AAE 490/590T Design Build Test

Proplet Propeller Design

Final Presentation

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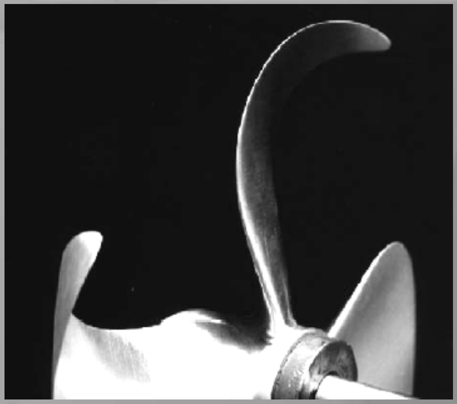
Presentation Outline

- Project Purpose
  - Introduction to Proplets
  - Design Mission
- Final Design Outcome
- Design Method overview
  - Spiral Design
  - Optimization techniques
  - Final Design Method
- Construction Method
  - Cutting acrylic plug
  - Making rubber mold
  - Laying up CF propeller
- Propeller Testing
  - Testing Methods
  - Comparison with design results
  - Comparison with standard propellers
- Conclusions

What is a Proplet?

- A proplet works the same way as a winglet on a wing
- Proplet changes lift distribution near blade tip to reduce induced drag
- Just as with a winglet, a proplet must be properly loaded to achieve a performance benefit
- Proplet Studies
    - Anderson, P. "A Comparative Study of Conventional and Tip-Fin Propeller Performance," Twenty-first Symposium on Naval Hydrodynamics 1997: pp. 930.
    - Sullivan, J.P., Chang, L.K. , and Miller, C. J., "The Effect of Proplets and Bi-blades on the performance and Noise of Propellers," *Transactions- Society of Automotive Engineers*, Vol. 90, No. 2, December 1982, pp 2106-2113,
    - Redman, AAE 415 Project Fall 2003
- Non-planar geometry is used in many marine propellers
- Limited Aircraft Proplet Research/Design



Propeller Concepts

Advance Ratio

$$j = \frac{V_\infty}{ND}$$

Efficiency

$$\eta_p = \frac{T \cdot V_\infty}{2\pi N \cdot M_x}$$

Thrust Coefficient

$$c_t = \frac{T}{\rho \cdot N^2 \cdot D^4}$$

Power Coefficient

$$c_p = \frac{TV_\infty}{\rho N^3 D^5}$$

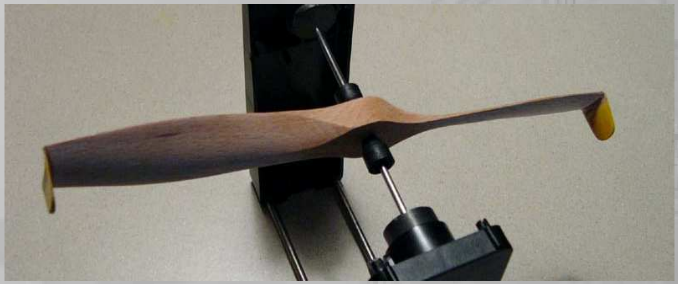
N [rev/sec]

Mx = torque

D = prop diameter

The Project: Design Mission

- The goal of this project is to design, build and test a propeller for electric remote control aircraft that uses proplets to increase the efficiency of the propeller in standard RC flight regimes.



- Specific Design Mission
  - Model High Altitude Airship – requires high static thrust for directional control. Propeller designed for AXI 2826-12 Motor.
  - Advance Ratios ~ 0<J<0.6

- General Application
  - Long Duration UAVs – efficiency of propulsion system relates directly to airtime. Propeller designed for specific motor characteristics.
  - Other RC aircraft
  - Advance Ratios ~ 0<J<1.5

Final Propeller

12 inch total Diameter

Quadratic twist distribution

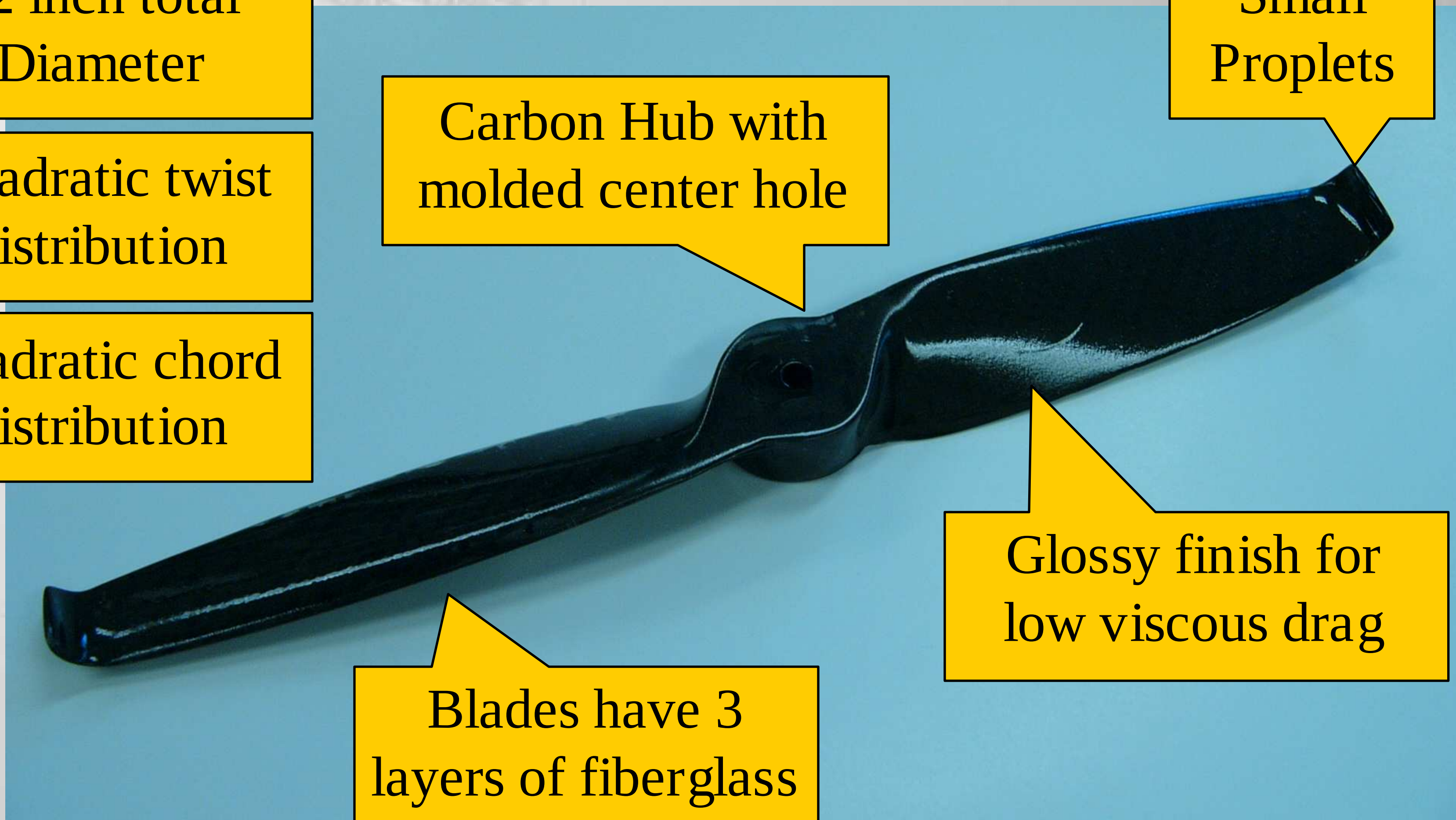
Quadratic chord distribution

Carbon Hub with molded center hole

Small Proplets

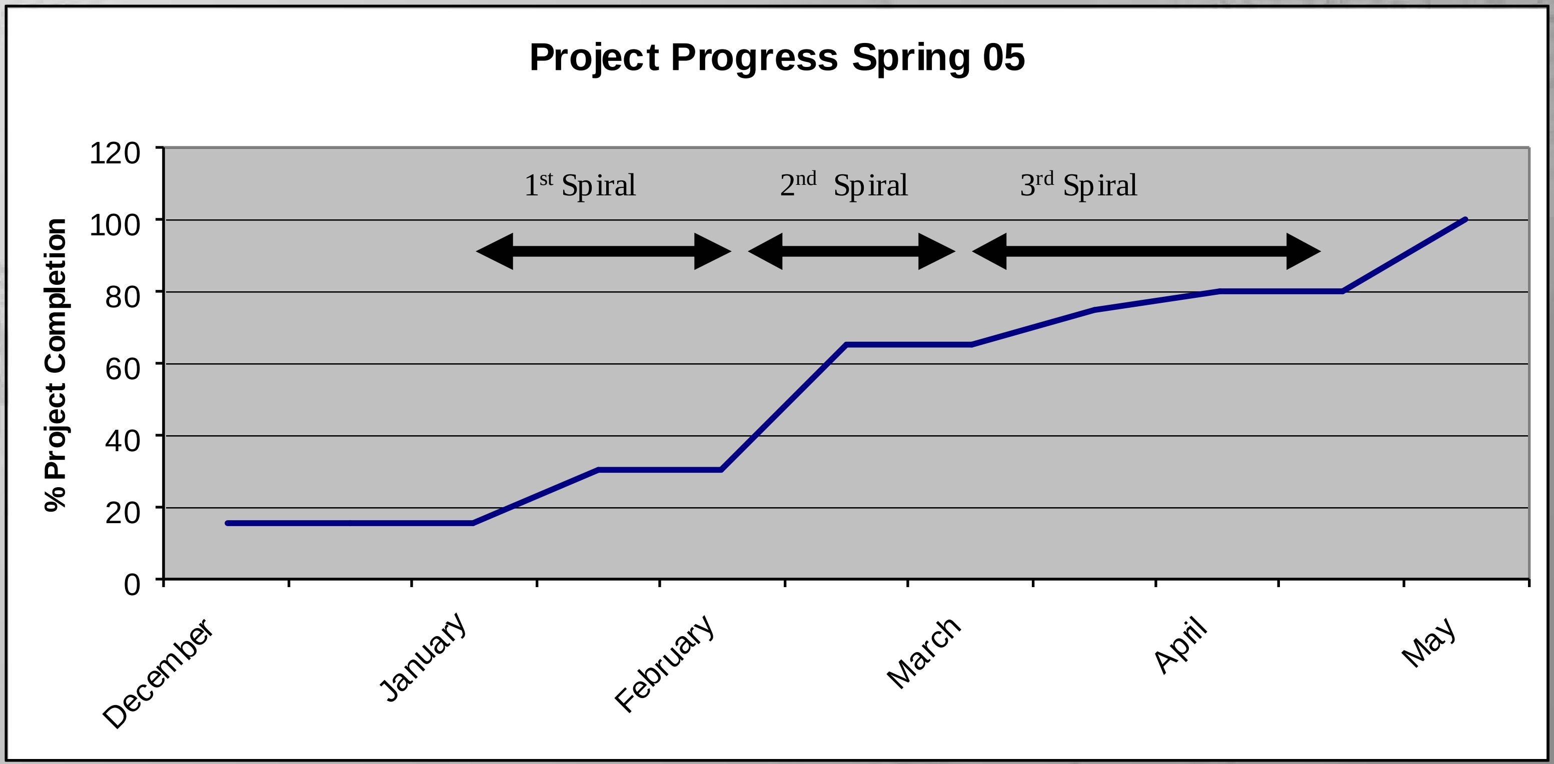
Glossy finish for low viscous drag

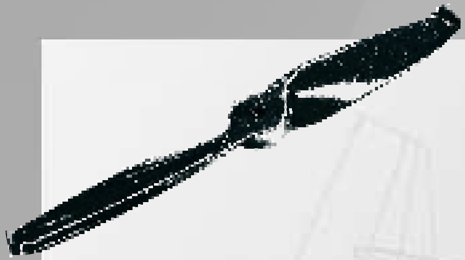
Blades have 3 layers of fiberglass on outside with carbon weave core



