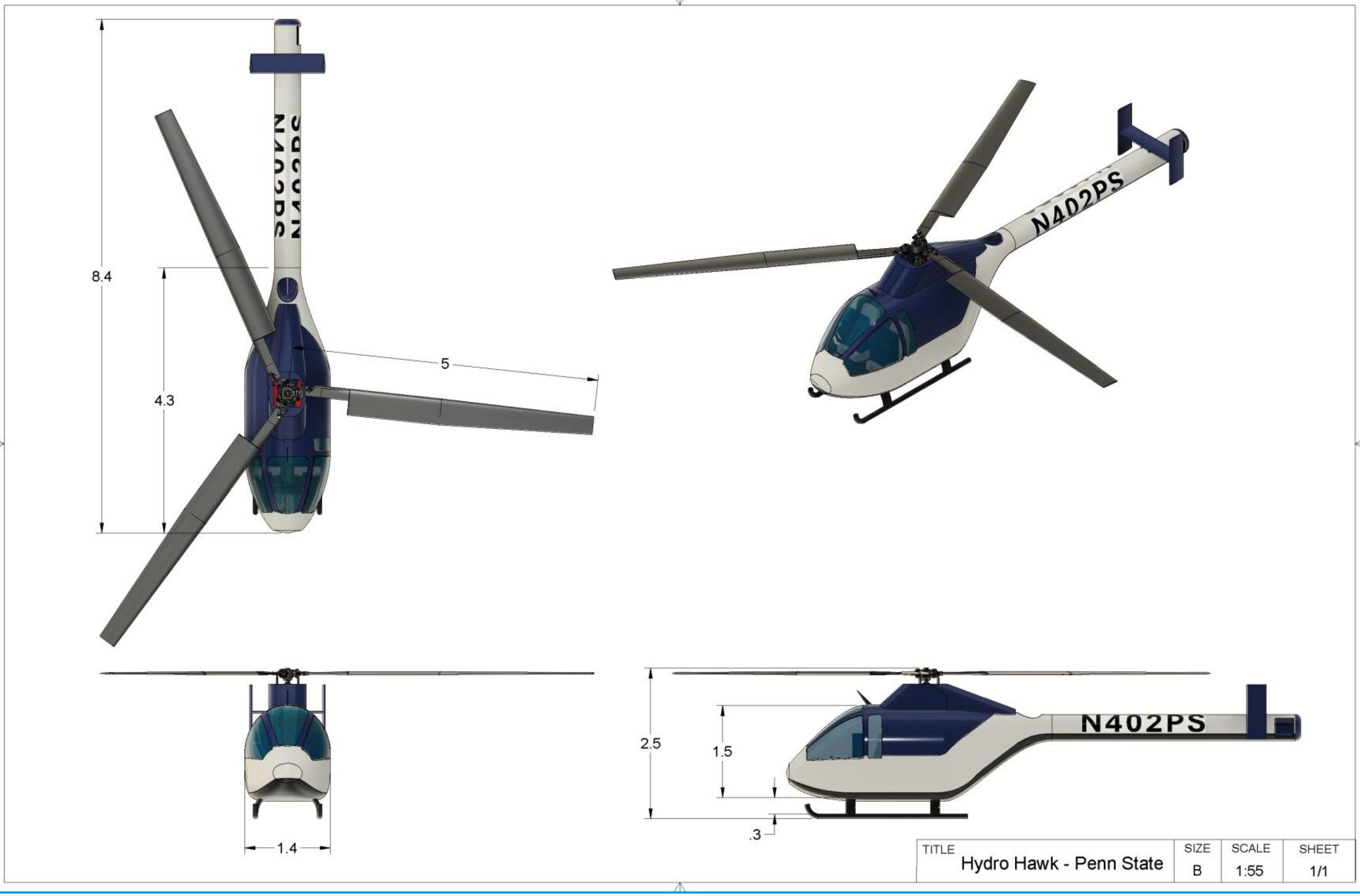
Vehicle Requirements
Stored within 10 m x 10 m x 4 m rectangular prism
Minimum interior usable cabin floor of 1.25 m (width) x 1.5 m (length)
Fully electric, powered by PEM fuel cells with gaseous hydrogen
Shall fly in SL ISA conditions

PEMFC Requirements
Stack voltage must not exceed 840 V
Stack should not operate at a steady-state temperature of more than 90°C
Hydrogen tank pressure should not exceed 700 bar

Design should be maximized for high endurance, overcoming PEMFC operating challenges (temperature, pressure, weight efficiency) as well as RFP sizing requirements. Primary mission is to loiter and observe over alligator river.

Vertical Flight Society, "42nd Annual Student Design Competition 2024–2025 Request for Proposal (RFP)," *vtol.org*, https://vtol.org/files/dmfile/rfp-1.0_airbus-pioneering-hydrogen-powered-vtol_sdc-2024-25.pdf. Accessed Sept. 12, 2024.

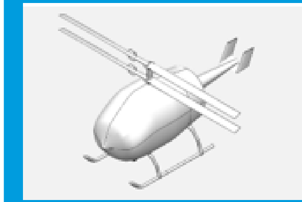
Design 3-View

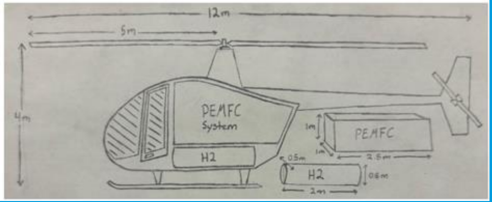


General size (meters) of the helicopter is small, compact, and is similar to other vehicles in its class.

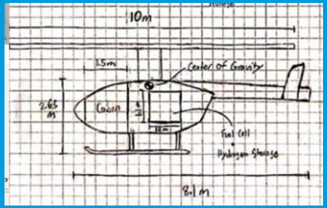
Trade Study & Downselect

Fall 2024 – Preliminary Design
3 teams created initial designs with basic sizing and performance metrics


