Critical Feature and Seawater Testing

Of Cross-Flow Rotor Components Fabricated with Additive Manufacturing

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U.S. DEPARTMENT OF ENERGY BATTELLE

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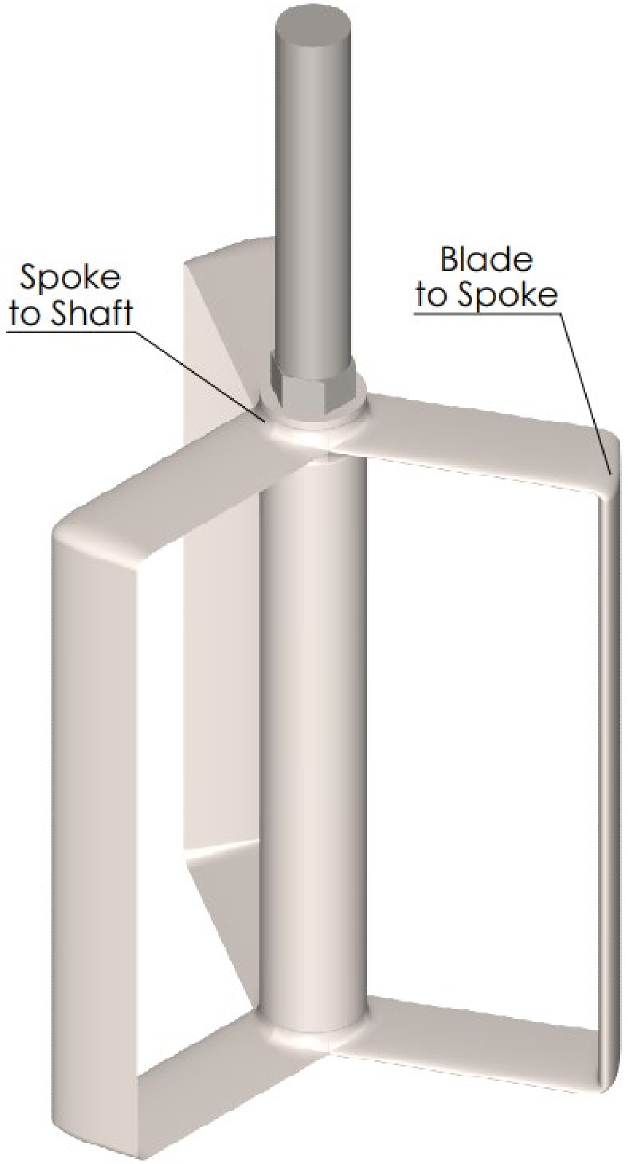
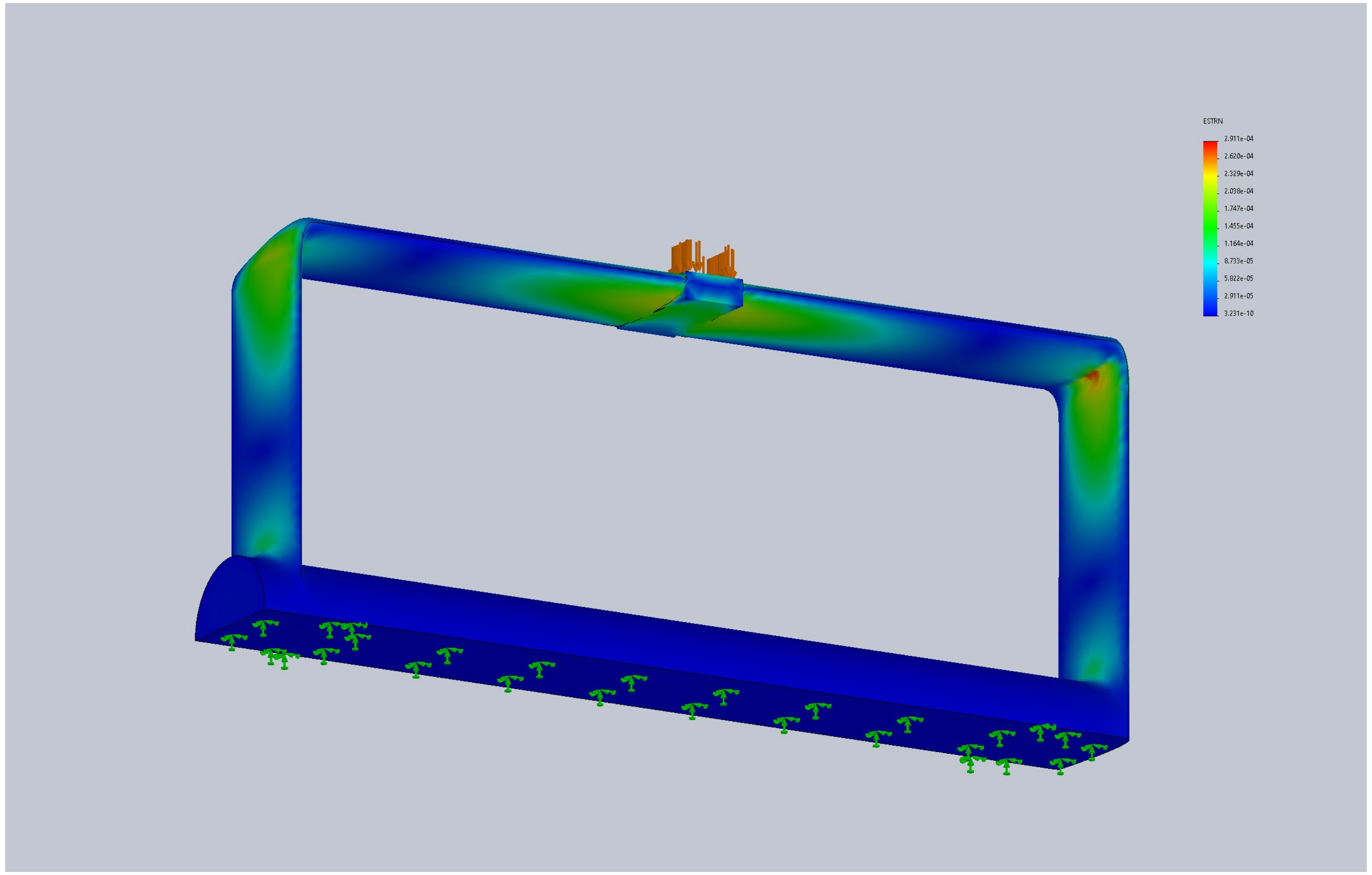
Motivation

