Performance Analysis and Data Processing for the High Solidity Test Campaign in the Jet Propulsion Laboratory 25-ft Space Simulator

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Outline

- Background
- Experimental Test Campaigns
- Motivation
- Test Objectives and Impact
- Test Set Up
  - Facility
  - Hardware
  - Conditions
  - Test Matrix
- Data Collection and Processing
- Results
- Summary and Conclusions

Background

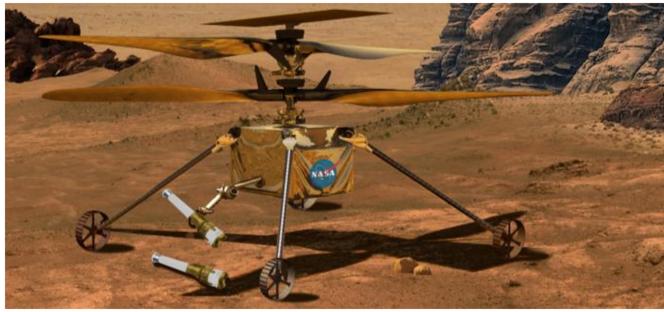
Ingenuity (2015 – 2024)
- First flew on Mars in 2021
- Flight technology demonstrator

Sample Recovery Helicopter (SRH) (2022 – 2024)
- Conceptual design for recovering sample tubes

Rotor Optimization for the Advancement of Mars eXploration (ROAMX) (2020 – 2025)
- Advanced Mars rotor design using optimization tool

Higher Payload Concept Vehicles (2019 – 2025)
- Mars Science Helicopter (MSH)
- Chopper

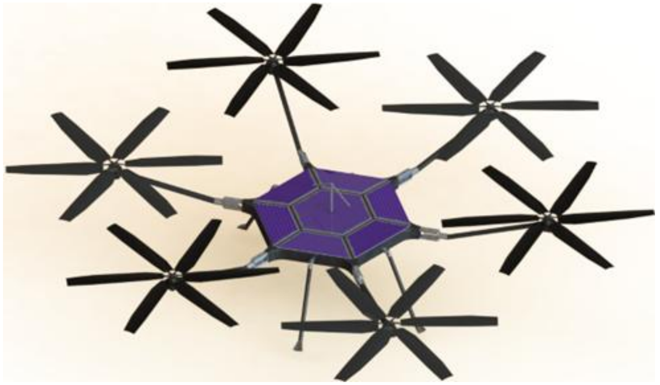
Ingenuity



SRH

ROAMX

Chopper

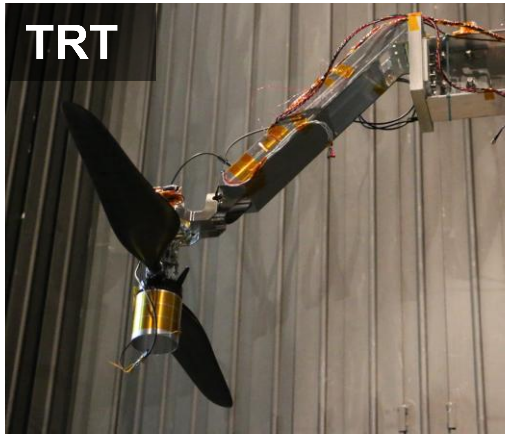


MSH

Experimental Test Campaigns

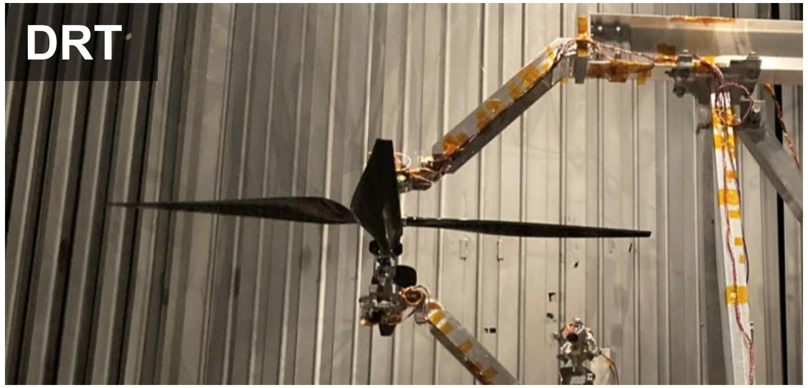
Engineering Development Model- (EDM-1) and Transonic Rotor Test (TRT)