Coaxial



Conventional with Tail Rotor



NOTAR

Assessment Metrics				
Loiter Time	Design Feasibility	Mission Fit	Weight	Safety

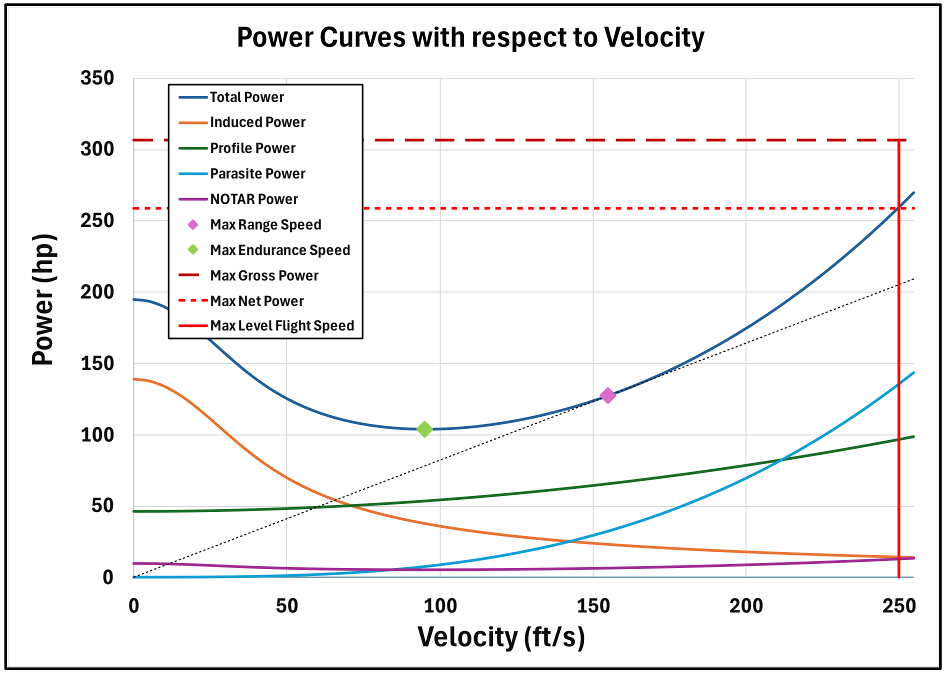
Weighted decision matrix determined **conventional configuration** to be the best design. Both coaxial and conventional excelled in loiter time, Conventional selected for more detailed/thorough analysis. NOTAR element is added for increased safety, noise reduction, and creativity.

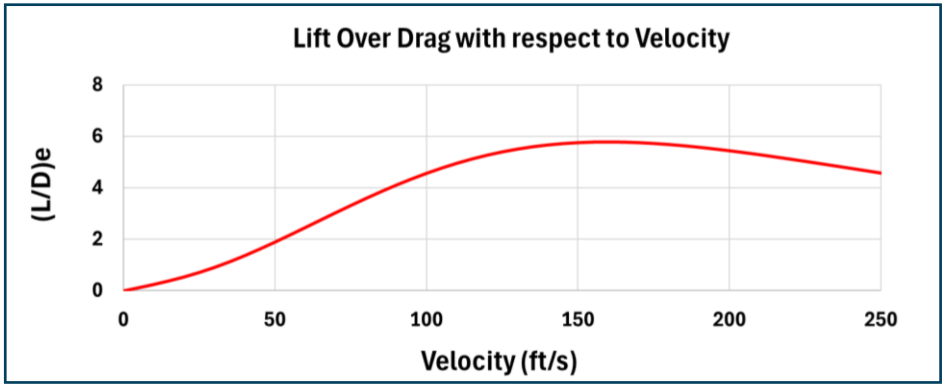
Spring 2025 – Detailed Design

- Maximize main rotor aerodynamics – best lift generation
- NOTAR anti-torque design – safe for ground operations, quiet
- Composite material selection and structural design – lightweight, efficient
- Detailed parasite drag calculation – minimize drag for best endurance
- Stability and control analysis – increased sizing accuracy
- Comprehensive performance and weight breakdown – ensure feasibility

Preliminary designs and trade studies of various configurations aid to the selection of a single main rotor with NOTAR – combining the best of several designs

Hydro Hawk Performance





Key Performance Metrics	
Max Level Flight Speed	75 m/s (247 ft/s)
Velocity for Max Range	147 m/s (155 ft/s)
Velocity for Max Endurance	29 m/s (95 ft/s)
Max Power Required for Mission	184 kW (247 hp)
Net Power Available	193 kW (259 hp)
L/D in Cruise	5.8

Endurance Metrics (Per Mission Profile)	
Total Flight Time	102 min
Loiter Time	**72 min**
Distance Covered (Compare to R44 Max Range)	520 km 550 km
Fuel Cell Current	150 Amps
Steady State Hydrogen Fuel Consumption	0.0748 kg/(kw-hr)
Fuel Cell Design Efficiency	0.33

When loitering at the best endurance speed, Hydro Hawk will have 72 minutes of loiter time.

Motor and Drivetrain Selection

Main Motor

Danfoss HD250

Specifications

- 3050 N-m of Continuous Torque
- 1558 Continuous RPM
- 250 kW Max Power
- 180 kW Continuous Power
- Weight: 134.1 kg (295 lb)
- Volume: 0.3 m^3 (1.2 m length x 0.5 m width x 0.5 m height)

- Designed for highway vehicles that meet power and continuous torque needs
- **Transmission Efficiency:** Avoids the need for an oversized transmission due to high continuous torque
- **Adaptation for Aerospace:** Customized and designed with NDARC to adapt the highway vehicle motor for aerospace applications

Main Rotor Drive Train System Requirements
Must supply 6100 N-m of torque
Must output continuous torque of 2048.4 N-m in cruise
Must have its speed transferred down to 296 rpm
Motor should have specific power larger than 1 kW/kg

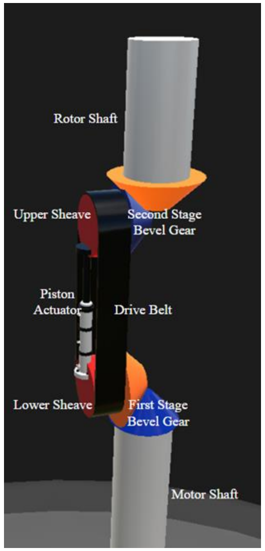
Many motors meet power requirements, but torque specifications limit options.

Gearbox: Motor to Rotor

- 2 stage gearbox to reduce RPM and increase torque
- R22 style clutch system
- Weight: 11.6 kg

Configuration

a) [2.3 : 1] - first stage gear reduction
b) Clutch via belt & piston
c) [2.3 : 1] - second stage gear reduction



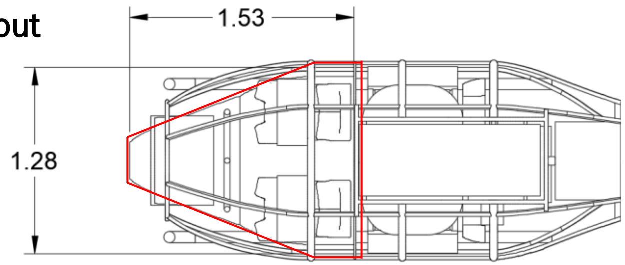
Motor and drivetrain are customized for power and torque needs, maximizing efficiency of the system without unnecessary gearing and add-ons.

"UQM/Danfoss PowerPhase HD2 220+ M+C+T," *Legacy EV* Available: https://legacyev.com/products/22.
Prouty, R. W., *Helicopter Performance, Stability, and Control*, Krieger Publishing, Malabar, FL, 2002. Accessed April. 1, 2025.