- Cross-flow turbines may be suitable for remote locations or distributed loads
- Have critical features prone to failure
- The topology of these turbines allows these critical features typically assembled with joints to be printed as single parts
- Additive manufacturing (AM) techniques are still rapidly evolving, including for producing parts from high-performance metals and polymers
- We seek to determine if existing AM processes and materials are suitable for this application and for use in marine energy, in general

Cross-Flow Turbines - Overview





AM Processes and Material Selection

- Many choices for process and material
- Requirements – highest to lowest ranking
  - Fatigue life/limit
  - Strength to weight ratio
  - Corrosion resistance
  - Toughness
  - Elastic modulus
  - Water uptake
  - Surface finish
  - Cost of material
  - Cost to print
  - Biofouling potential

AM Processes and Material Selection

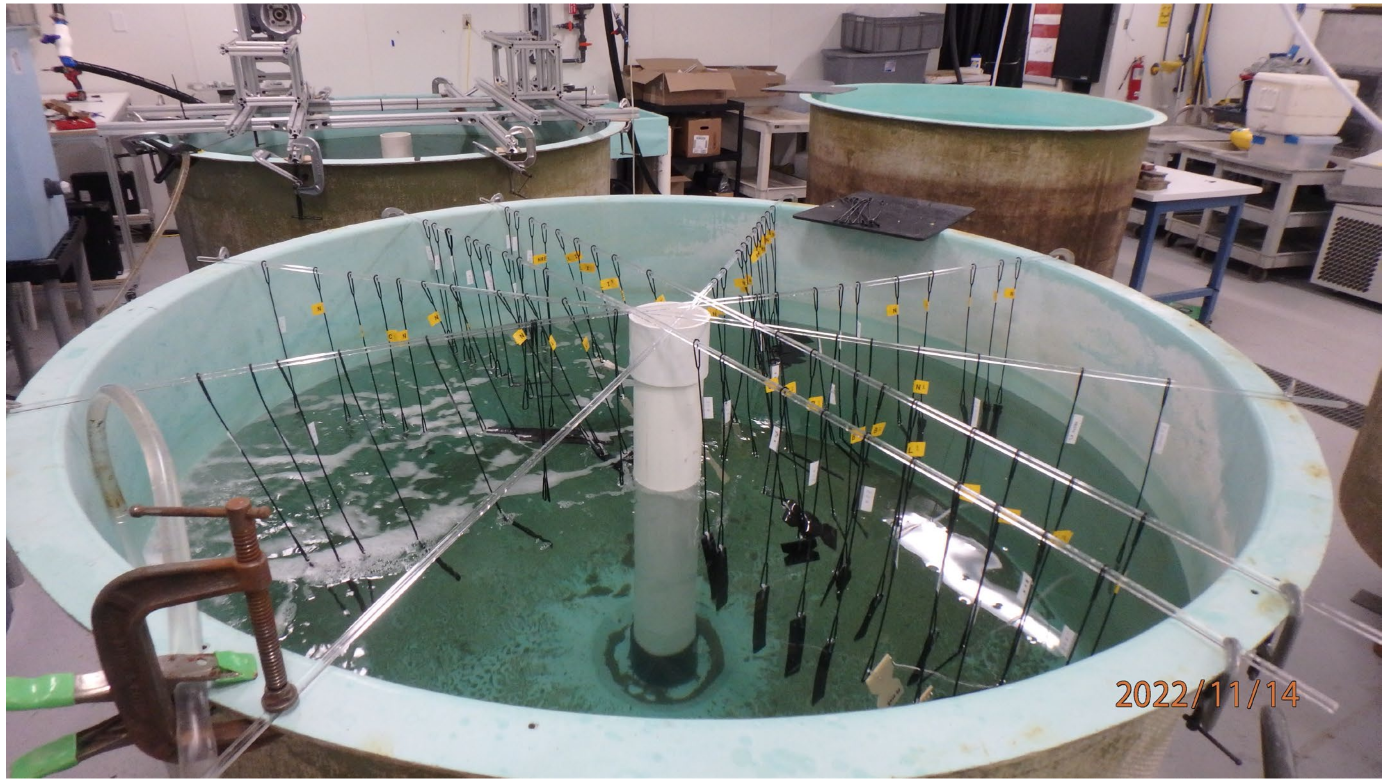
			FDM							DMLS	
		Datum Option	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7	Option 8
Design Criteria	**Weight [0,4]**	CNC-machined 6061 Al	PEKK	CF PEKK-A	**Nylon (Essentium CF-25)**	CarbonX Ultem 1010	**Nylon (Onyx)**	CarbonX Ultem 9085	**Inconel 718**	**Ti-6Al-4V**
Fatigue life/limit	4	0	1	1	1	1	1	1	3	3
Strength to weight ratio	3	2	2	2	3	3	3	2	0	1
Corrosion resistance	3	0	4	4	4	4	4	4	4	4
Material toughness	3	3	1	1	1	1	1	1	4	4
Elastic modulus	2	2	1	1	1	1	1	1	4	4
Water uptake	2	0	0	0	0	0	0	0	0	0
Surface finish	2	4	1	1	1	1	1	1	3	3
Cost of material	2	4	3	3	3	3	3	3	1	1
Cost to print	2	2	3	3	4	3	4	3	0	0
Biofouling	1	0	0	0	0	0	0	0	0	0
Sum		39	41	41	**46**	44	**46**	41	**52**	**55**

Seawater Tank Testing

Bay-to-bench lab capability

- Continuous flow of raw seawater
- Ensures consistent conditions with natural environment

PNNL-Sequim (Washington State, USA)



Material Sample Tank

Seawater Tank Testing

Seawater Conditioning

- Printed coupons suspended with non-conductive materials
- Samples were labeled and weighed to the nearest 0.1g and conditioned 11/14/2022 - 4/20/2023
  - Timing limited biological growth
  - Monthly photo documentation for corrosion and biofouling
- Samples removed, photographed, and wiped clean with a cloth to remove growth and surface moisture, then weighed a second time
- Final tensile testing performed to quantify the effects of seawater