- Ingenuity rotor to see how much lift can get, in anticipation of Sample Return Helicopter (SRH)
- Increase in collective pitch and RPM



Dual Rotor Test (DRT) for SRH

- Model used to assess performance gains with redesigned rotor blade (increased area and optimized planform/twist) to meet SRH lift requirements



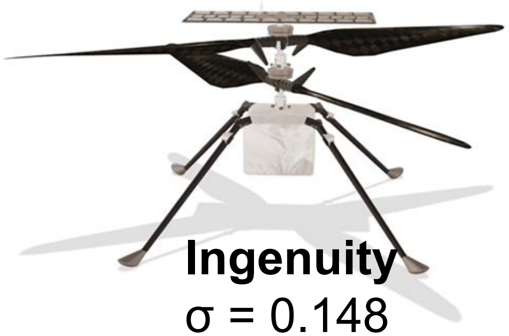
High Solidity Test (HST)

- Chopper (with ROAMX airfoils), to see effect of high solidity

Motivation for High Solidity Test (HST)

- Rotor designs typically have solidities (σ) of ~0.04 - 0.15
- Future Mars missions will require increased payload/range/endurance for a fixed size, therefore **more lift needed** *(Example: Mars Science Helicopter and Chopper)*
- More blade area gives thrust **and** better efficiency
  - **High rotor solidity** (different planform and blade number) affects performance as measured by FM vs C_T/σ

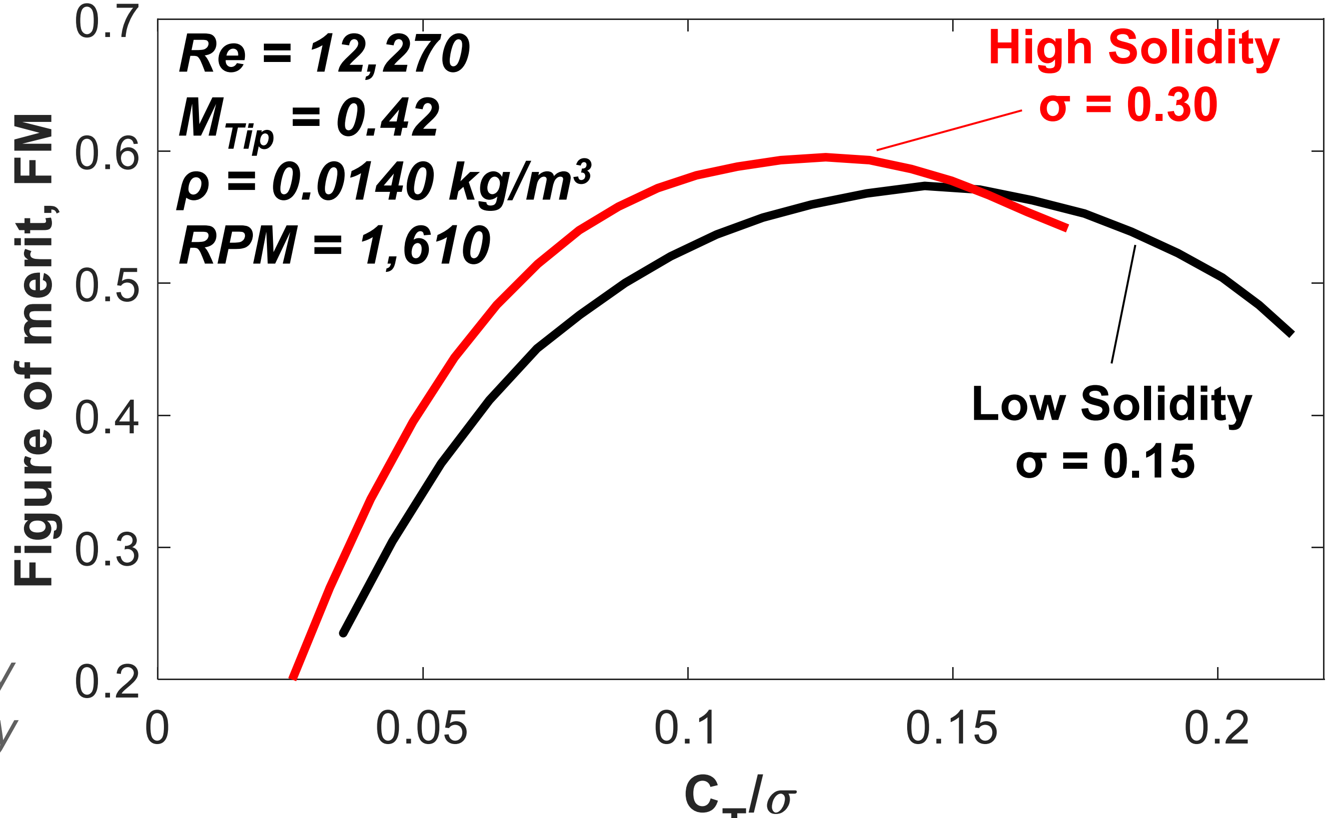
Aircraft Design I, Technical Session C: Wednesday at 2:15 PM - 2:45 PM "Optimization of High Solidity Rotor Performance in a Martian Environment"