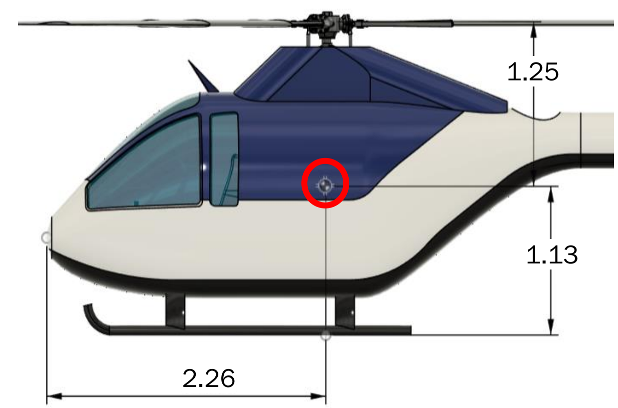
General Sizing and Dimensions

Interior Cabin Layout

Meets minimum dimensions: 1.5 m x 1.25 m



Center of Gravity

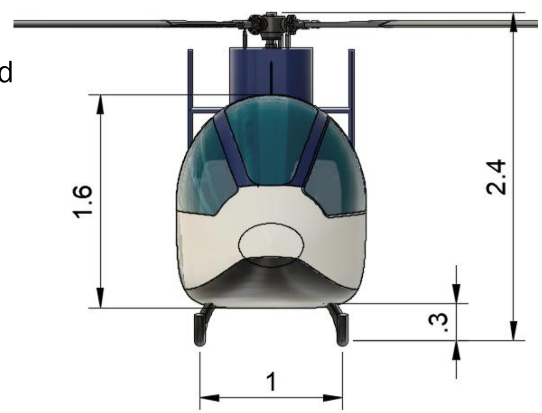


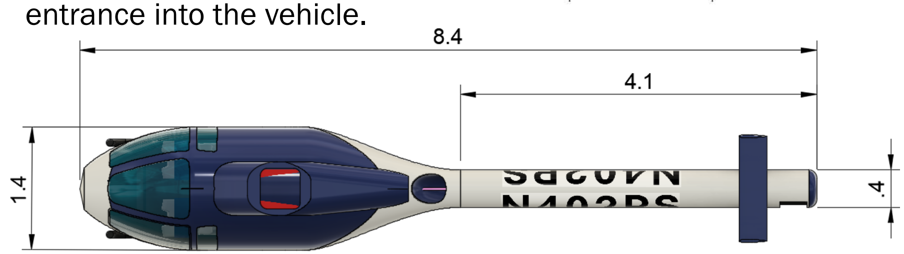
General Dimensions

Fuselage size is minimized to fit components without considerable extra space to conserve weight.

Meets Minimum Height Dimension: 4 m

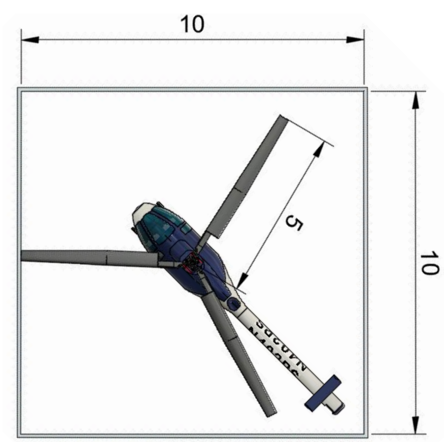
Side windows raise up as entrance into the vehicle.





Maximum Storage Requirement

Meets max dimensions: 10 m x 10 m (with any rotor position)

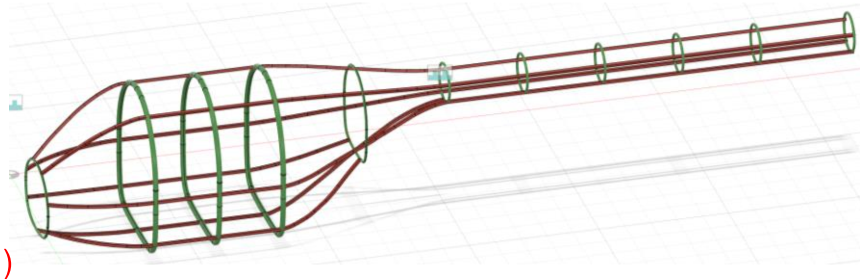


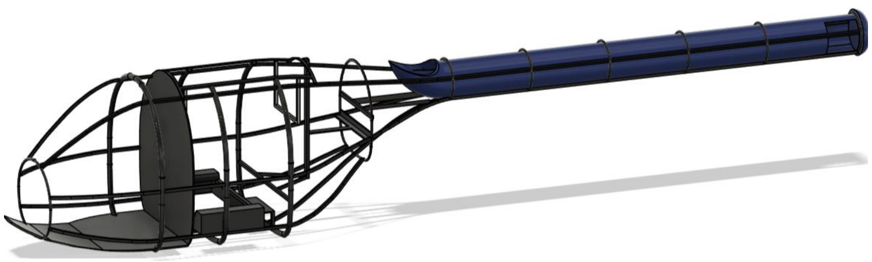
Hydro Hawk meets all dimensional constraints outlined in the RFP. All dimensions are provided in meters.

Fuselage Structure

Fuselage Framing

- Material: Prepreg 3900 (unidirectional Carbon fiber/ epoxy resin)
- Semi-monocoque design
- Formers/Bulkheads: Shape/rigidity (Green)
- Longerons (Hat-type): Prevent buckling (Red)





Additional Structure

- Floor and back panel added for cabin interior
- Additional framing and cutouts to secure and support internal components' weights
- Inner skin for NOTAR control volume added

Skin

- 2 mm of Skin added for final shape and CFD drag analysis
- Front/side windows and door added for visibility and access
- Cutouts for NOTAR and main rotor/motor

Structural weight is minimized by using carbon fiber composite. Structure is built to designed skin shape and accounts for internal components.

Structural Analysis – Fusion 360 FEA

Fusion 360 utilized to run a qualitative, first-pass, check to ensure the basic airframe, with all interior components and weights, can sustain gravity plus high maneuver loads without obvious red-flags.

Key Findings

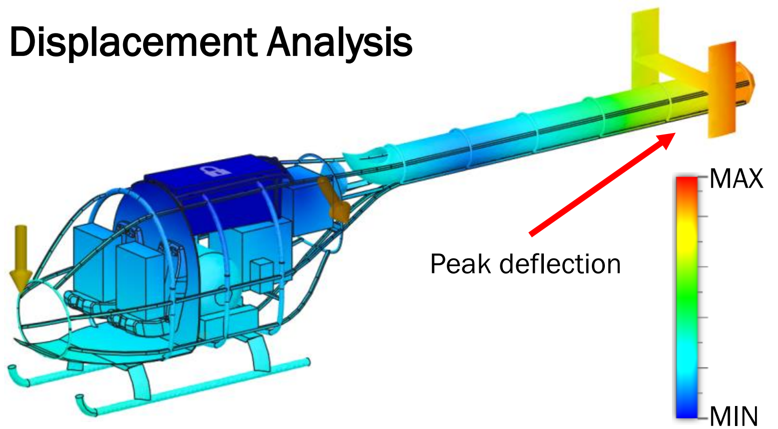
- Maximum stress occurs in the main bulkheads – housing internal components
- Maximum displacement occurs at aft tip of the tail boom
- Deformation pattern tracks expected load paths
- No gross instabilities or unrealistic hot-spots; load flow is credible for this fidelity level