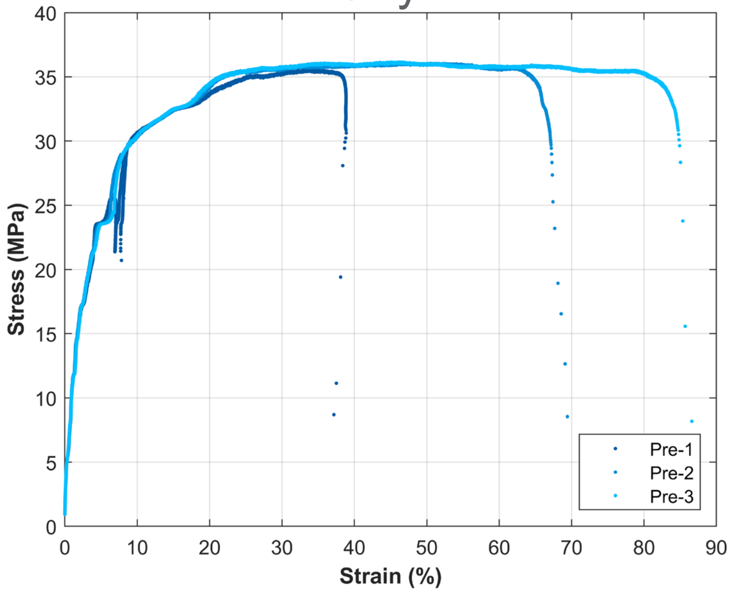
Tensile Tests

Material Testing Methods

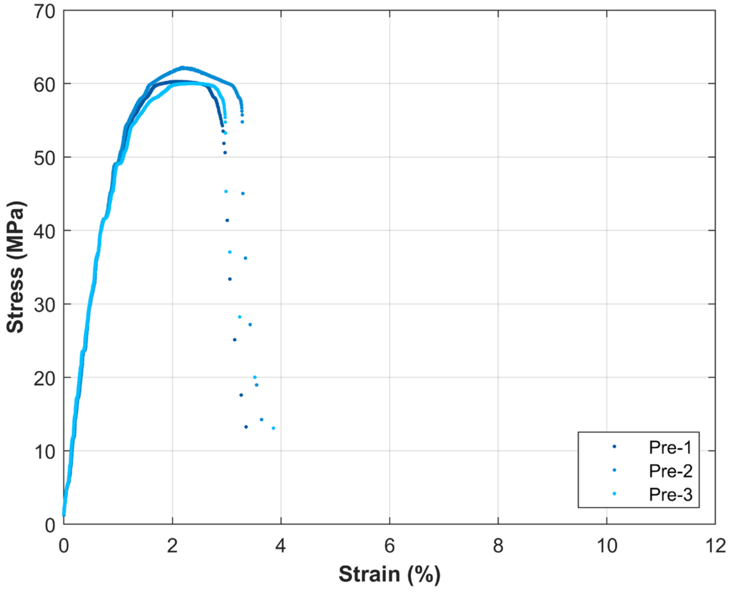
- Three dogbone-shape samples of each material were tensile tested on an Instron 5582 load frame with a strain rate of 0.45 mm/m to failure
  - Metal dogbones - ASTM E8 Standard, 30kN load cell, and 13.3 N preload
  - Plastic dogbones – ISO 527, Type 1BA Standard, 5kN load cell, and 10 N preload