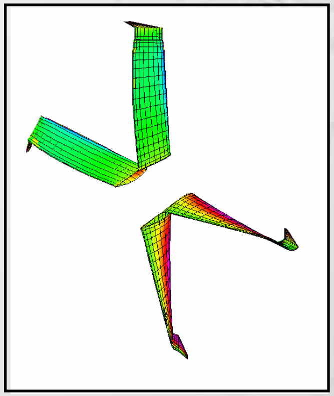
Spiral Design

- In the design of this propeller a spiral design method was used.
- Each spiral consisted of Design, Build, and Test sections





1^{st} Spiral Summary

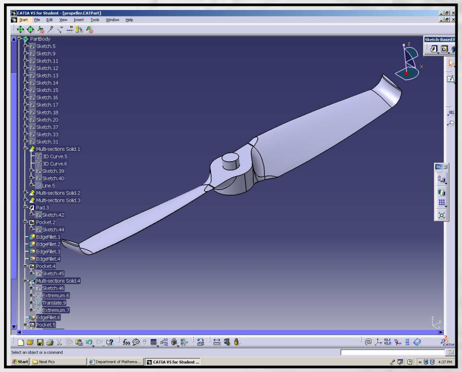


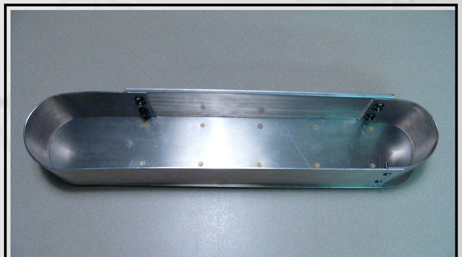
- **Design**
  - Matlab script to generate CMARC input complete
  - Vortex Lattice Code Partially completed
  - Catia Model and Automation Underway
  - Software Tools Partially integrated

- **Construction**
  - Constructed proplet propeller from existing propeller blades
  - Investigated methods for making molds

- **Testing**
  - Test stand completed
  - Propellers successfully tested
  - Compared Test results with Computational methods

2nd Spiral Summary



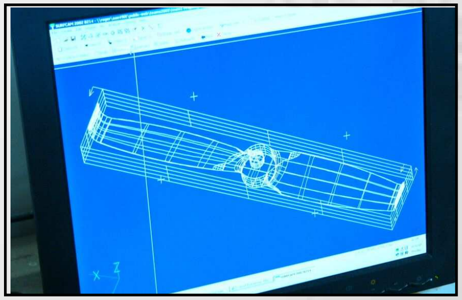


- **Design**
  - Finalized Design Software
  - Optimization techniques used
  - Proplet Trade Study
  - Automated Catia Model Completed

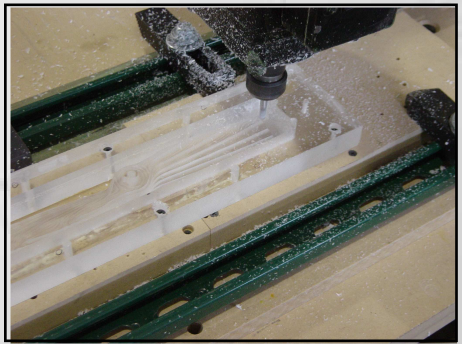
- **Construction**
  - Researched Molding techniques
  - Tested mold release
  - Build Mold Basin
  - Acquired materials

- **Testing**
  - Investigated Increasing test accuracy

3rd Spiral Summary



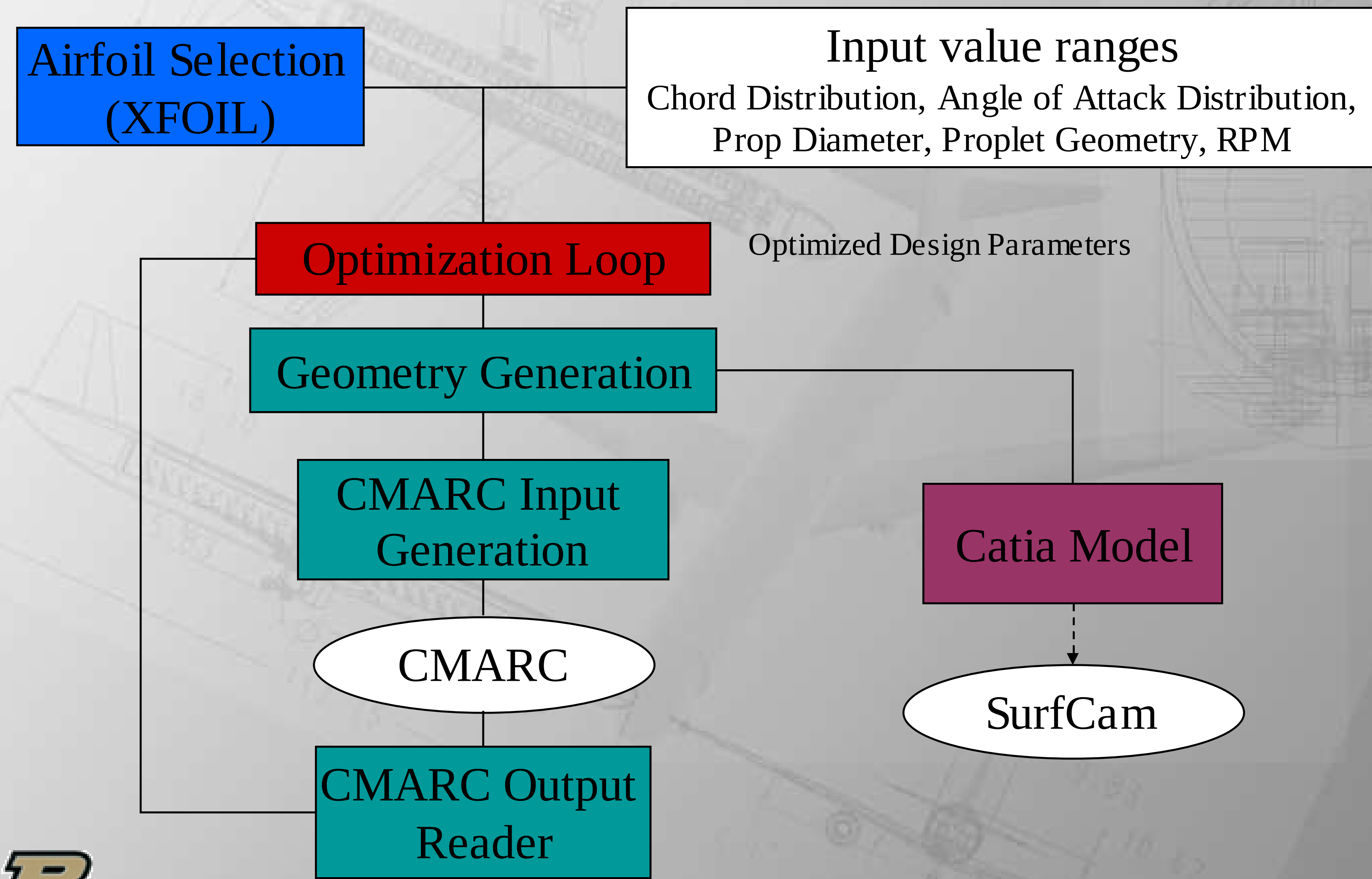
- **Design**
  - Modified and finalized design
  - Completed CNC tool paths
  - Generated test comparison data



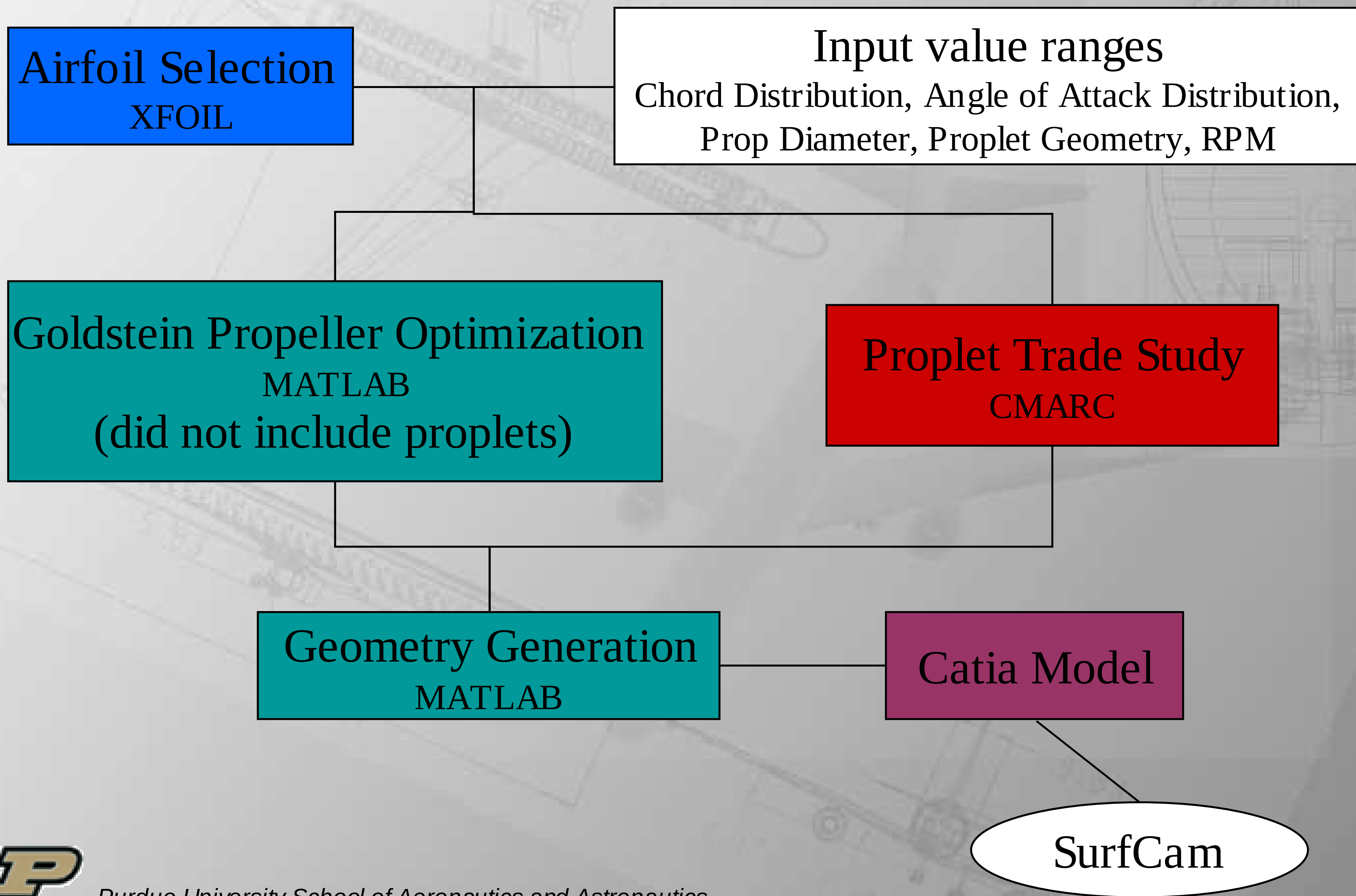
- **Construction**
  - Cut acrylic Propeller
  - Created Rubber mold
  - Built 2 composite propellers