Load Case

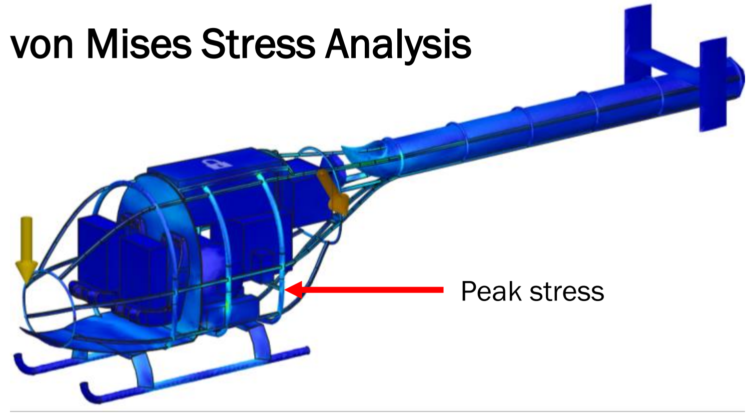
- Acceleration (under gravity) simulating a banked climb maneuver (opposite direction of arrow)
  - x-direction (roll): 10 m/s^2
  - y-direction (yaw): 3 m/s^2
  - z-direction (pitch): 14 m/s^2
- Constrained at rotor connection point

Limitations: Framing geometry/positioning is preliminary. Local stiffeners, fasteners and manufacturing details not yet included. Material estimated as a uniform composite. *Study is intended to show trends, not gather true stress values.*

Displacement Analysis



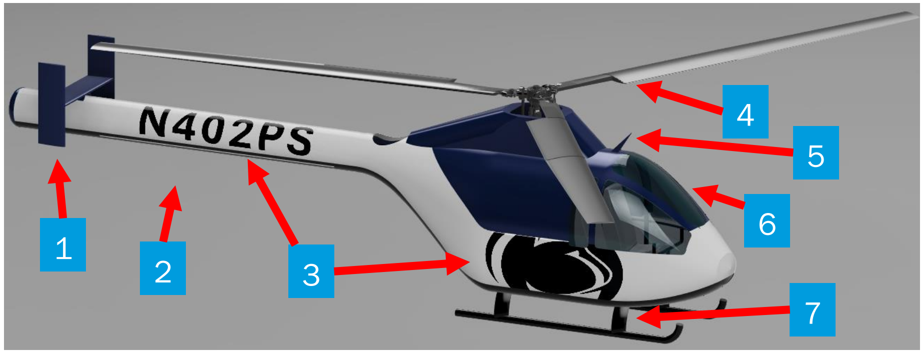
von Mises Stress Analysis



Simulation contours confirm that preliminary structure carries maneuver loads along intended paths. Hotspots will guide more detailed structure geometry outside of current project scope.

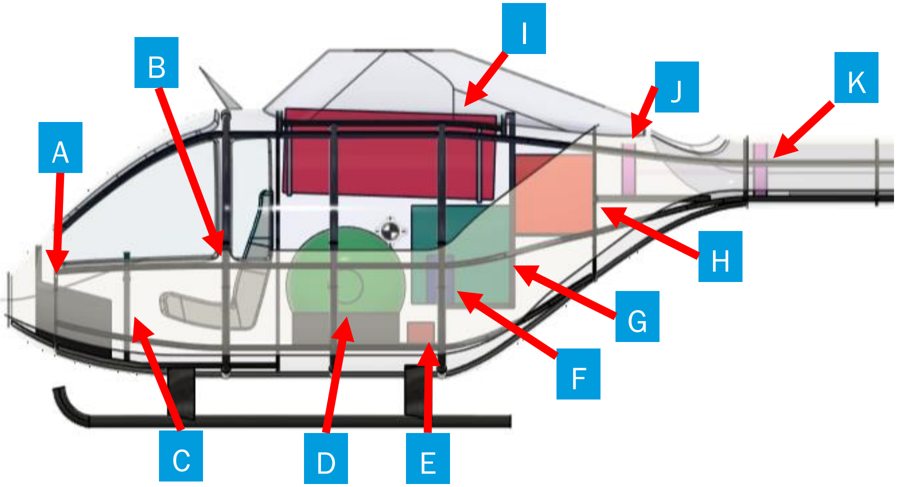
Features and Components

Key Features



	Feature
1	Dual vertical stabilizer & horizontal stabilizer.
2	NOTAR anti-torque system eliminates loud, hazardous tail rotor by using Coanda effect.
3	N-number corresponding to AERSP capstone class #402 at Penn State. Nittany lion logo.
4	Rotor with root-cutout blades to save weight.
5	Cable cutter to ensure safety while low flight loitering.
6	Right window opens as a door, maximizing visibility.
7	Faired skids minimize parasite drag.

Internal Components

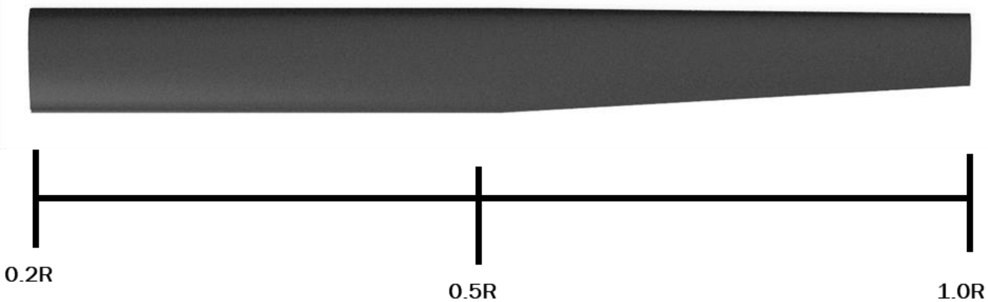


	Internal Component & Volumes	
A	Avionics	0.021 m^3
B	Seating	0.057 m^3
C	Cyclic Stick	0.02 m^3
D	Hydrogen Tank	330.6 L
E	Starter Battery	0.006 m^3
F	Low Temp Radiator	0.0064 m^3
G	PEMFC	0.169 m^3
H	High Temp Radiator	0.112 m^3
I	Motor & Drive Train	0.290 m^3
J	NOTAR Motor	0.003 m^3
K	NOTAR Compressor	0.003 m^3

Features provide creative mission solution. Internal components optimize space while balancing CG.