Ingenuity
σ = 0.148

UH60
σ = 0.0826

CAMRAD II predictions for HST rotors



Test Objectives and Impact

Mars Exploration Program (MEP) funded a joint test campaign between NASA's Jet Propulsion Laboratory, NASA Ames Research Center, and AeroVironment, Inc. to validate performance predictions for low- and high-solidity rotor variants at Mars pressures.

Objectives

Characterize the performance of increased thrust-weighted solidity

1. Low solidity (3-blades)
2. High solidity (6-blades)

Results will aid in future Mars rotorcraft development by providing data for validation efforts

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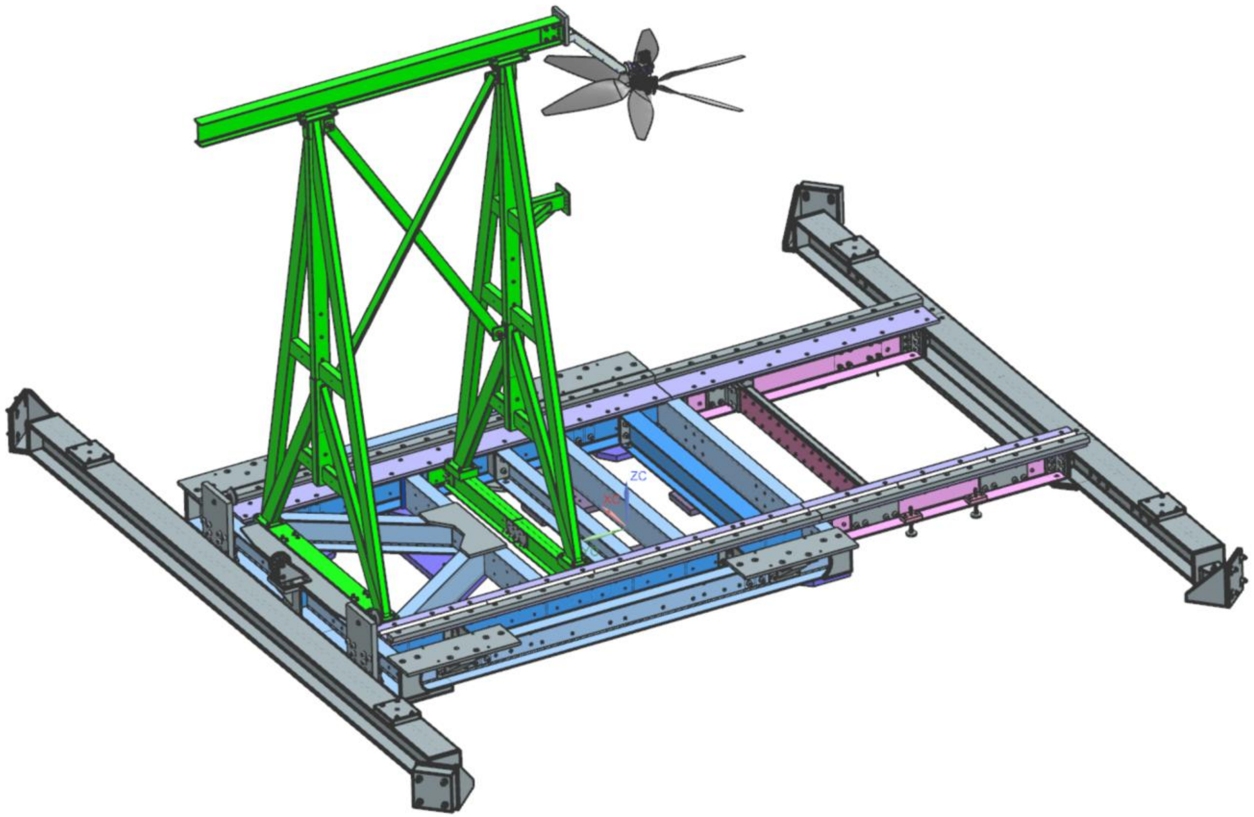
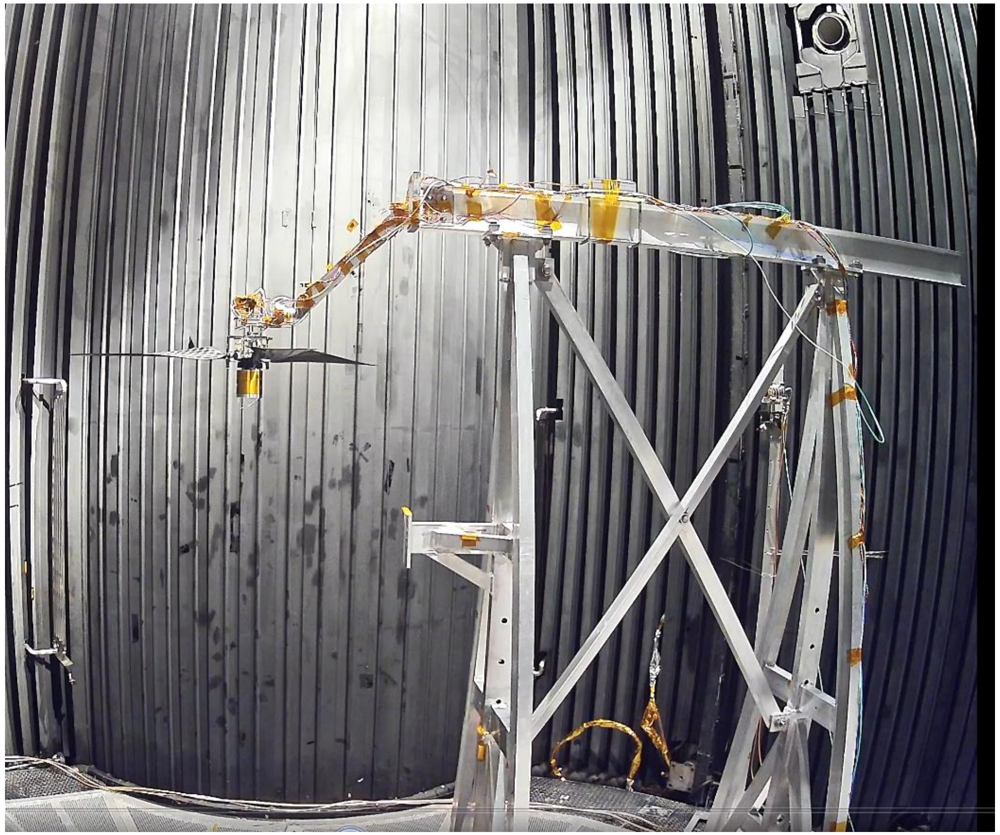
Testing Facility

- 25-ft Space Simulator located at NASA's Jet Propulsion Laboratory
  - Evacuated of all air and then backfilled with CO_2 to the target density
  - Temperature not controlled for this test (19 – 27 degrees Celsius)

Test setup

- Low and high solidity test articles mounted in the 25-ft Space Simulator
- Test articles supported on gantry
- Instrumentation included force/torque sensor, 4 cameras, microphone, and accelerometers





Rotor geometry

	Ingenuity	SRH	ROAMX	HST
Total number of blades	4	4	4	3 and 6
Radius (m)	0.605	0.706	0.720	0.675
Chord (75%R) (m)	0.0740	0.0700	0.10	0.1167
σ (thrust-weighted)	0.148	0.126	0.167	0.150 and 0.300
Outboard airfoil	CLF5605	CLF5605	roamx-0201	2.5% t/c ROAMX