- **Testing**
  - Tested final proplet propeller
  - Tested non-proplet propeller
  - Tested factory propellers
  - Compared test results with computational methods

Design: Software Flowchart



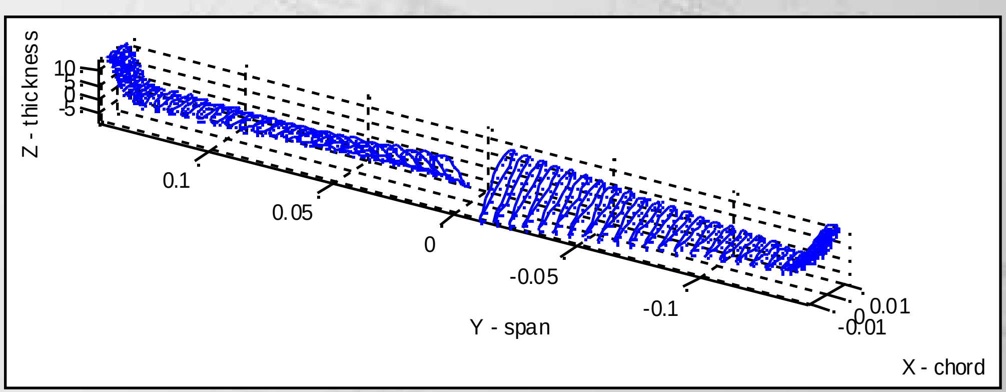
Design: Modified Software

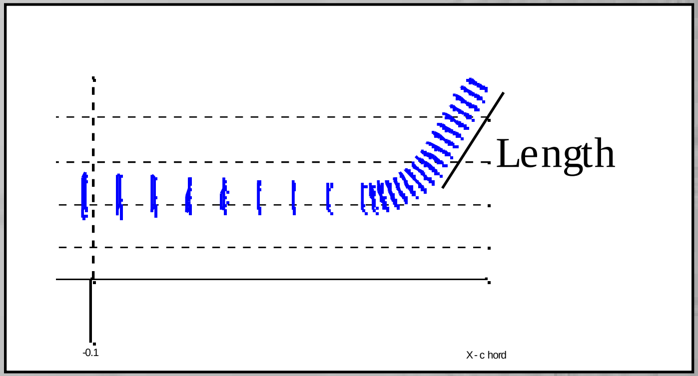


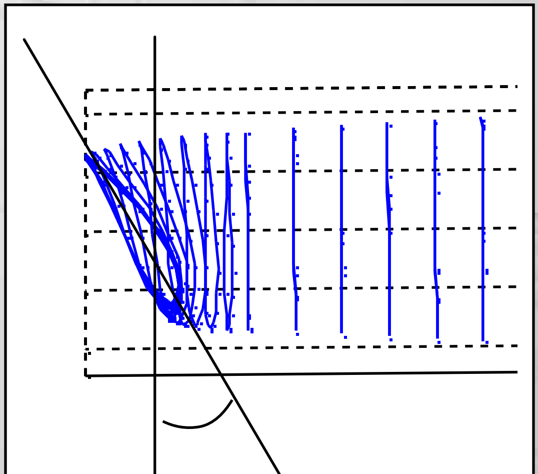
Design Variables

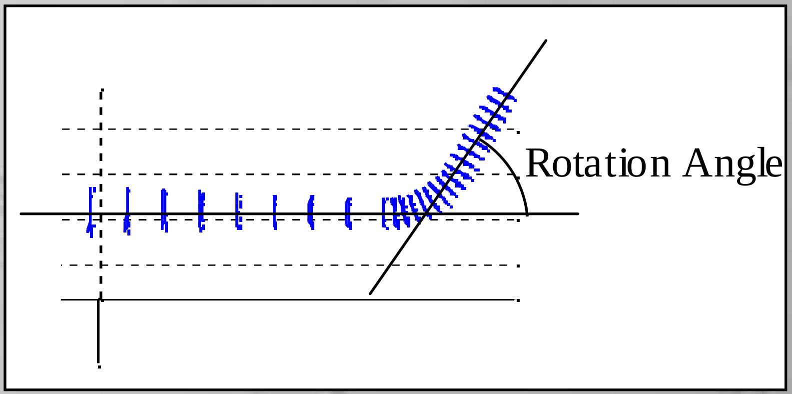
Design Variables			
Propeller Diameter	constant	12	inches
Propeller Vinf	constant	30	ft/sec
Design Thrust	constant	3	lbf
Chord Distribution	root	0.5 to 1.5	inches
	TR	0.2 to 1	
	coefficient	-4 to 0	
Beta Distribution	Root	0 to 90	deg
	tip	0 to 45	deg
	coefficient	-100 to 0	
Proplet Length		0.05 to .2	% R
Proplet theta		30 t0 90	deg
Blend Radius		0.01 to .05	meters
Proplet incidence angle		-5 to +5	deg