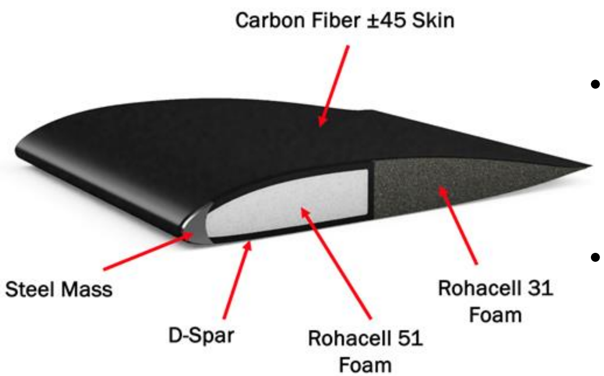
Main Rotor Design and Characteristics

Rotor Performance	
Disk Loading	147.0 N/m² (0.021 psi)
Thrust Coefficient	0.0078
Blade Loading Coefficient	0.13
Figure of Merit	0.77



- Linear blade twist and taper, based on optimum hovering rotor theory, selected to minimize induced and profile power while maximizing L/D
- Semi-articulated hub chosen to reduce vibration and weight

Rotor Blade Planform	
Number of Blades	3
Radius	5 m (16.4 ft)
Solidity	0.06
Blade Twist	Linear -10°
Taper Ratio	2:1 @ 0.5R
Root Cutout	0.2R



Airfoil: ONERA OA212

- Lightweight composite structure with foam cores maintains forward CG and uses carbon-fiber skin
- Ensures strength and load-bearing without sacrificing efficiency

OA212:

$C_{L\,Max}$	1.5
C_{D0}	0.01
C_{M0}	0

FEA – Structural Modes

First Lag Frequency
4.02 Hz

First Flap Frequency
21.6 Hz

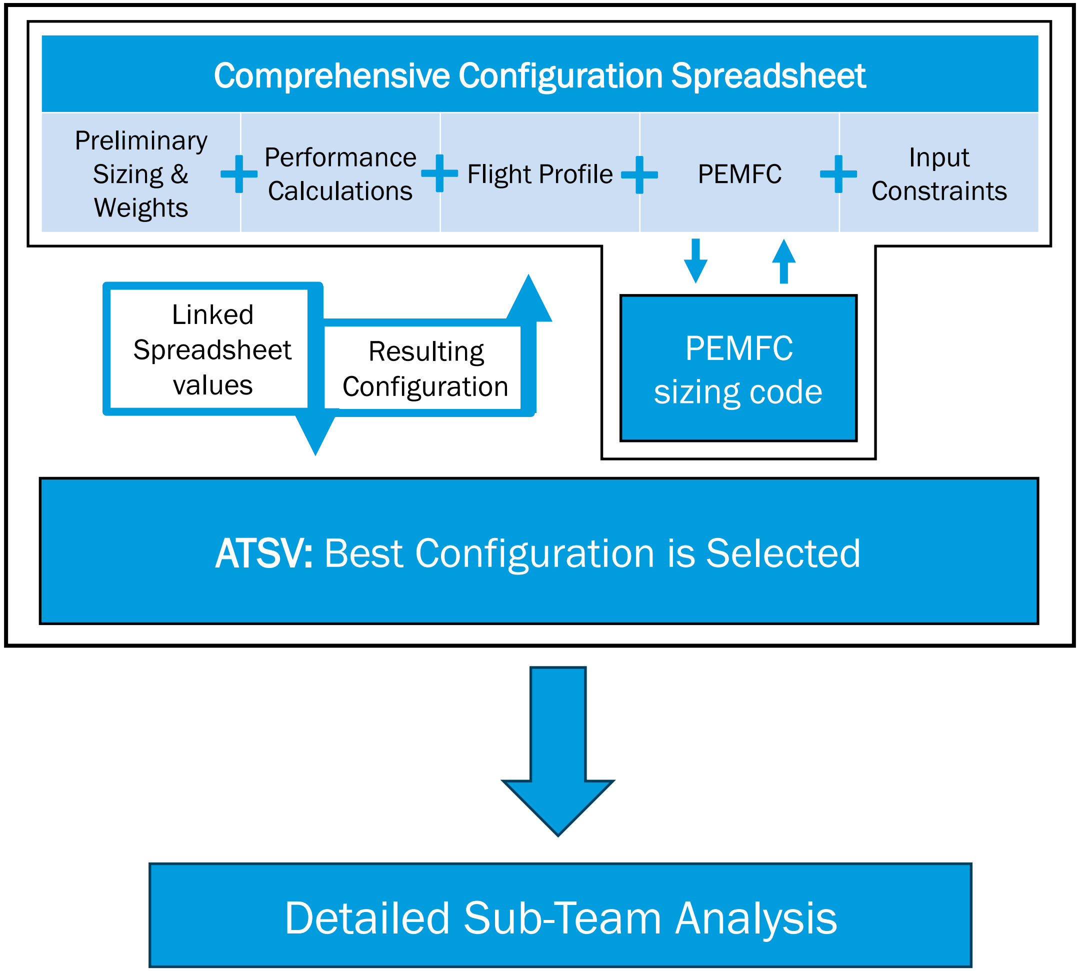
Second Flap Frequency
70.3 Hz

Single-airfoil rotor blade features are designed for maximum endurance and loiter performance.

Integrated Software

A team-built integrated software connects three processes into one comprehensive spreadsheet.

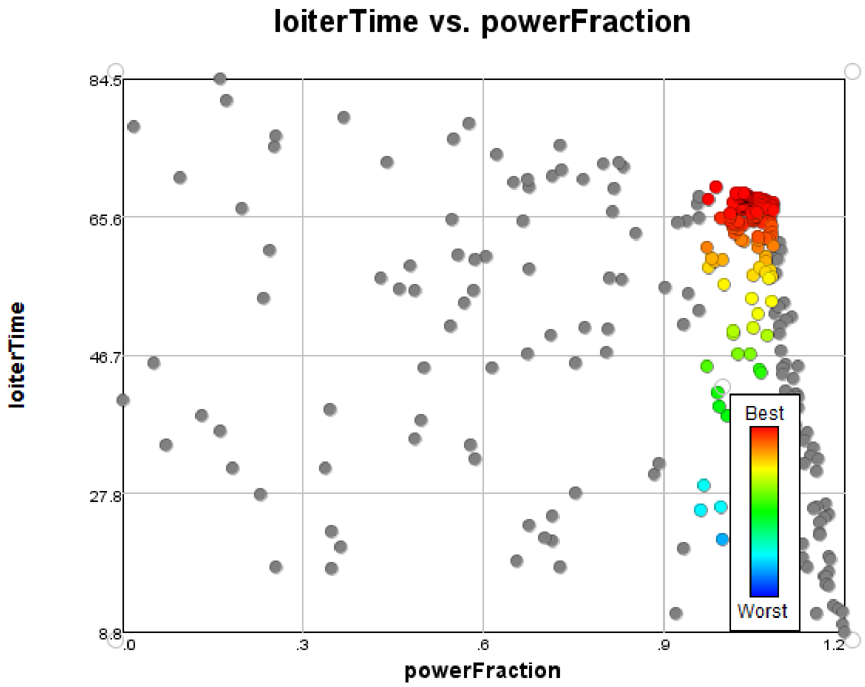
- Configuration spreadsheet includes multiple sub-sheets containing inputs and formulas for power, weight, and sizing.
- Configuration spreadsheet linked to Dr. Datta's PEMFC sizing code to ensure concurrence for every iteration.
- Power data factors in the mission profile per the RFP, ensuring accurate endurance metrics.
- Penn State's ARL Trade Space Visualization software (ATSV), directly edits the configuration spreadsheet, and PEMFC code by proxy, varying inputs to obtain data for thousands of configurations.
- Data from converged feasible design is distributed to sub-teams for detailed analysis



A comprehensive spreadsheet integrates PEMFC sizing, performance analysis, and trade space evaluation to generate viable configurations. Optimal design is selected by maximizing loiter time and meeting "power fraction" ratio.