Material Sample Testing – Pre-Conditioning

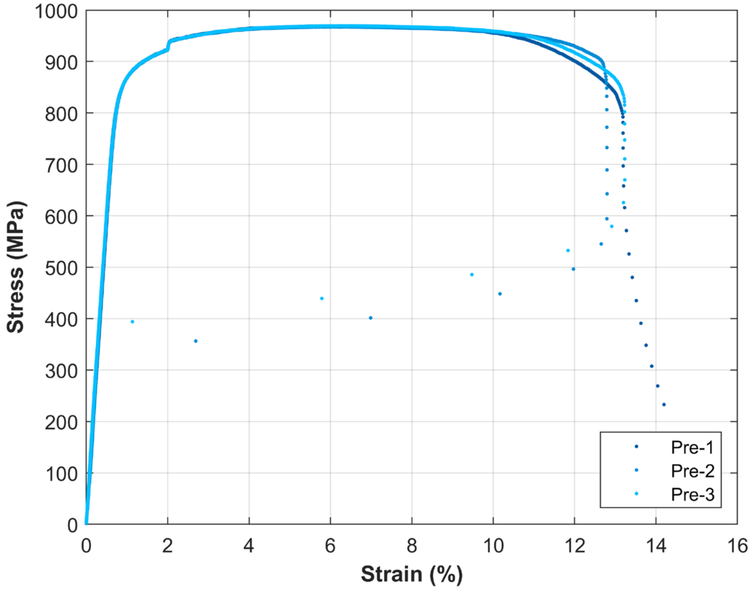
Onyx



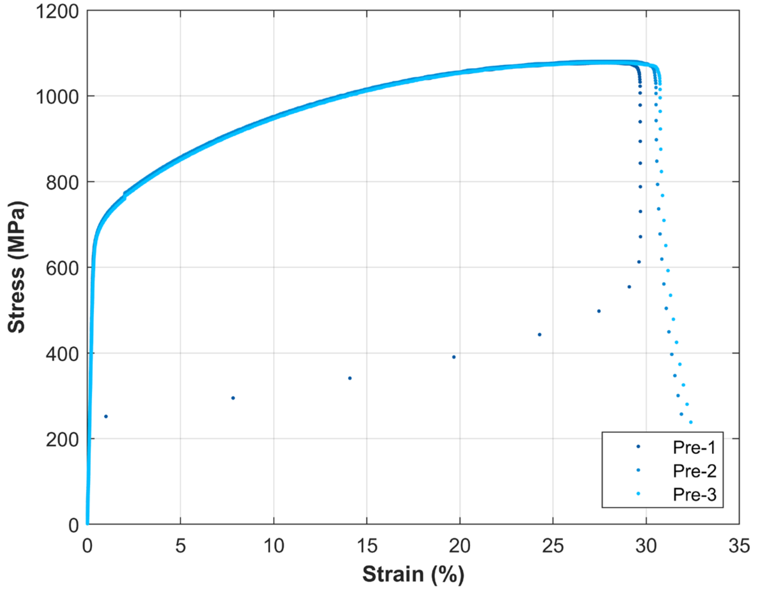
Essentium



Titanium

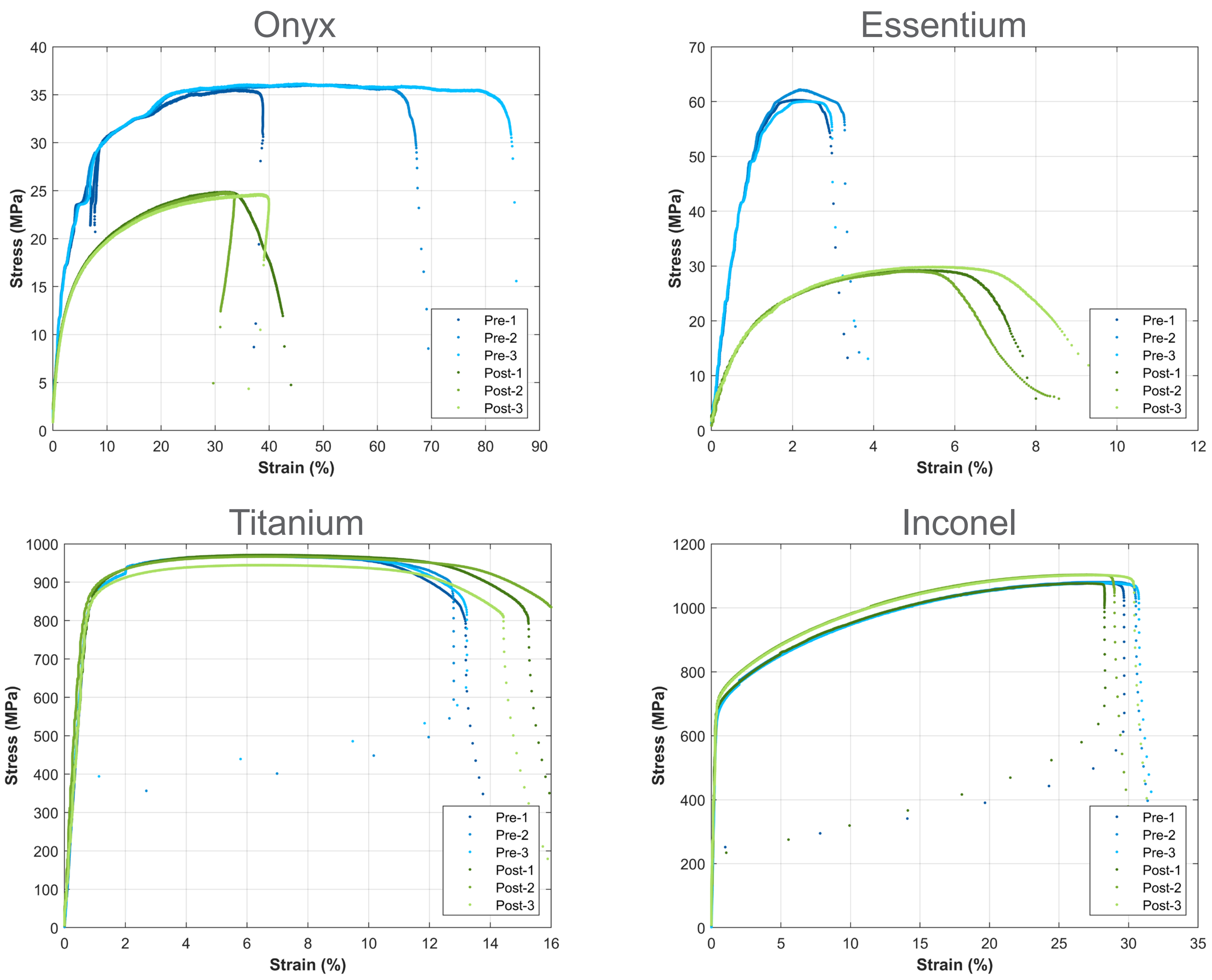


Inconel



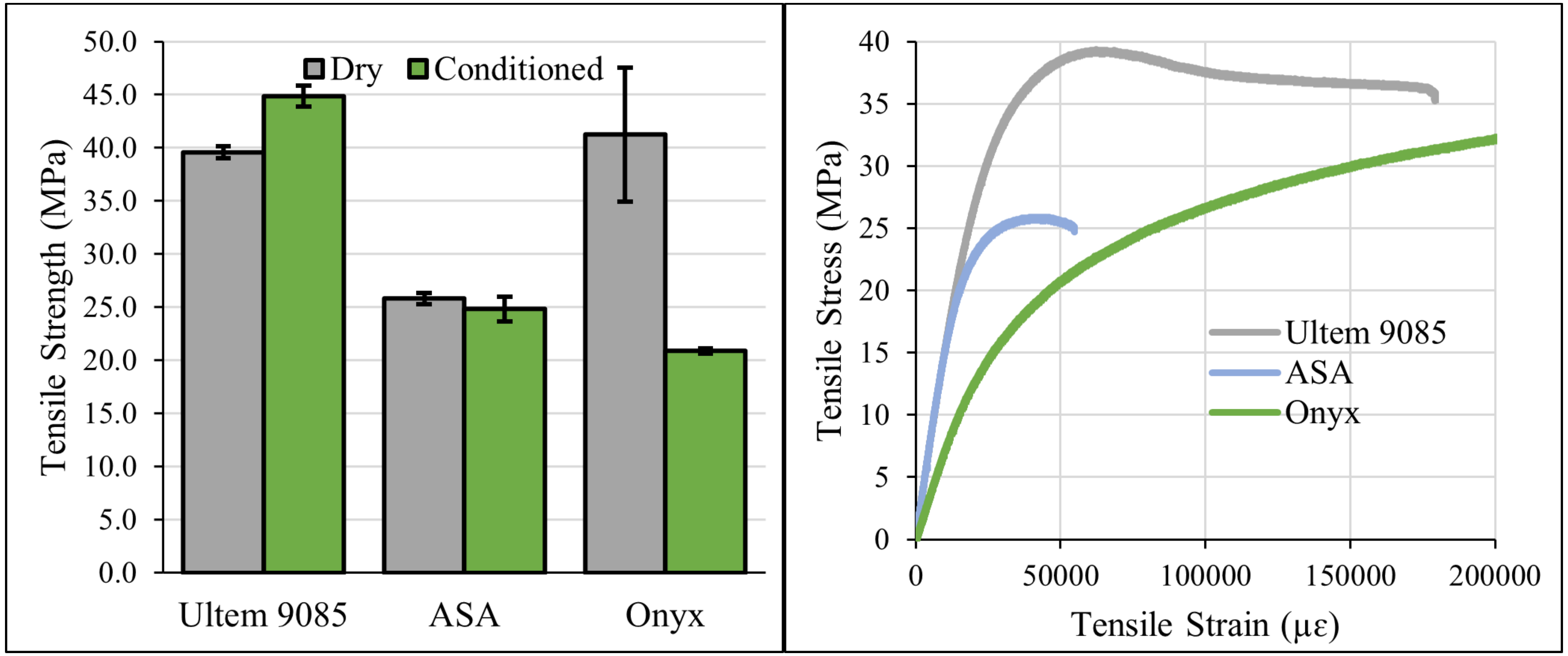
Elastic Modulus [MPa]	Pre-Conditioning
Markforged Onyx	2450
Essentium CF-25	6920
Titanium (Ti-6Al-4V)	121600
Inconel 718	205000

Material Sample Testing – Post-Conditioning



Elastic Modulus [MPa]	Pre-Conditioning	Post-Conditioning	Change [%]
Markforged Onyx	2450	685	-72.0
Essentium CF-25	6920	2164	-68.7
Titanium (Ti-6Al-4V)	121600	121500	-0.1
Inconel 718	205000	182500	-10.9

Material Sample Testing – NREL Samples



Murdy, Paul, O'Dell, Joshua, Barnes, David, McVey, James R., and Rumple, Christopher. *Investigating Marine Environmental Degradation of Additive Manufacturing Materials for Renewable Energy Applications: Preprint*. United States: N. p., 2023. Web.