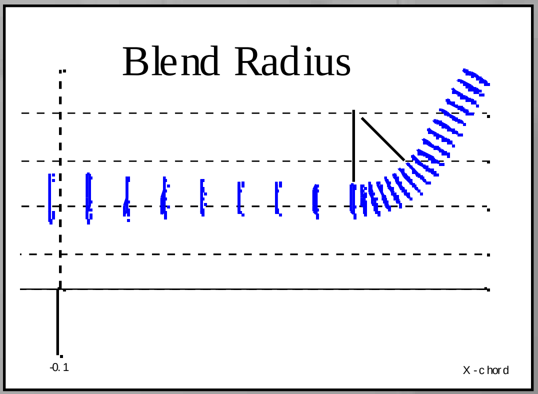
Proplet Geometry Variables



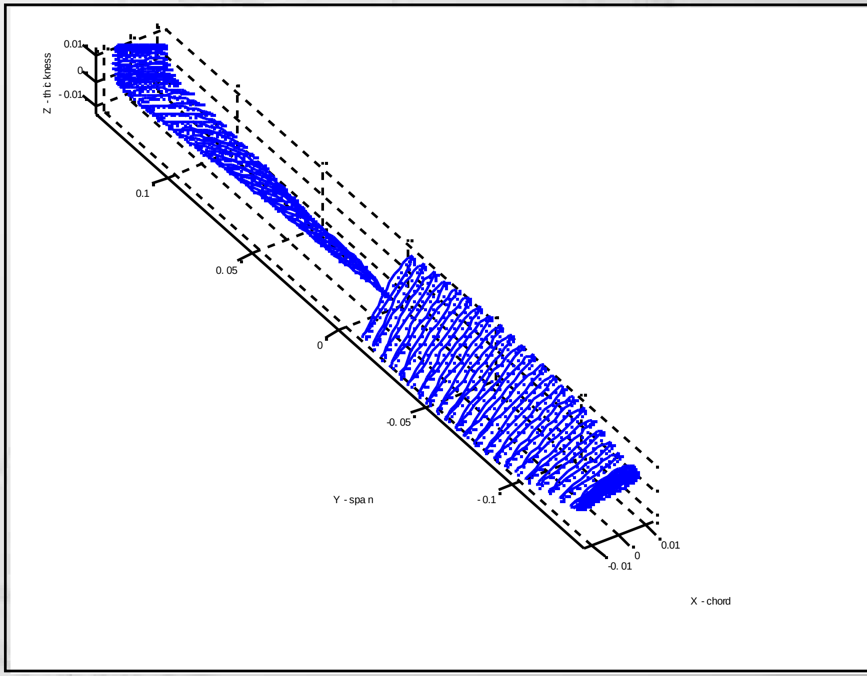


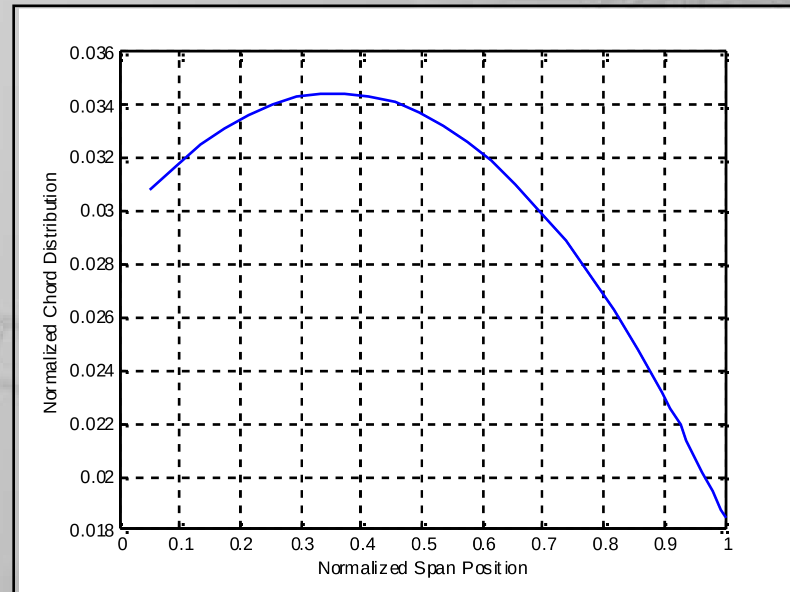


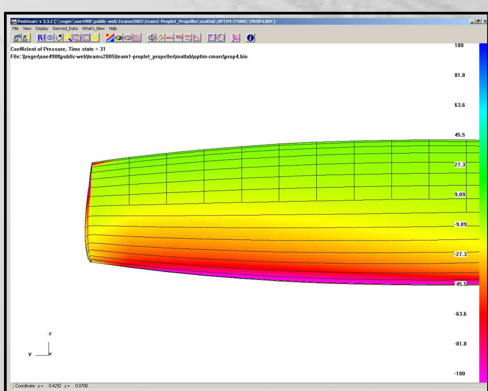


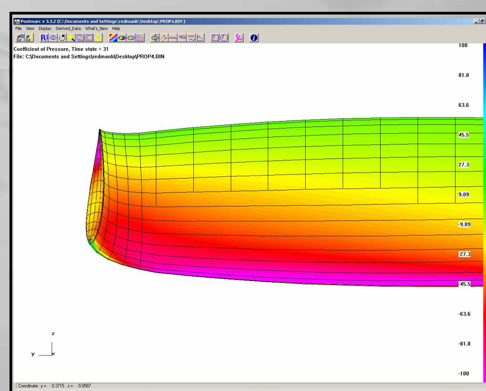


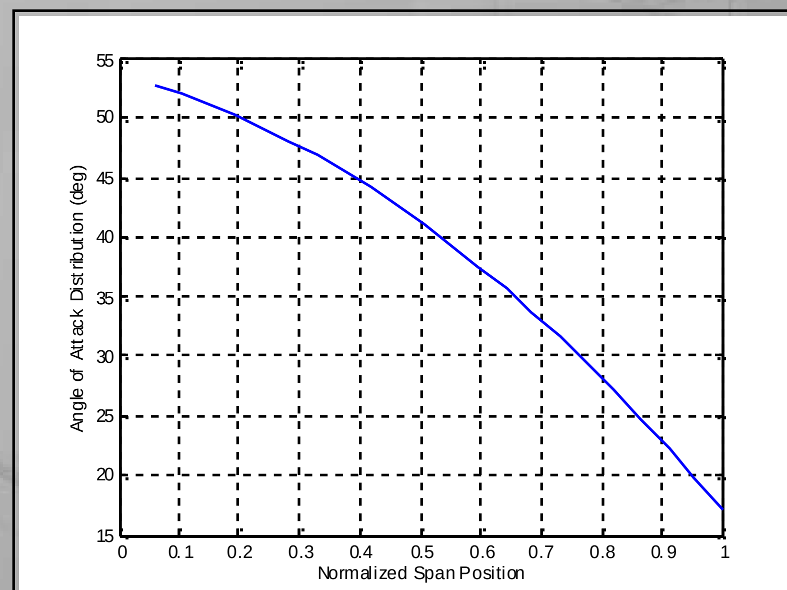
Design: Geometry







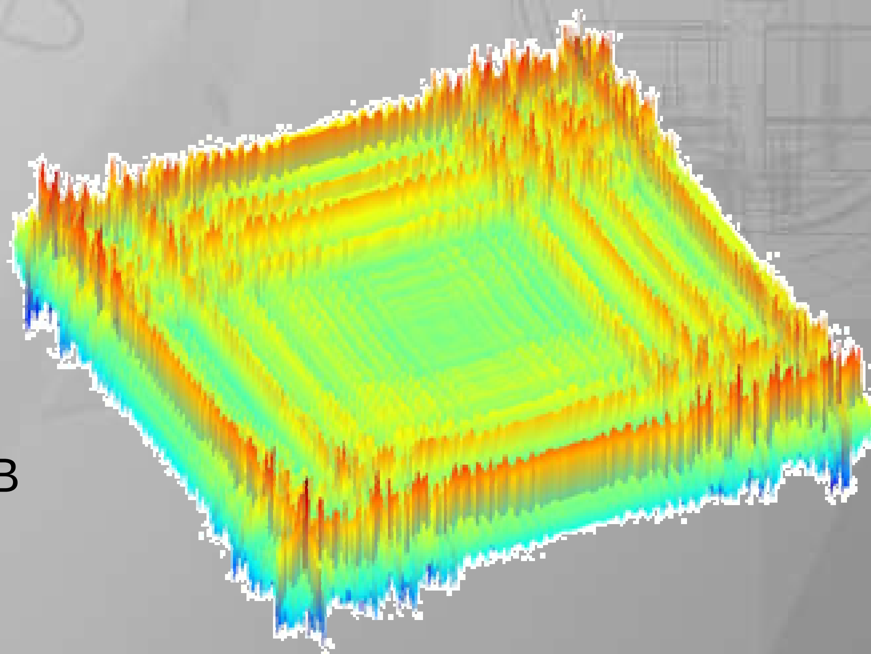




Design Optimization

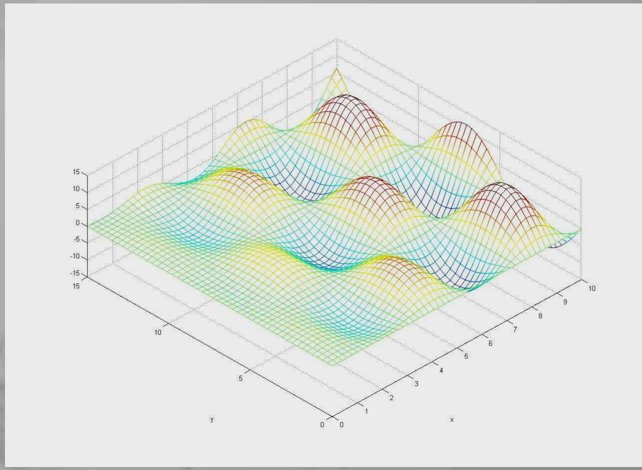
- Minimization of objective function
  - Maximize efficiency
  - Minimize (-1)*efficiency
- Subject to constraints
  - Design variable bounds
- Multi-objective optimization
  - Combination of objective functions

- Sequential Quadratic Programming
  - Creates local quadratic sub-problem
    - Quadratic objective
    - Linearized constraints
  - 'FMINCON' implements SQP in MATLAB
    - Objective function
    - Linear and non-linear constraints
    - Variable bounds
    - Initial design point



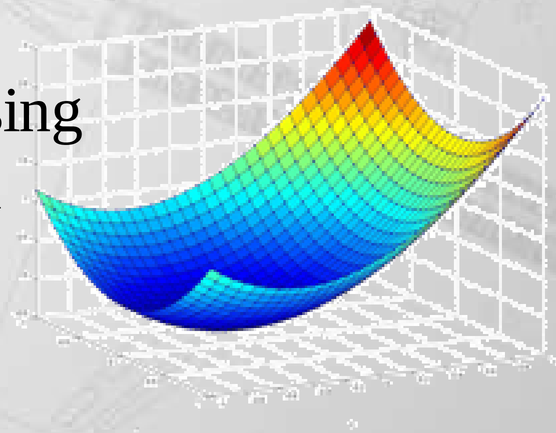
Design Optimization

- Objective:
  - Optimize efficiency over several advance ratios
    - Efficiency evaluated as cost function of design variables
    - RMS weighting is a means to the best performance over range of advance ratios
  - Subject to a minimum thrust requirement
- Common difficulties with optimization
  - Computation time
  - Local minima

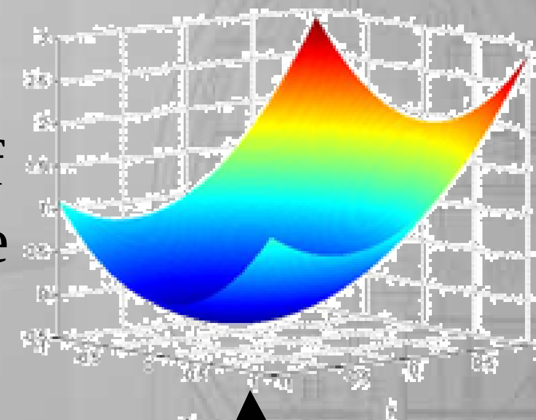


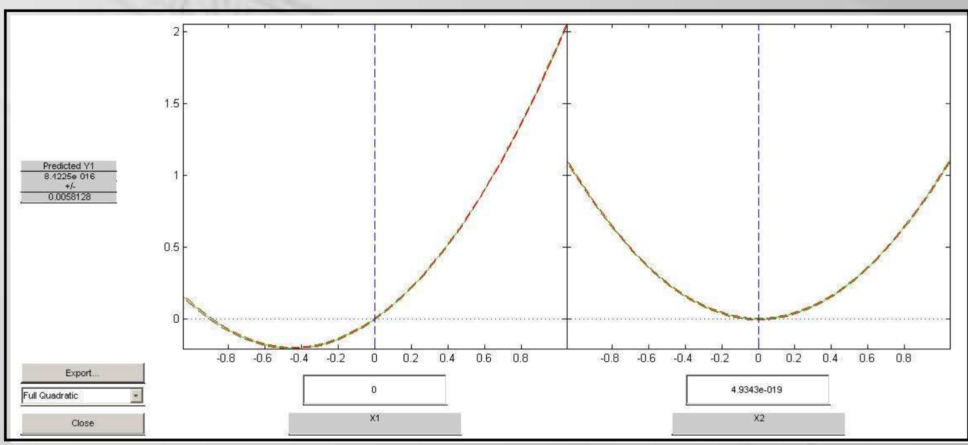
Response Surface Method

Set of points generated using analysis tool



Algebraic approximation of analysis response



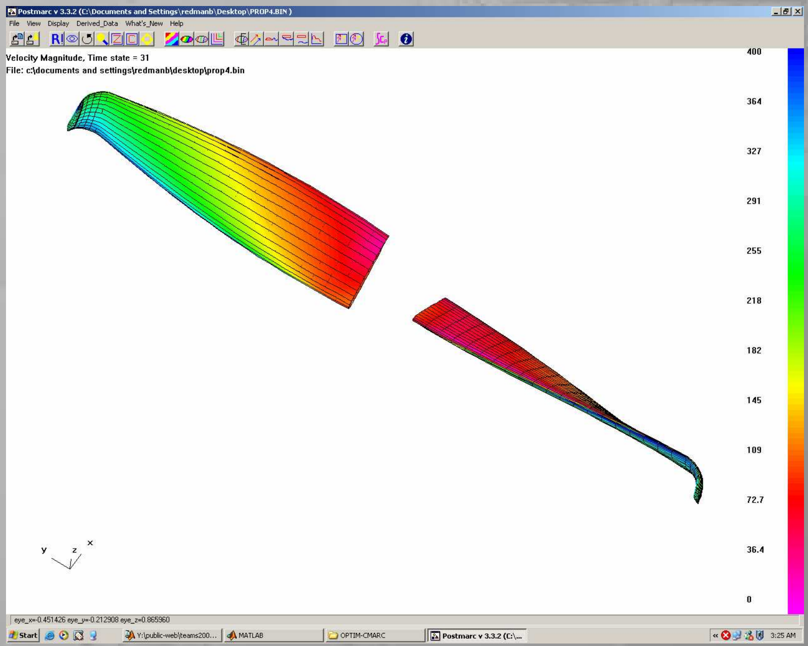


$$
\begin{aligned}
response = {} & b_0 + b_1x_1 + b_2x_2 + b_3x_3 + \ldots \\
& b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + \ldots \\
& b_{11}x_1^{\ 2} + b_{22}x_2^{\ 2} + b_{33}x_3^{\ 2} + \ldots
\end{aligned}
$$

Coefficients generated by rstool are used to generate the response surface with linear, interactive, and quadratic terms

Optimization Design Sequence

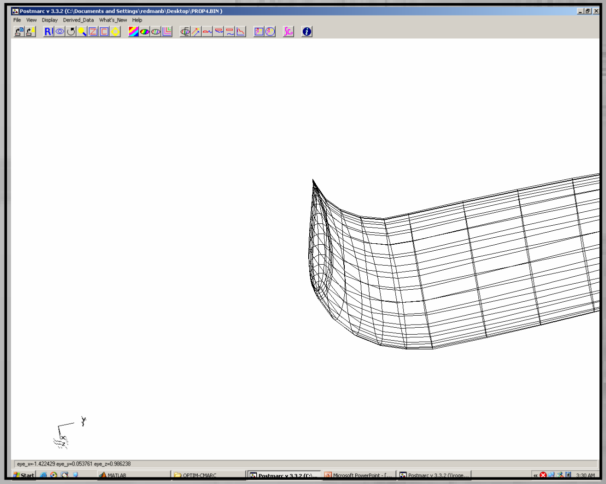
- Optimize proplet and blade geometry concurrently
  - Aerodynamic analysis: CMARC
  - Design variables (9)
  - Distribute objective function weighting using RMS scheme
    - Optimized over range of J