Multi-objective Design Optimization – ATSV

2-Dimensional Convergence Plot - ATSV

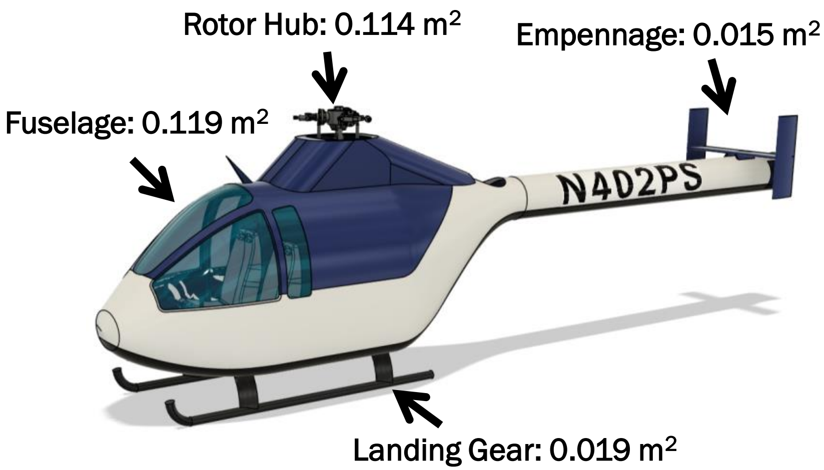


- Initial optimization processes determine sizing metrics and primary performance inputs
- Further iterations are completed isolating hydrogen fuel weight and design power as inputs to analyze
- ATSV run hundreds of times with preference functions to maximize loiter time
- **Power fraction (net PEMFC power/maximum required power)** is constrained to greater than 1 to ensure power requirements are met
- Convergence occurs when outcomes cluster and cease to improve (red points)

Key Configuration Metrics					
Design Power	Fuel Weight	Loiter Time	Power Fraction	GTOW	Total Volume
228.8 kW	11.95 kg	72 min	1.05	1187 kg	0.496 m^2

Desired ATSV configurations are concentrated and compared with undesired configurations (do not meet design constraints), which are greyed ("brushed") out.

Parasite Drag Calculation



OH-6A: Similarly sized helicopter for baseline comparison. (See Prouty Drag, table 4.3)

Parasite drag was calculated using component buildup method with Hoerner's drag.

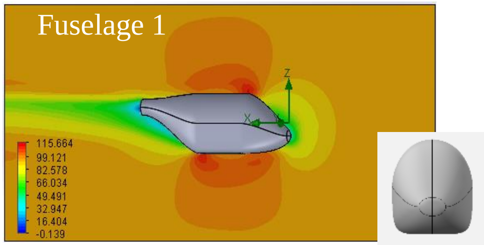
TOTALS					Comparison OH-6A Results	
Component	Equivalent Flat Plate Area (f) m^2		% of Total Drag			
Basic Fuselage	0.119		31%		0.139	30%
Rotor Hub	0.114		29%		0.111	24%
Empennage	0.015		4%		0.009	2%
Landing Gear	0.019		5%		0.046	10%
Rotor-fuselage Interference	0.027	0.120	7%	31%	0.158	34%
Miscellaneous	0.029		8%			
Discrete Roughness and Leakage	0.065		17%			
TOTAL	0.387		100%		0.465	100%

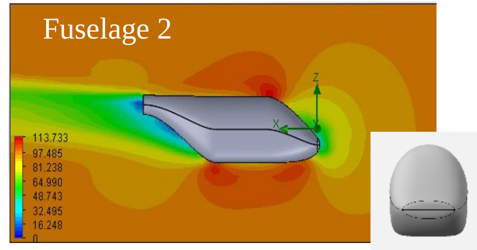
Parasite drag is calculated using empirical methods and compared to OH-6A data for baseline comparison.

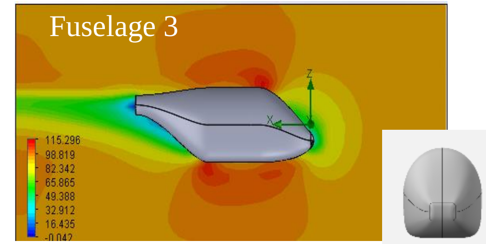
B. Renaud, "OH-6A Cayuse (image 05)," ArtStation, digital image, Feb. 2023. [Online]. Available: https://cdnb.artstation.com/p/assets/images/images/061/299/571/large/bastien-renaud-cayuse-05.jpg. [Accessed: May 7, 2025].

Prouty, R. W., *Helicopter Performance, Stability, and Control*, Krieger Publishing, Malabar, FL, 2002. Accessed April. 1, 2025.

Fuselage Shape Design Analysis

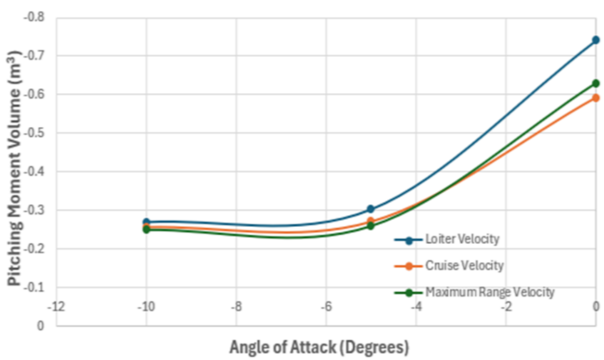




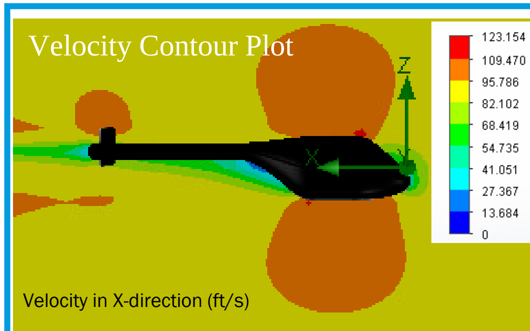


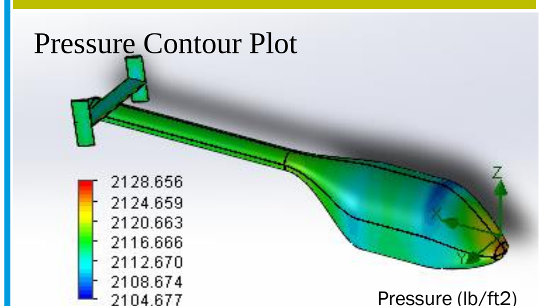
- SolidWorks Flow Simulation was used to run CFD with a velocity of 29 m/s.
- The solver employs FVM to solve Reynold's Averaged Navier-Stokes equations.
- Fuselage 1 showed the least flow separation, drag area and optimal M/q.