Material Sample Testing Conclusions

- DMLS metal printing of titanium and Inconel produced material samples with stress-strain behavior in-line with standards for materials
- Printed metal parts showed no degradation in performance over the conditioning period
- Carbon-reinforced nylon materials exhibited significant degradation over the conditioning period
- Impressive performance of metal parts warrants further consideration for use
  - Cost is currently high: $2000 for a printed 2-bladed rotor (20x17 cm)
  - Sizes are limited, but technology is rapidly advancing

Rotor Printing: Metals

- Quality results on DMLS vary significantly based on design, material, and vendor
- => Difficult and expensive to produce metal parts consistently
- => High-strength, non-reinforced thermoplastics might be more cost effective

Rotor Printing: *Formlabs* Thermoplastics

- Saw promising results from Ultem 9085
- *Formlabs* GreyPro and Rigid-10k have similar material characteristics to Ultem family
- Currently conducting seawater conditioning on *Formlabs* materials

	Ultem 9085	**Grey Pro**	**Rigid 10k**
Elongation at break [%]	5.4	13	1
UTS [MPa]	68	61	55
Modulus [GPa]	2.5	2.2	9

Flume testing at University of Washington

- Design: print rotor, buy shaft, clamp together
- Print 1- and 2-bladed rotors
- Print 2 different strut-blade joints
- Goal: inform loading on blade for fatigue testing

Flume testing at University of Washington

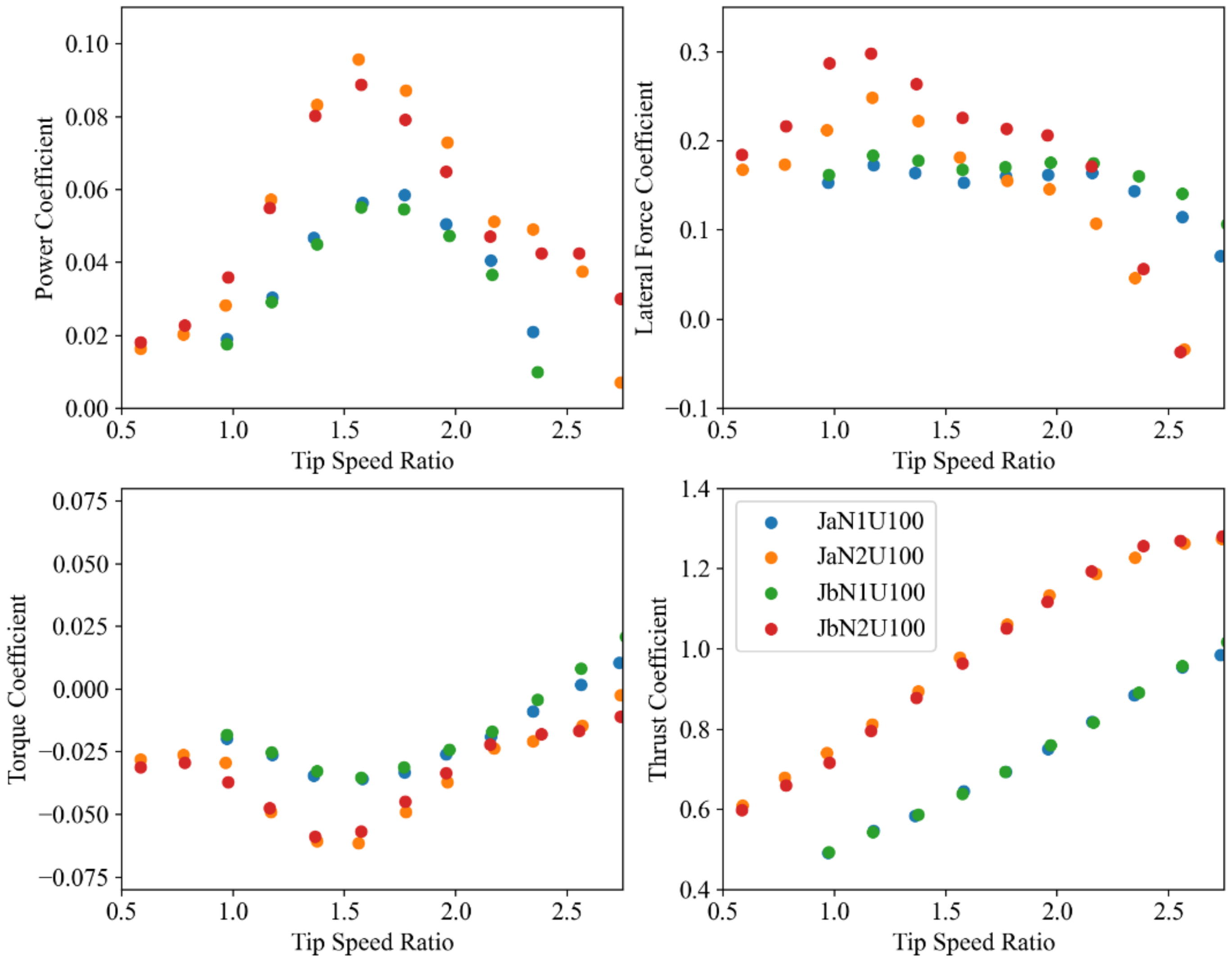
Tests run:

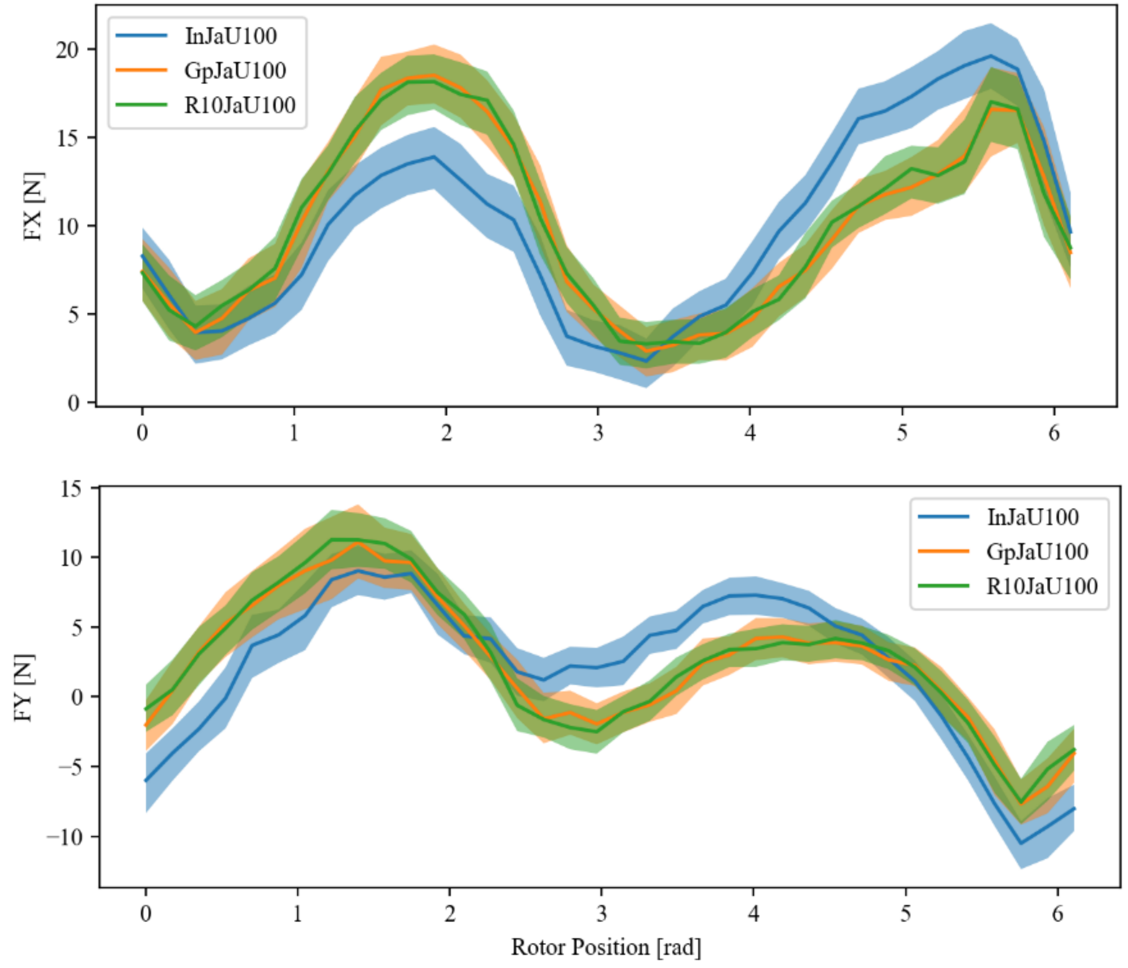
- Power coefficient curves
- Multi-axis phase-resolved loads
- Flow speeds at 0.75 and 1.0 m/s, 20 degC
- TSRs between 0 and 4

Rotor stats:

Radius (cm)	8
Chord length (cm)	3
Height (cm)	19

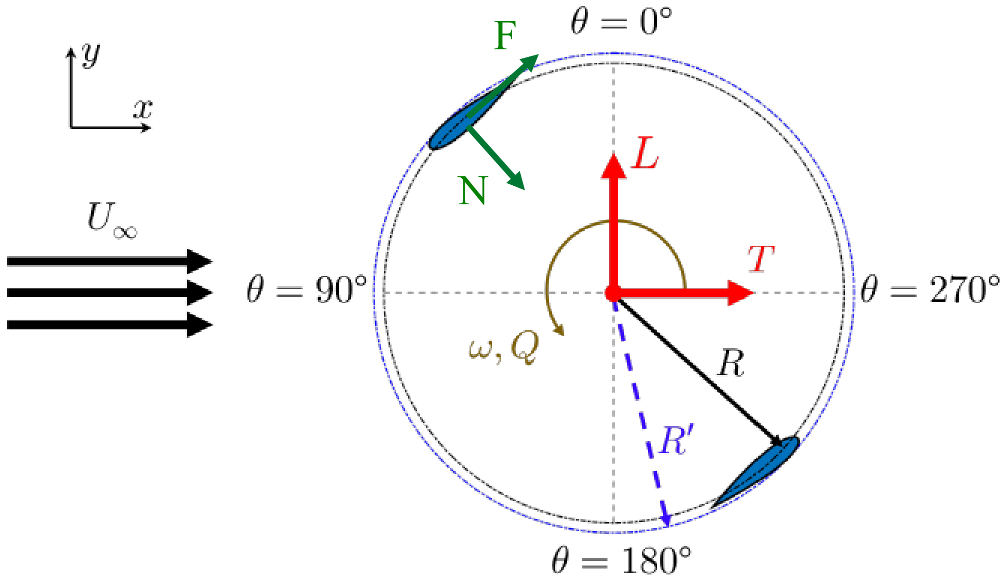
Flume testing at University of Washington