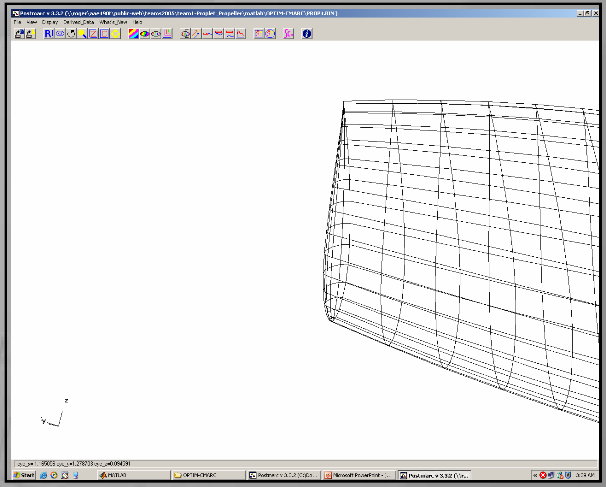


- **ISSUES**:
  - Computation time
    - Function evaluations >> 10e3
    - Run time per function evaluation approx. = 40 sec
    - Total t >> days
  - Local minima
  - Software compatibility

Final Design Sequence

- Performed trade studies
  - Proplet
    - Analysis: CMARC
    - Design variables (5)
    - Total cases > 3e3
    - Computation time approx. = 37 hrs
      - Run time per function evaluation approx. = 40sec
    - Produced proplet trade study plots
  - Blade
    - Analysis: Gold.f
    - Design variables (6)
    - Total cases > 200e3
    - Computation time approx. = 20 hrs
      - Run time per function evaluation approx. = 0.2sec
    - Produced blade performance response surface
    - Informed starting point for SQP operation

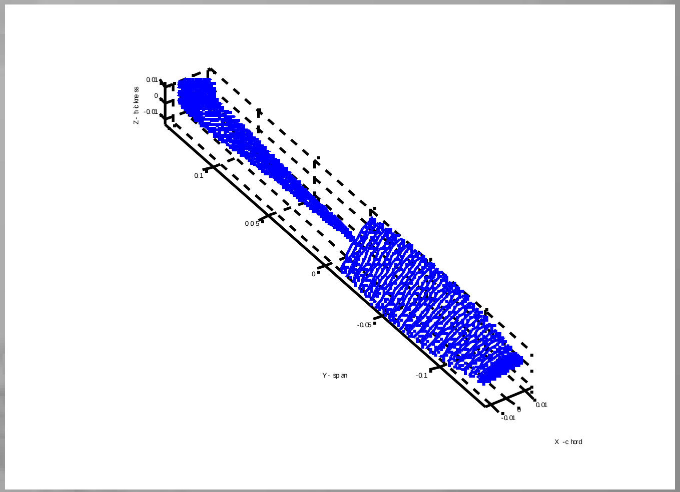




Final Design

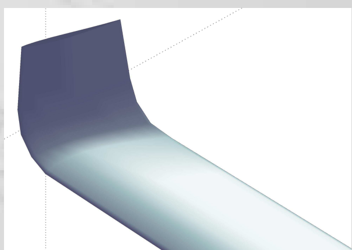
- Combined trade study data
  - Interpreted proplet trends
  - Applied SQP to blade
    - Optimization using response surface starting point

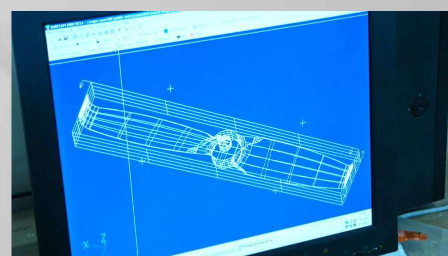
- Mated best individual proplet with best individual blade



Build Method

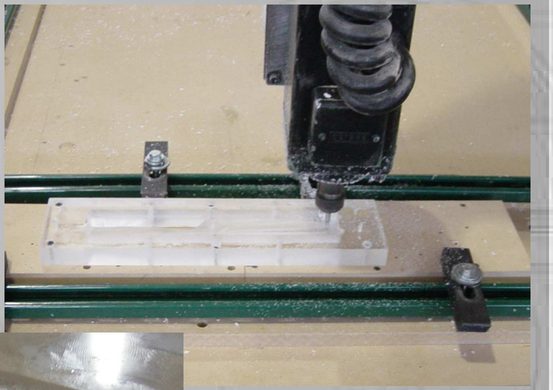
- Catia® Model Created from design software
- Cut an acrylic propeller on 5-axis CNC machine
- Create a female mold using silicon rubber
- Mold a solid composite propeller

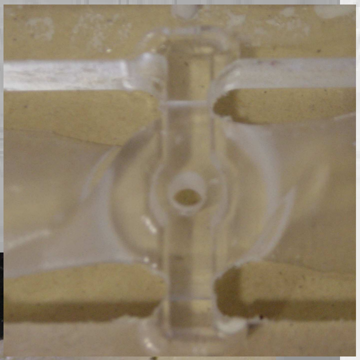


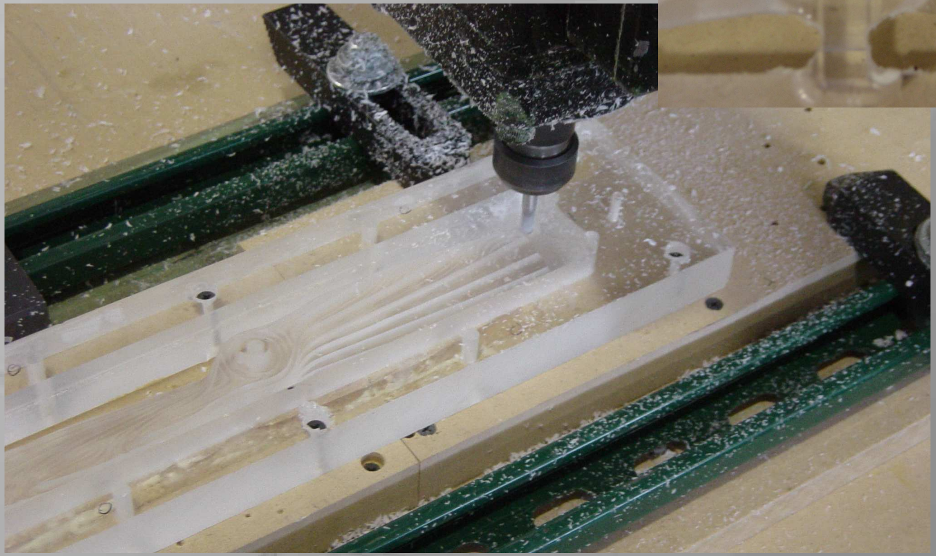


CNC acrylic propeller

- Method
  - Created tool paths in Surfcam®
  - Cut top side of propeller with hub and proplets still attached to stock
  - Filled first cuts with Great Stuff® expanding foam
  - Flipped and Cut lower surface
- Obstacles
  - Small geometry is very sensitive to error (thickness)
  - Great stuff® dries overnight so machine must be re-zeroed
  - Chipping of trailing edge







Molding Materials

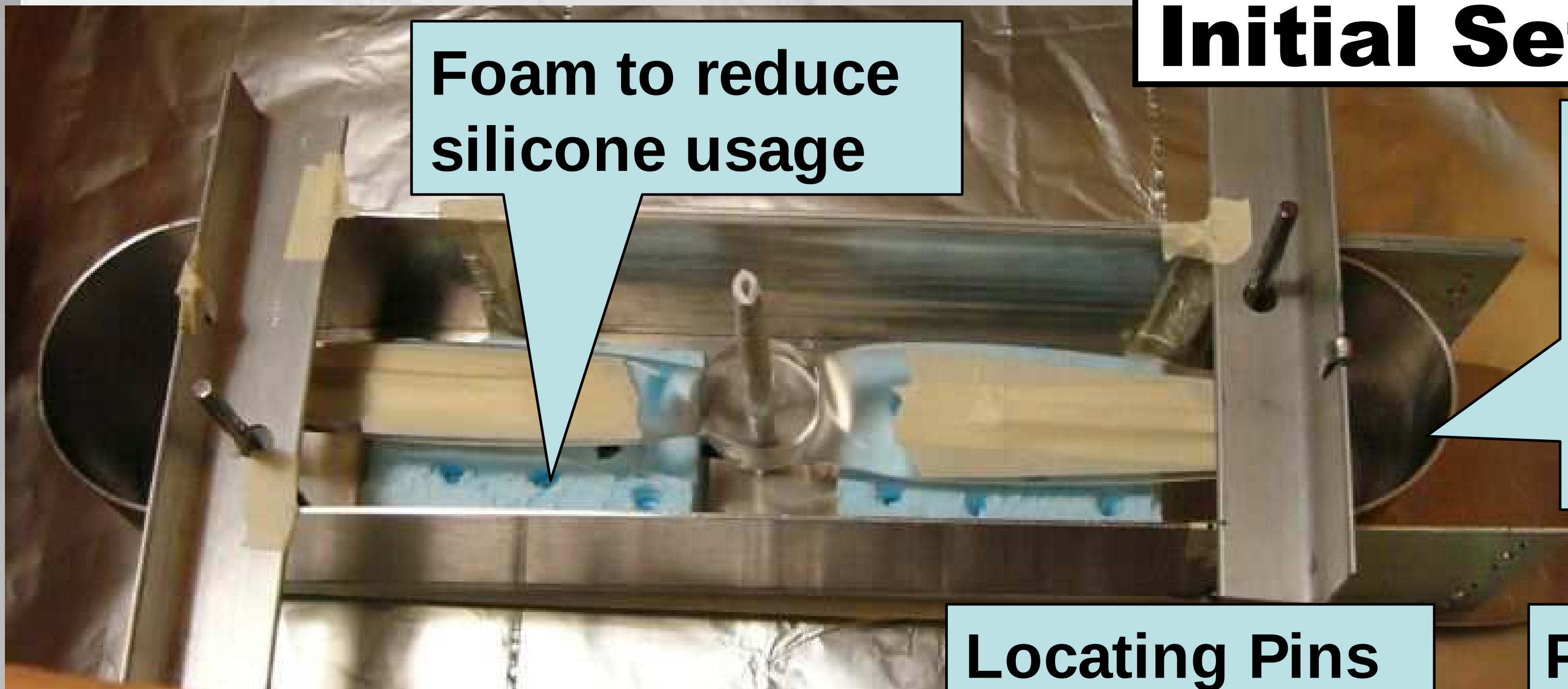
- Silicon rubbers such as Silastic have been used in the past with success.
- Molds are flexible enough to release well from composite materials and complex geometries.
- Silastic proved to be too expensive so a similar material called Hobby Mold® was chosen instead
- Test showed that no mold release was necessary for Hobby Mold and surface quality was excellent

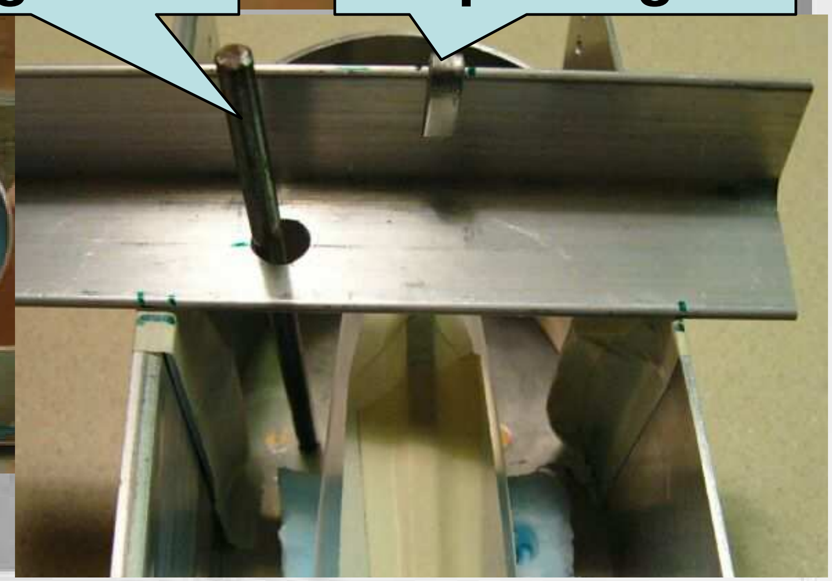
Mold Construction

- Pour-molding method chosen for ease in manufacturing.
- Created for variable length and volume.