- Fuselage 1 was chosen as the optimal shape.
- CFD run on fuselage, tail boom, and stabilizers with the same velocity.



Pitching Moment Volume vs AoA curves show consistent positive slopes indicating static longitudinal stability with stronger restoring moments at lower speeds.





- **Velocity contour plot** shows airflow around the helicopter. High velocity flow occurs in the front indicating forward motion. The wake suggests how the fuselage redirects the flow.

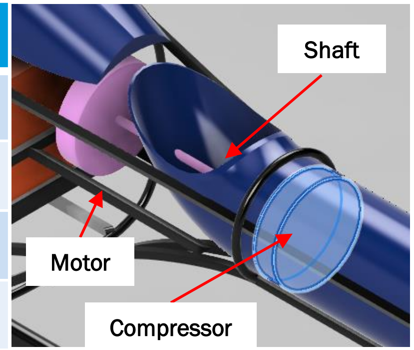
- **Pressure contour plot** shows the distribution of pressure on the surface of the helicopter body. High pressure occurs near the nose while a low pressure is maintained along the top and sides.

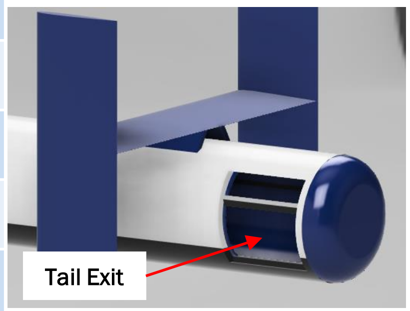
The fuselage shape with a circular nose was chosen as the optimal design. CFD on the configuration with fuselage, tail boom, and stabilizers show optimal results.

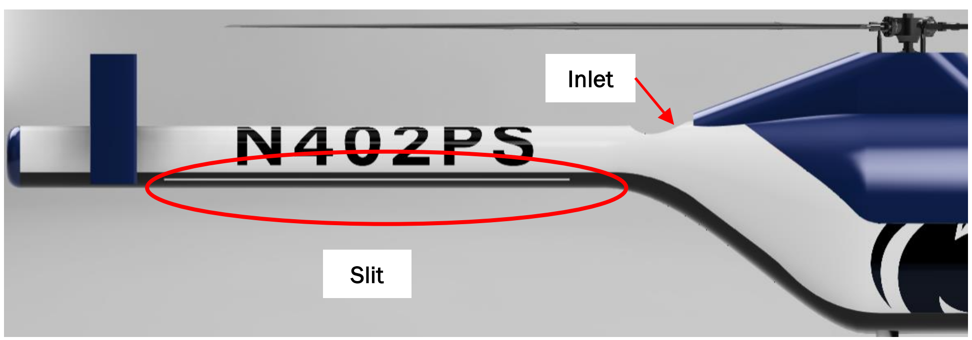
A. Sobachkin, "Numerical Basis of CAD-Embedded CFD," *solidworks.com*, 2014. https://www.solidworks.com/sw/docs/Flow_Basis_of_CAD_Embedded_CFD_Whitepaper.pdf

NOTAR Anti-Torque System

NOTAR Dimensions	
Rotor to Slit Start	2.30 m (7.55 ft)
Rotor to Slit End	5.04 m (16.54 ft)
Rotor to Tail Exit	5.33 m (17.49 ft)
Slit Length	2.74 m (8.99 ft)
Slit Height	1.43 mm (0.06 in)
Tail Exit Length	0.30 m (0.98 ft)
Tail Exit Height	0.30 m (0.98 ft)
External Radius	0.20 m (0.66 ft)
Internal Radius	0.186 m (0.61 ft)







NOTAR System Requirements	
Slit Torque	4684 N-m (3454 ft-lb)
Tail Exit Torque	3123 N-m (2303 ft-lb)
Maneuvering Torque	830 N-m (612 ft-lb)
Max Power Required	16.2 kW (21.6 hp)
Min Power Required	15.0 kW (20.1 hp)
Balancing Power	15.6 kW (20.9 hp)
Airflow	60.7 m^3/min (2144 ft^3/min)
Pressure Range	18.44 kPa -20.00 kPa (2.67 psi -2.90 psi)

NOTAR Motor

MGM Compro Rex 30 Electric Motor

Specifications

- 70 N-m Max Torque
- 6000 Max RPM
- 25 kW Max Power
- 17 kW Continuous Power
- Weight: 5.25 kg
- Volume: 0.003 m^3 (216 mm diameter x 74 mm length)

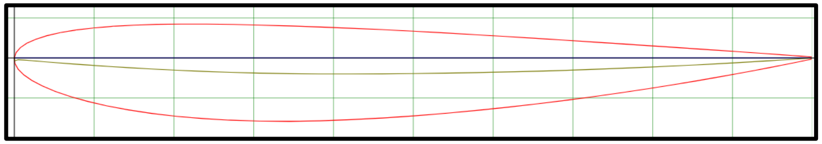
By implementing the Coanda effect, the NOTAR provides anti-torque without using a tail rotor. The NOTAR uses an individual motor and compressor, drawing power from the PEMFC.

propagon.cz, T. F.-, "25 KW electric motor," *MGM COMPRO* Available: https://www.mgm-compro.com/electric-motor/25-kw-electric-motor/.

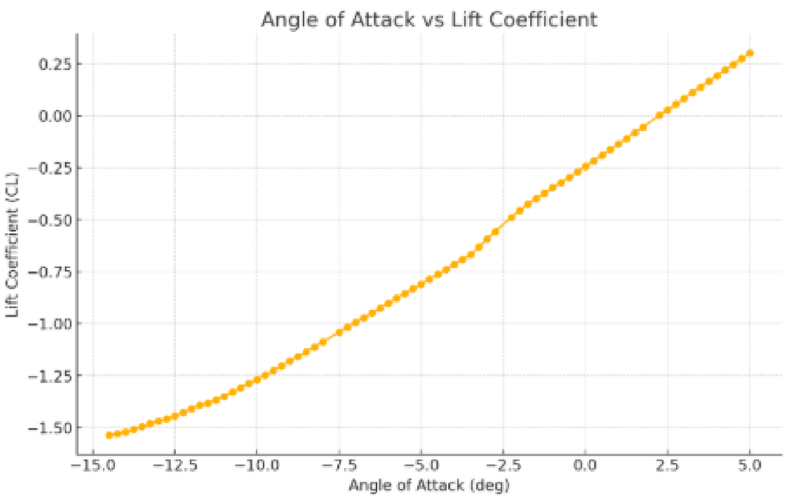
Tail Surfaces and Stability

Horizontal Stabilizer

- Inverted NACA 2412
- Improved flow and drag compared to symmetrical counterpart