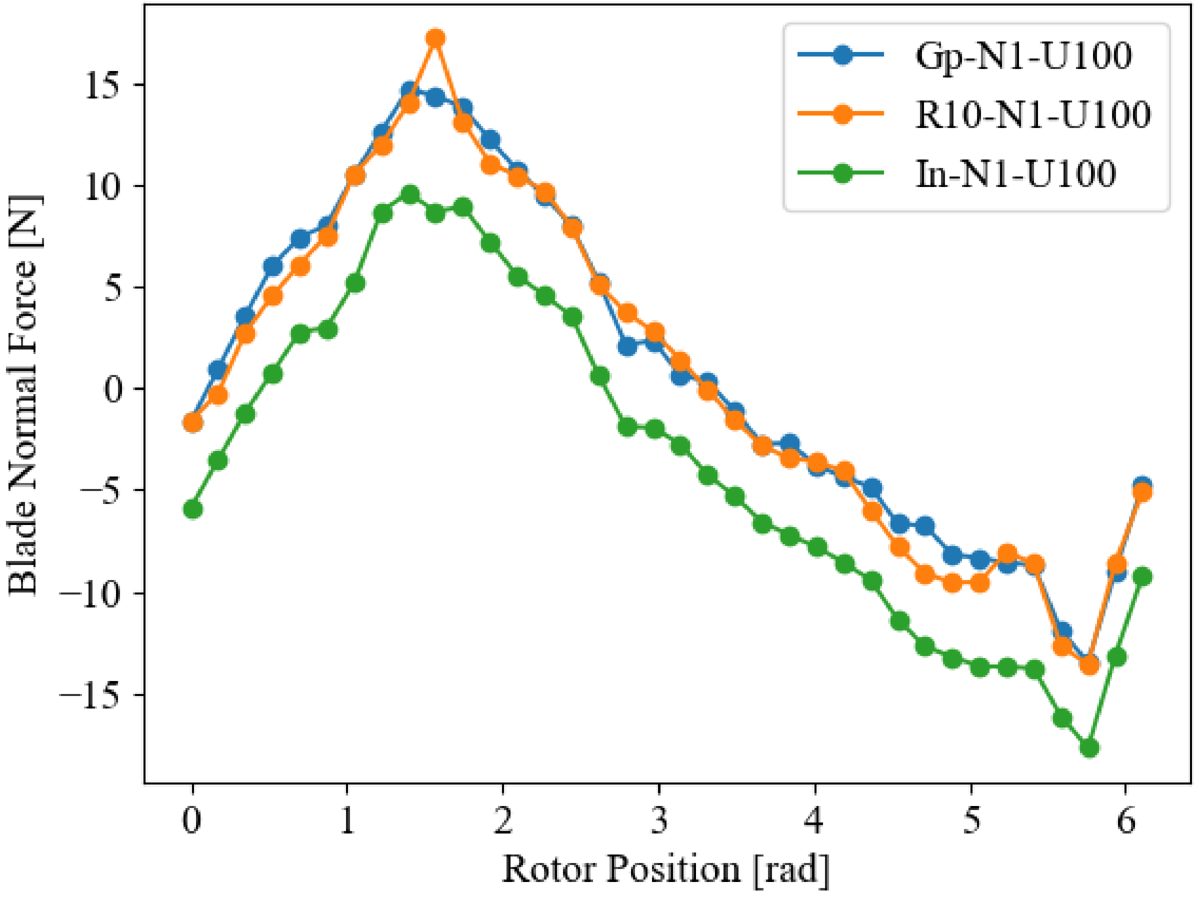




Flume testing at University of Washington

- Find normal force on single blade from measured lateral and thrust forces

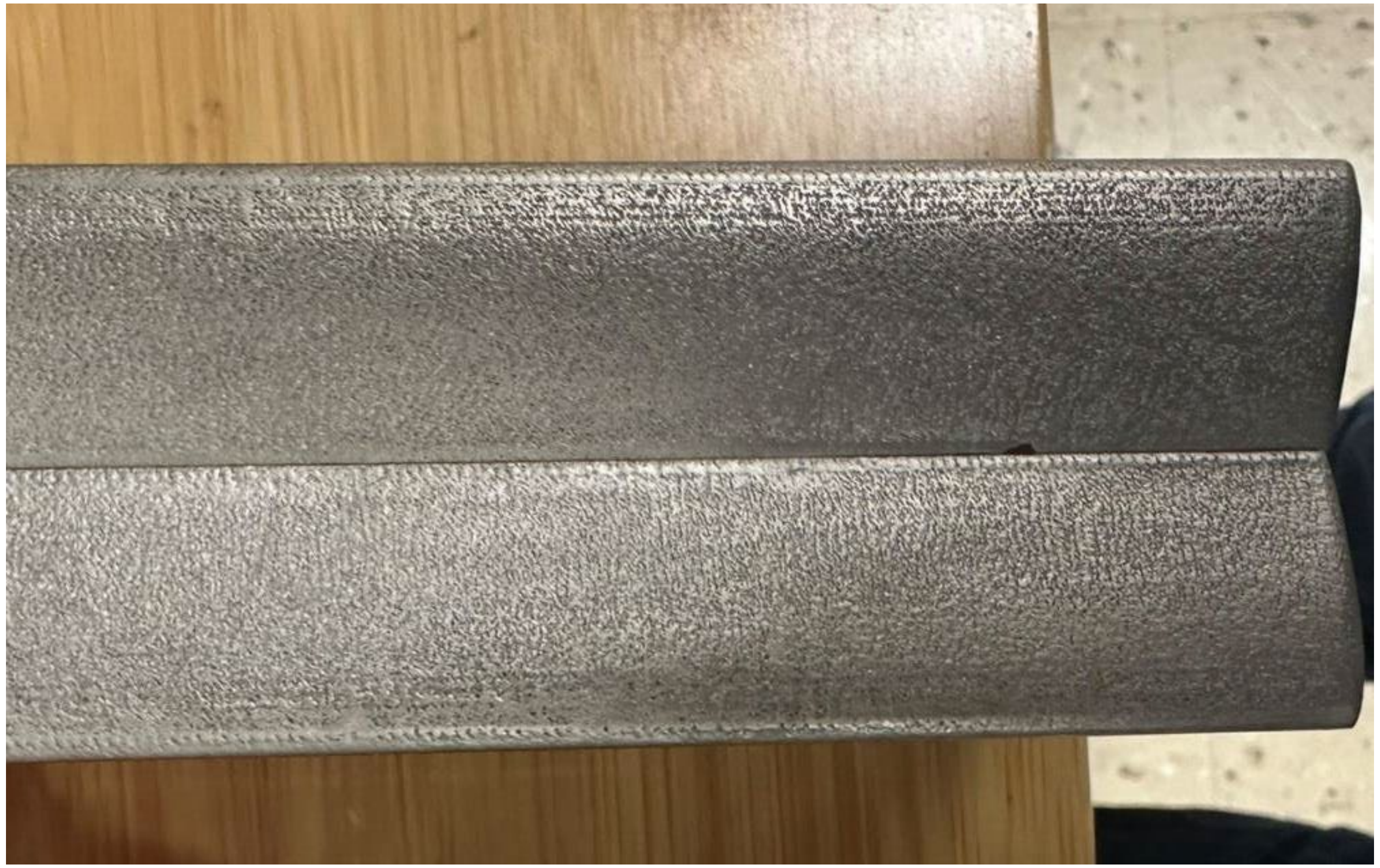




Hunt, Aidan, et al. "A parametric evaluation of the interplay between geometry and scale on cross-flow turbine performance." arXiv preprint arXiv:2310.20616 (2023).