- Nut-plates which are common to aircraft access panels were used so the mold can be adjusted and disassembled.

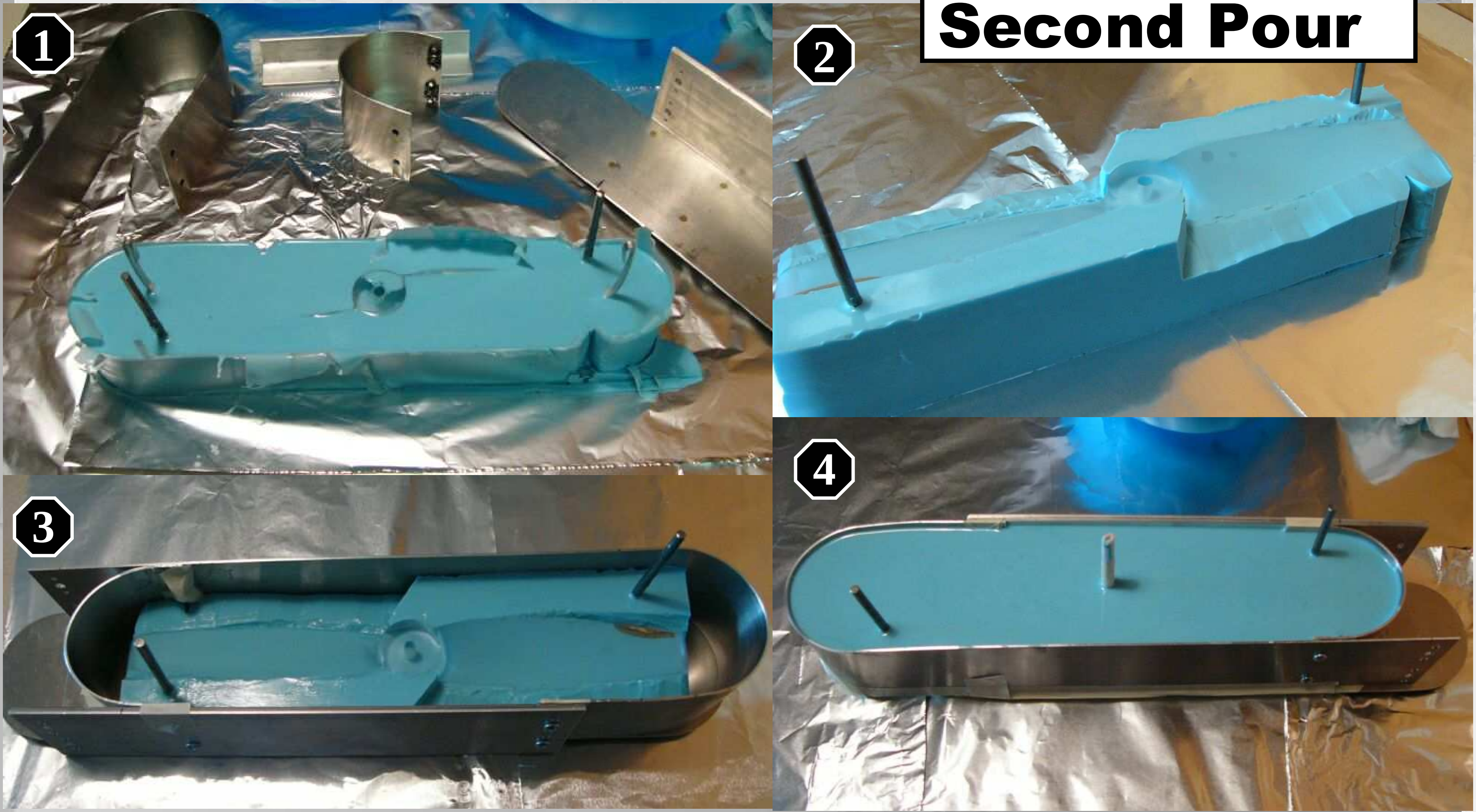
Mold Construction





Mold Construction

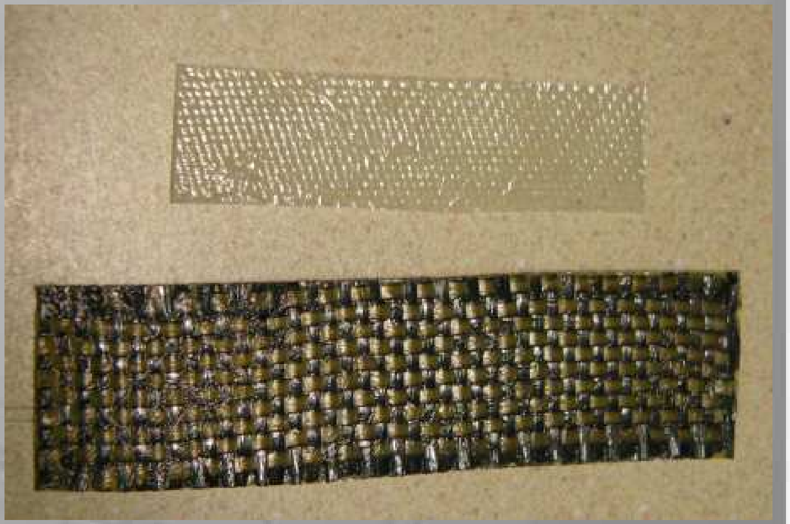
Second Pour



Composites Selection

- Carbon fiber
  - Higher bending resistance, lower impact resistance
  - Available from Solar Car Team
- S-glass
  - Higher impact resistance
  - Inexpensive, available
- Final Choice:
  - 3 layers of small weave S-glass was used on the outer surface of each blade (0-45-0) for impact resistance and surface quality
  - Strands of carbon used spanwise for first propeller, weave used for second propeller blade for stiffness
  - Hub filled with S-glass for first prop, Carbon for second

	Graphite Composite (aerospace grade)	Graphite Composite (commercial grade)	Fiberglass Composite
Cost $/LB	$20-$250+	$5-$20	$1.50-$2.00
Strength (psi)	90,000-200,000	50,000-90,000	20,000-35,000
Stiffness (psi)	10×10^6 - 50×10^6	8×10^6 - 10×10^6	1×10^6 - 1.5×10^6
Density (lb/in^3)	.050	.050	.055
Specific Strength	1.8×10^6 - 4×10^6	1×10^6 - 1.8×10^6	363,640 - 636,360
Specific Stiffness	**200×10^6 - $1,000 \times 10^6$**	**160×10^6 - 200×10^6**	**18×10^6 - 27×10^6**
CTE (in/in-F)	-1×10^{-6} - 1×10^{-6}	1×10^{-6} - 2×10^{-6}	6×10^{-6} - 8×10^{-6}

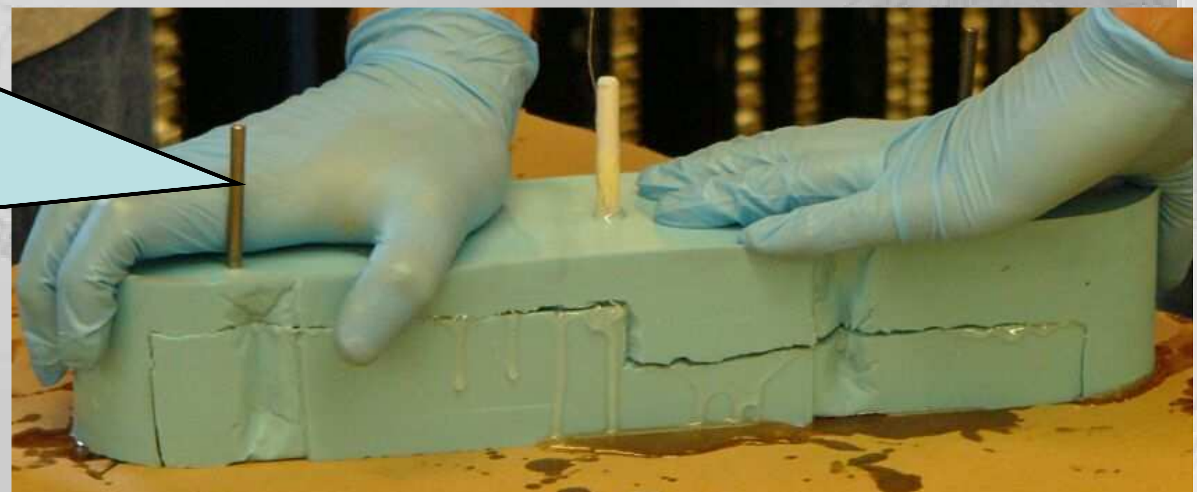


Composite Blade Lay-up

A pin in the hub maintains our mounting hole.

Composite Blade Lay-up

Locator pins helped to assure that the mold halves were properly aligned.



Resin was poured onto the final lay-up and excess resin was allowed to escape the sides of the mold.