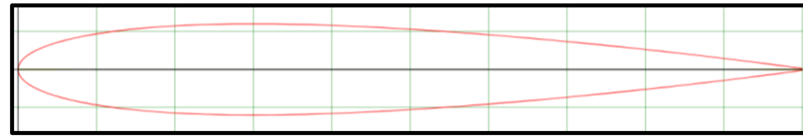


Dimensions: Span: 1.19 m (3.9 ft); Chord: 0.32 m (1.04 ft)

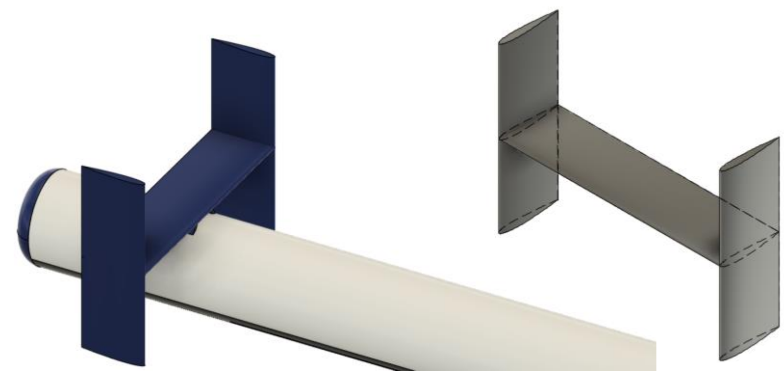


Dual Vertical Stabilizer Design

- NACA 0012 geometry
- Symmetrical design for best drag
- Useful for maneuvering both directions



Dimensions: Span: 0.88 m (2.9 ft); Chord: 0.32 m (1.04 ft)



Parameters: Main rotor disc area, rotor blades mean aerodynamic chord, tail moment arm
Assumptions: Volume coefficient of 0.30 (horizontal stabilizer), 0.02 (vertical stabilizers)

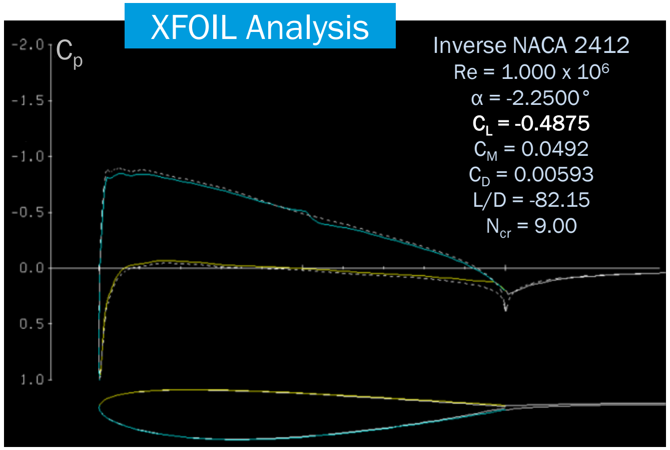
Stabilizer design maximizes counteracting pitching moment and minimizes drag.

Prouty, R. W., *Helicopter Performance, Stability, and Control*, Krieger Publishing, Malabar, FL, 2002. Accessed April. 1, 2025.

Stability Analysis

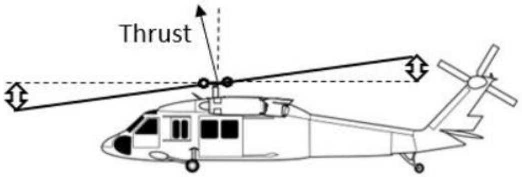
Horizontal Stabilizer

- To stabilize forward pitching moment, a declined angle is required
- Incidence found using lift slope curve, zero-lift angle of attack, and pitching moment
- Nose-down incidence of 2.25° is determined for pitching moment balance



Hover

- CG is forward of main rotor → Helicopter tends to downward pitching moment
- NOTAR counteracts Main Rotor torque → Constant side force from fan
- Need blade flapping in hover to equilibrize pitching moment and side force
- Using Prouty, trim flapping angles are derived directly from blade element theory



Longitudinal Trim Angle - 1.85°

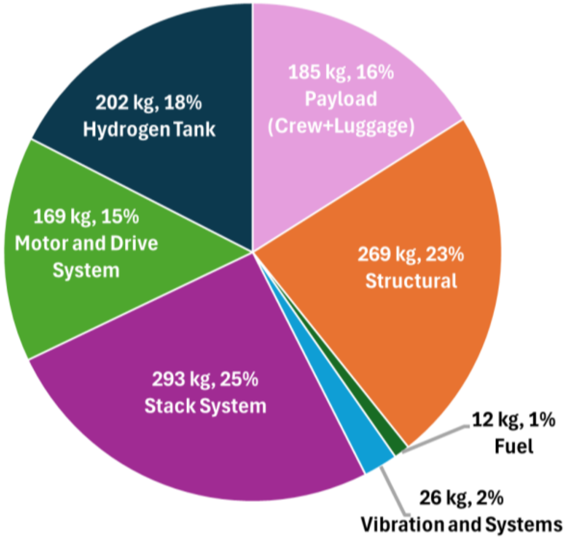
Lateral Trim Angle - 1.57°

Horizontal tail exhibits viable C_L and C_D in operating conditions. Proper CG, torque counteraction, and blade flapping further elevate stability, required for mission success.

SpinningWing. "Helicopter Controls." Accessed April 4, 2025. https://www.spinningwing.com/the-helicopter/helicopter-controls.

Weight Breakdown

Component	Weight (kg)	Weight (lbs)	% of Total
Fuselage	181.68	399.7	15.31%
Rotor Hub	27.89	61.5	2.35%
Rotor Blades	67.92	149.4	5.72%
Avionics and Seating	27.27	60.0	2.30%
NOTAR Compressor and Compressor Motor	18.89	41.6	1.59%
Main Drive Train System	152	334.4	12.81%
Main Motor Cooling System	18.18	40.0	1.53%
Fuel Stack + Air + Electrical Components	119.18	262.2	10.04%
Hydrogen Tank	202	444.4	17.02%
Weight of Hydrogen	11.95	26.3	1.01%
High Temperature and Low Temperature Cooling	174.43	383.8	14.70%
Total Empty Weight	**1001**	**2204**	**84.33%**
Maximum Takeoff Gross Weight	**1187**	**2611**	**100.00%**



A total MTOW of 1187 kg is reported with majority of weight coming from the vehicle structure and hydrogen propulsion system. The total weight and weight distribution is on par with similar helicopters in this category.

Summary

In response to Airbus and VFS 2024-25 student design competition, “Pioneering Hydrogen-Electric VTOL”, **Penn State presents Hydro Hawk.**

Hydro Hawk is an endurance maximized vehicle built with a high technology readiness level. Implementing the safer and quieter NOTAR anti-torque system, the helicopter is optimized for observation and loiter capabilities with a loiter time of 1.2 hours.

Comparable to its petroleum counterparts on the market, Hydro Hawk is a capable, lightweight, sustainable alternative. Taking advantage of Hydrogen PEM Fuel Cells, Hydro Hawk is emission free without the weight and range consequences of fully battery powered electric vehicles.