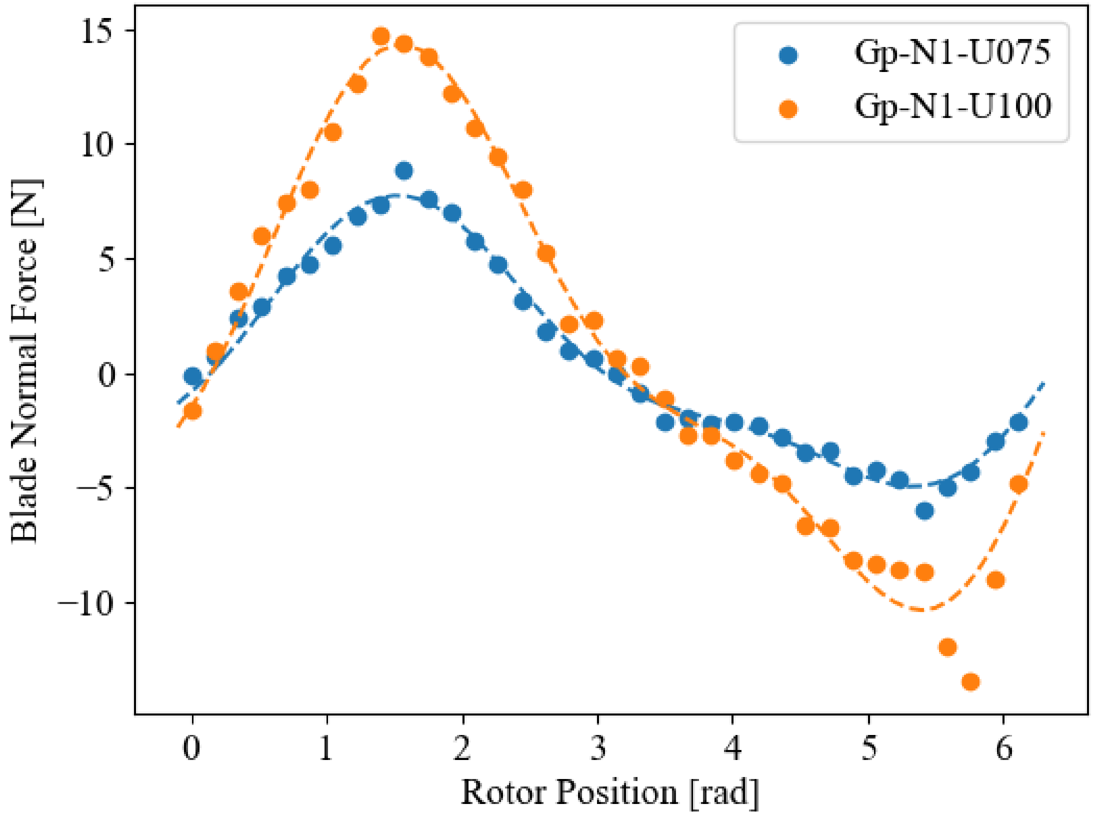
Metal Surface Finish

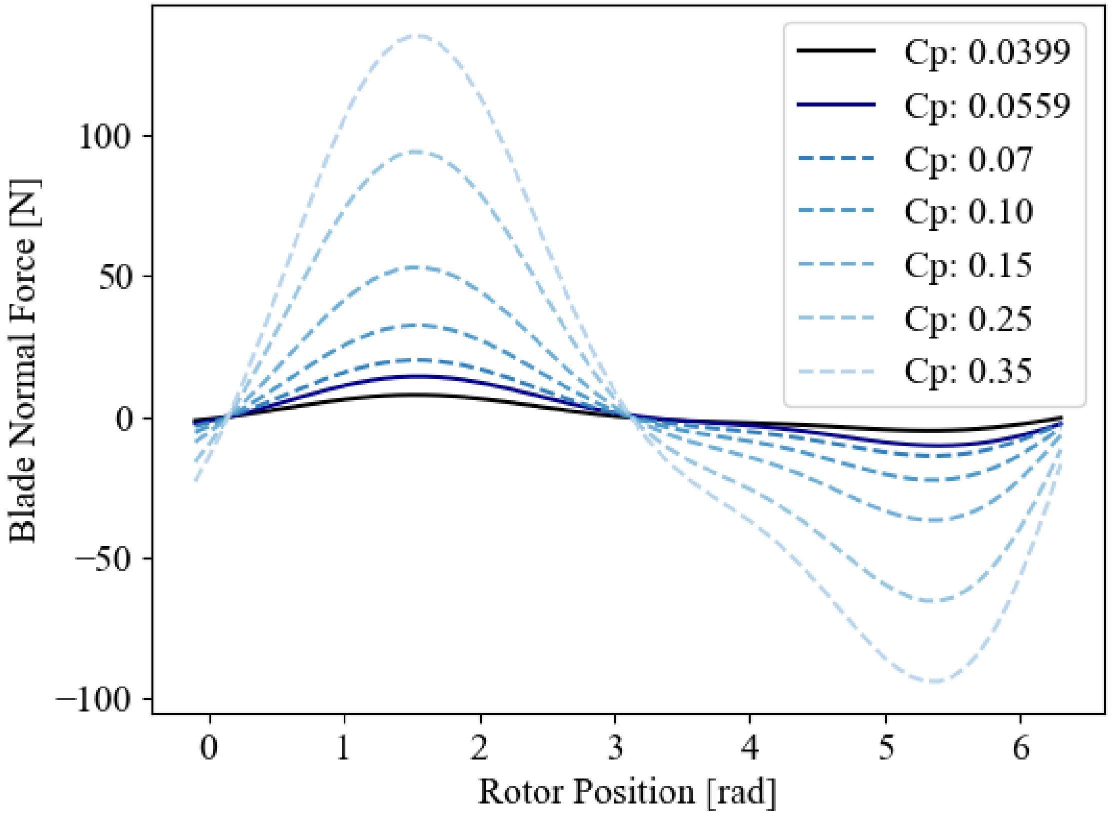
- Difference in power coefficient likely related to surface finish
- Currently conducting roughness measurements with profilometer



Informing Fatigue Testing

- Least-squares optimization on sinusoidal equation
- Extrapolate normal force curve to higher power coefficients
- Need higher performance rotors to validate this approach





Flume Testing Conclusions

- Power coefficient lower than desired – preset blade pitch angle likely too high
- Negligible difference in performance between both blade-strut designs
- Difference between normal force curves likely because of surface finish
- Fatigue load tests would benefit from improved rotor design

Next Steps

- Improve rotor design
- Run rotors through fatigue cycling on mechanical load frame
  - Compare printed blade-strut designs to bolted blade-strut design
- Biofouling tests on coated vs uncoated rotors

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Thank you

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