Proplet Propeller

Trimmed up

2

Clear-coated for a better surface and balance

Reference Propeller

Proplets removed and balanced

Testing

- For comparison with the designed proplet propeller several propellers were tested
  - Final proplet propeller
  - First proplet propeller
  - First propeller without proplets
  - Wood propeller
  - Molded plastic propeller





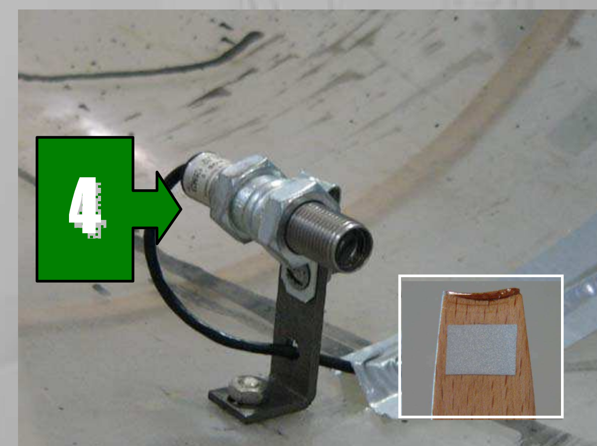
Testing Method

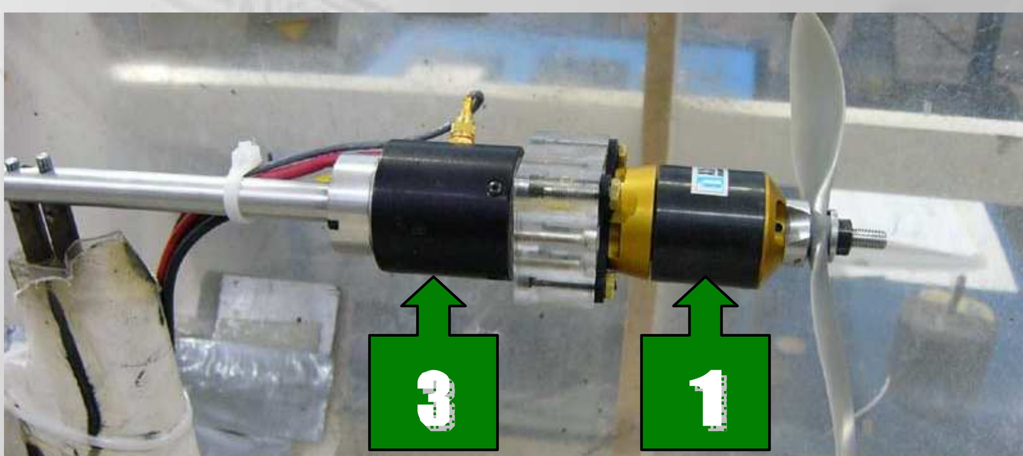
- **Need to Generate:**

– Free Stream Velocity	White Tunnel
– Rotation of Propeller	(1) Electric Motor (AXI 2826-12)
– Power for Motor	(2) DC Power Supply
– Voltage Control	Radio Controller and ESC

- **Need to Measure:**

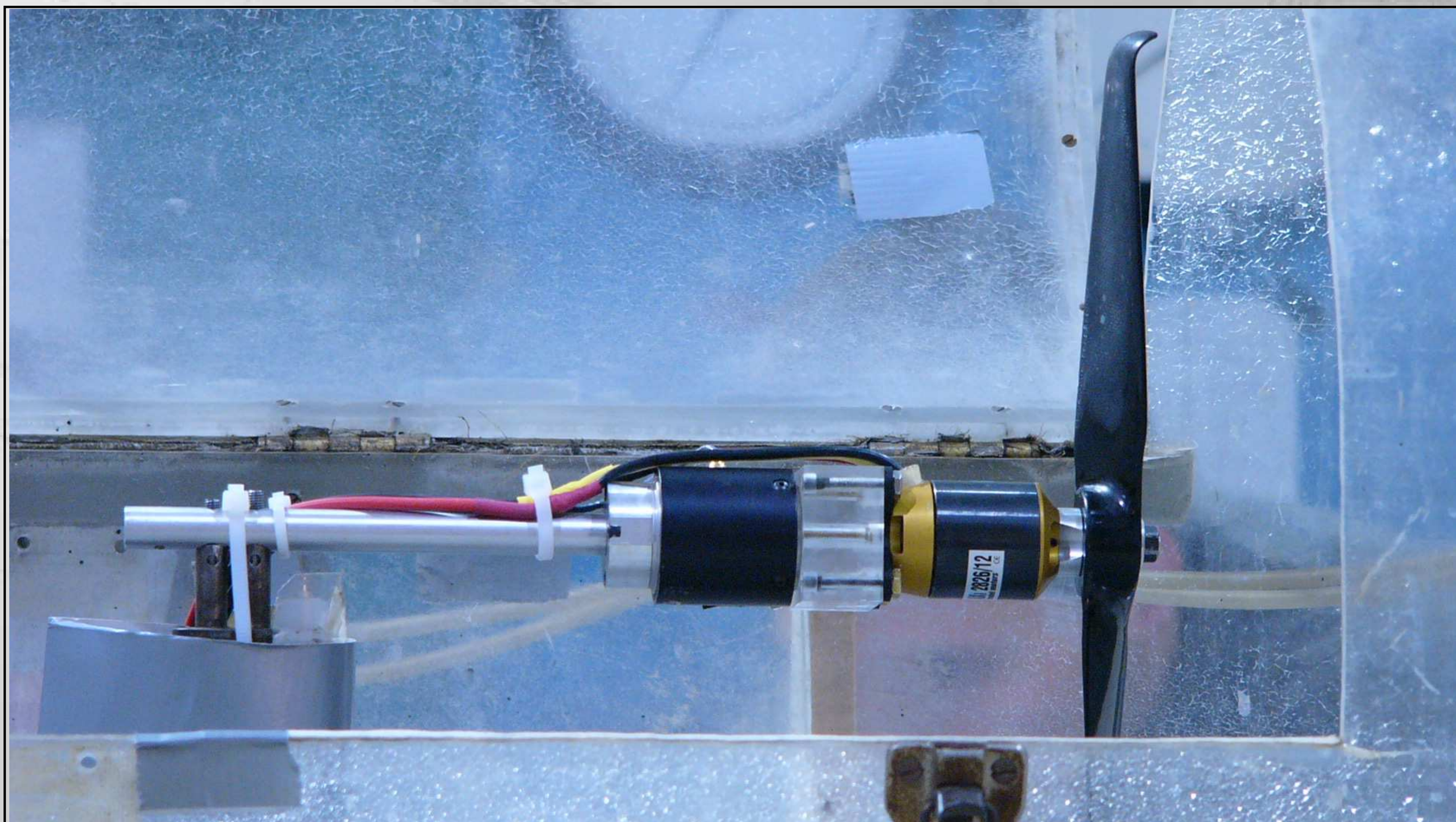
– Thrust (and drag)	Force Balance
– Torque	(3) 50 in-oz torque cell
– RPM	(4) Optical tachometer
– Power In (V and A)	(2) DC power Supply
– Free Stream Velocity	Pitot probe and Manometer





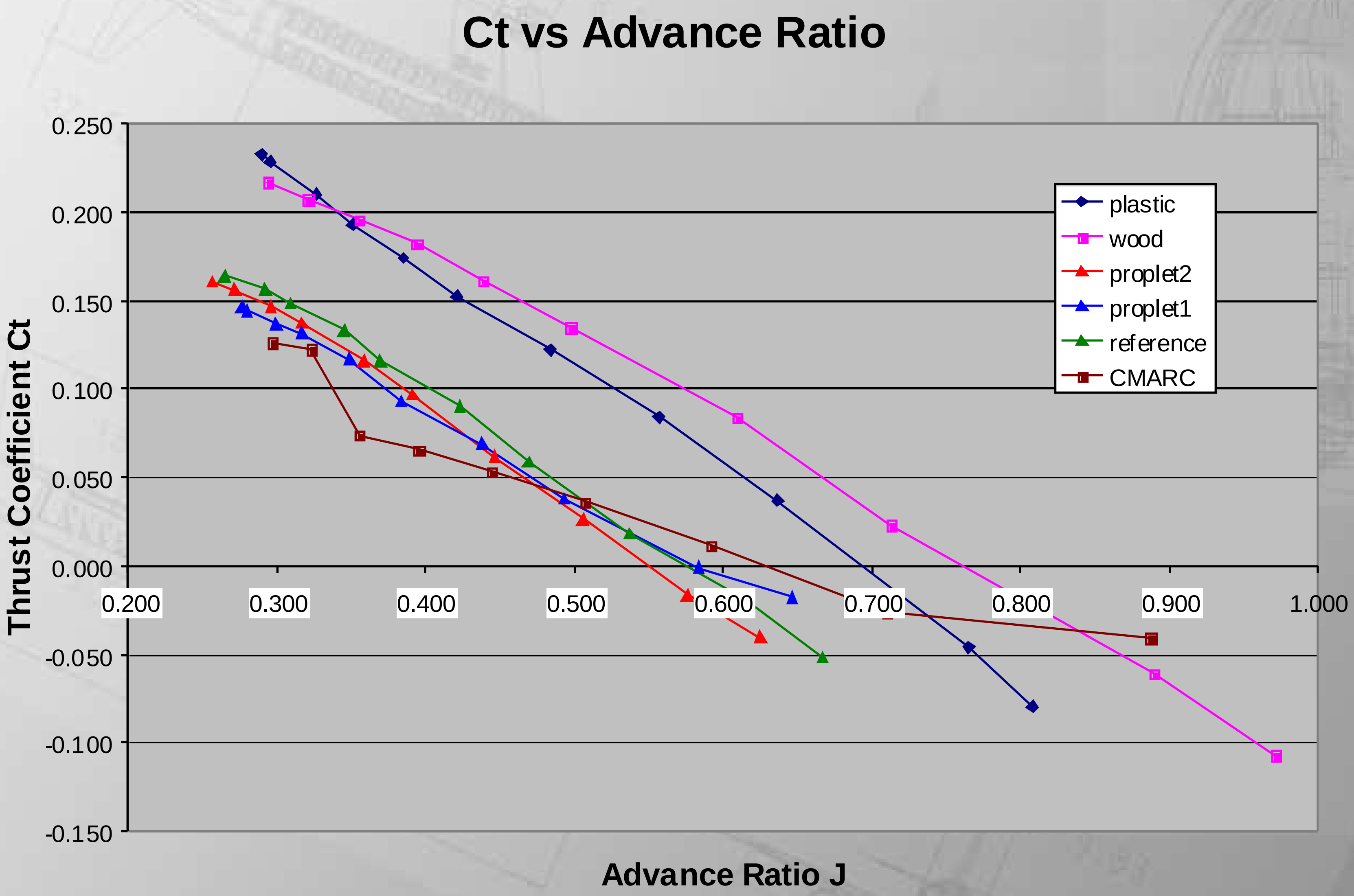
Test Apparatus

Motor Mount Assembly

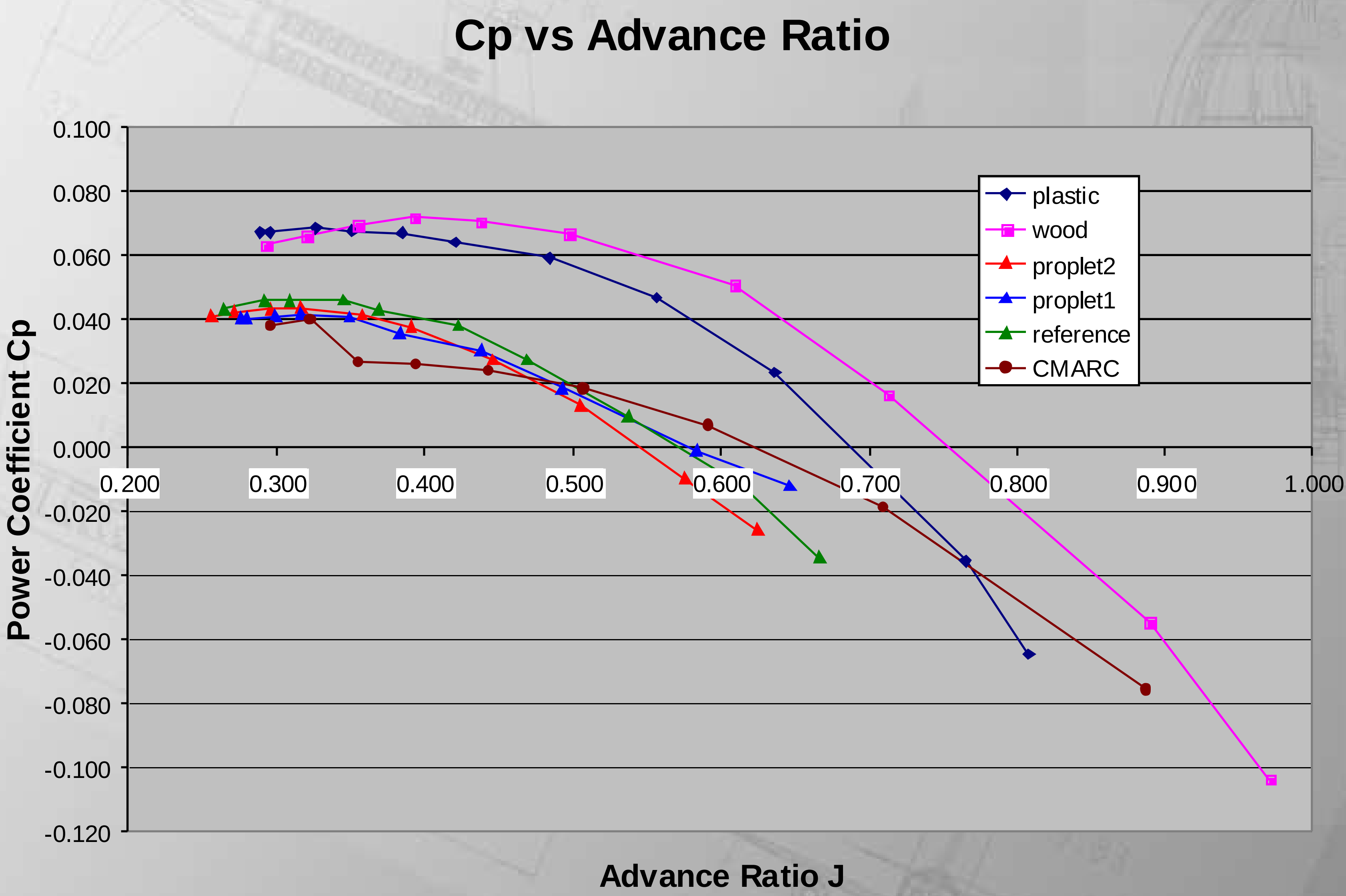


Testing Apparatus

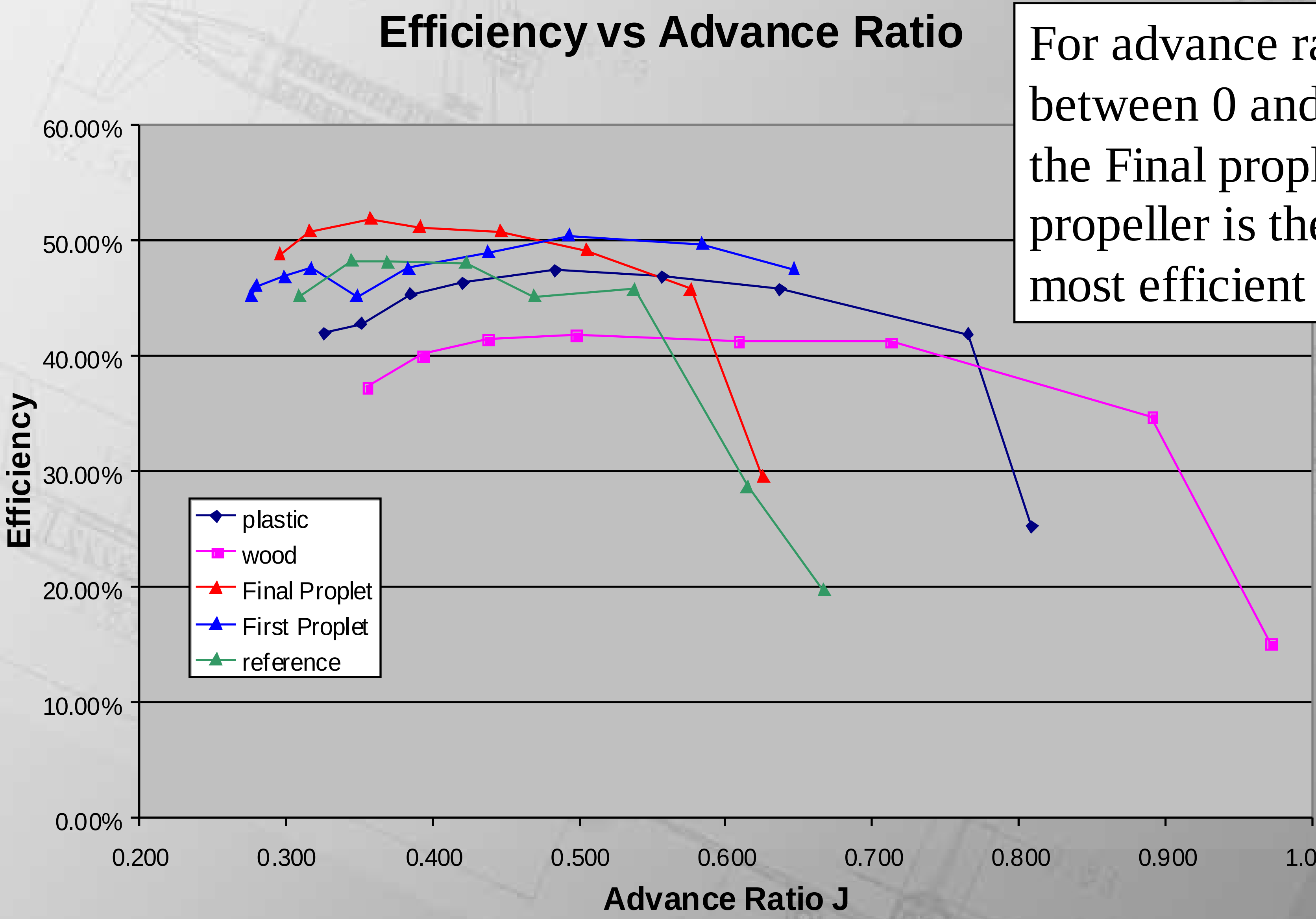
Test Results



Test Results

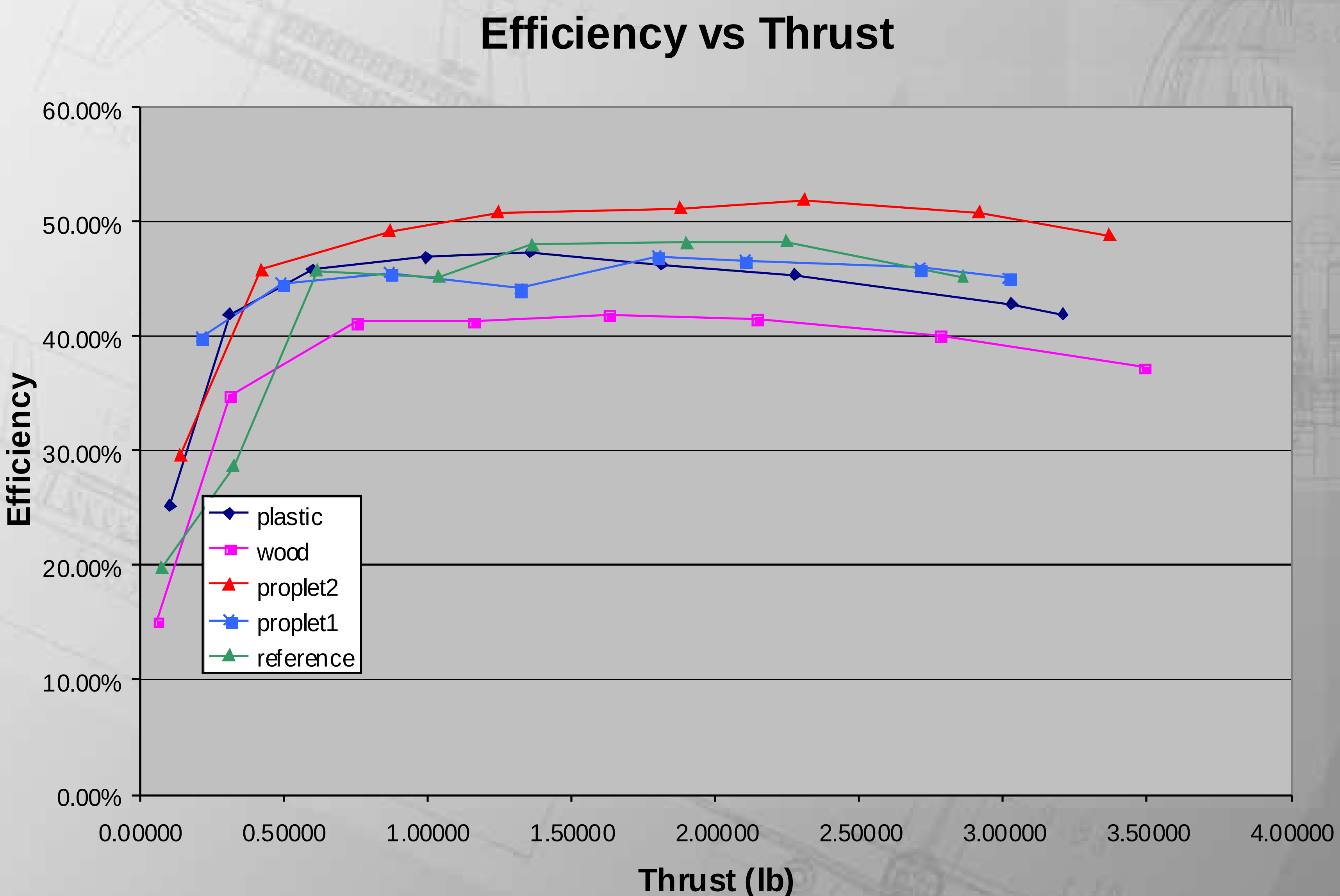


Test Results



For advance ratios between 0 and 0.6 the Final proplet propeller is the most efficient

Test Results



Conclusions

- Proplets can increase the efficiency of an RC size propeller
- The designed proplet propeller performs best at advance ratios lower than 0.6
- The designed propeller performs more efficiently then the currently used factory propellers for the HAA model
- To maintain a performance benefit, the proplets must be very thin
- Silicon rubber is an excellent mold material for making composite propellers
- A hybrid Fiberglass and CF layup can be used to make a propeller which is stiff and impact resistant
- CMARC is a good tool for simulating propeller performance where viscous effects are small but not when they are large as with this project

Design Recommendations

- Propeller would benefit from being thinner. Thickness was chosen for structural considerations and construction.
- Airfoil selection could be included in the optimization.
- Hub could be smaller and still structurally sound.
- With enough time and computing resources an integrated optimization could be used to improve the design.
- Genetic algorithm would be a better fit for this multi modal design space than an SQP optimization.
- Integrating structural analysis into optimization could yield a better design.
- An aerodynamic analysis tool that includes viscous effects would also increase propeller performance.

Lessons Learned

- Optimization is hard and very time consuming
- Cutting something small and thin on the CNC machine is very difficult
- Secure propeller nut VERY tightly (or conduct impact resistance test)