- High solidity is a result of increased number of blades and chord distribution

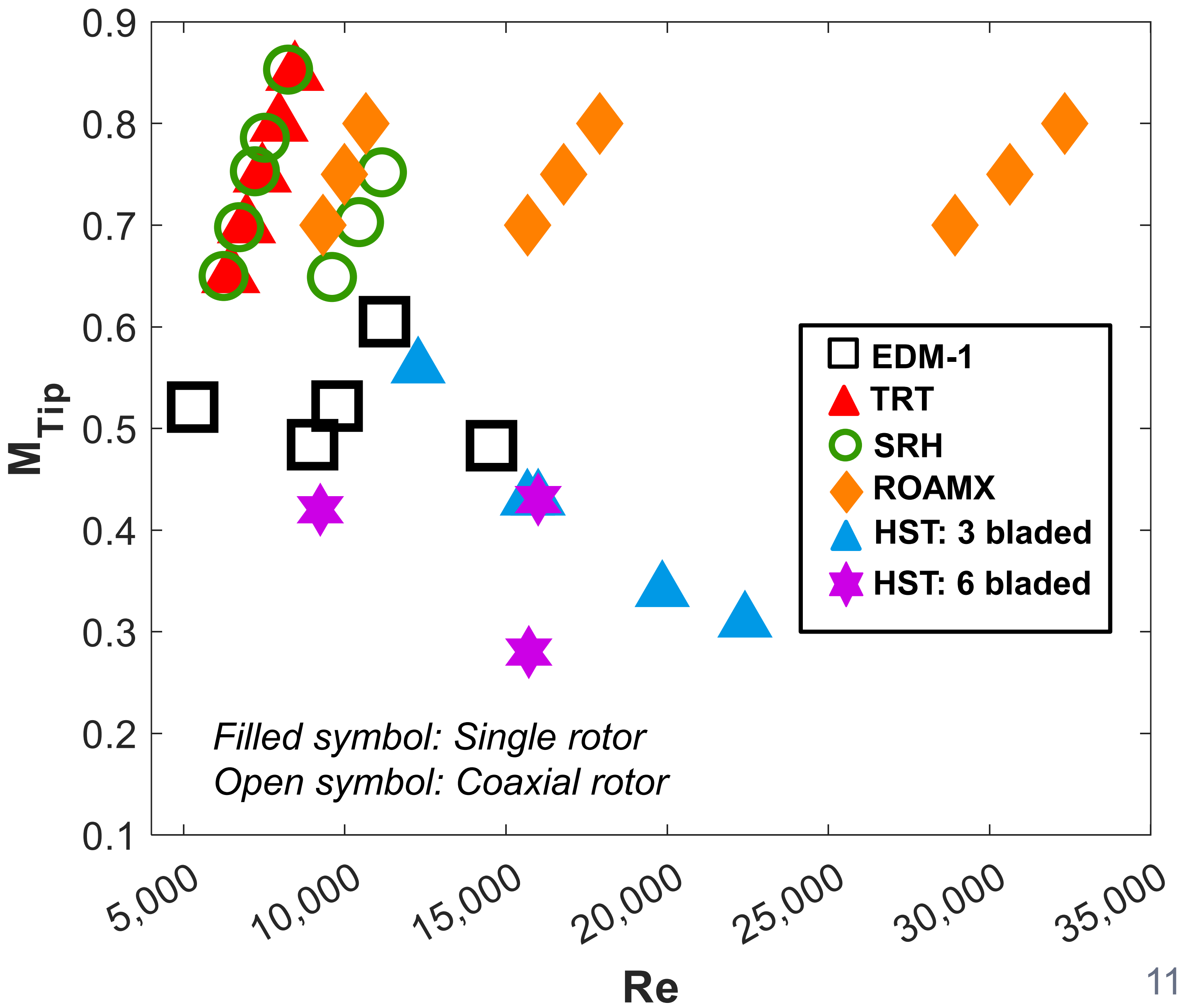



Test Conditions

- Previous test conditions were set to simulate the densities at Jezero Crater rim and lower

$$Re = \frac{\rho\, V_{.75} c_{.75}}{\mu}$$

- Additional conditions for HST included higher Reynolds number due to the increased chord and density variation



Test Matrix

Rotor system	Density (kg/m^3)	M_{Tip}	Reynolds number
3	0.014	0.56	12,270
	0.023	0.43	15,660
	0.024	0.43	16,000
	0.038	0.34	19,850
	0.047	0.31	22,410
6	0.014	0.42	9,240
	0.036	0.28	15,710
	0.024	0.43	16,000

- To get higher Reynolds number the density was increased without increasing M_{tip}
- Low M_{Tip}, no compressibility/shock effects

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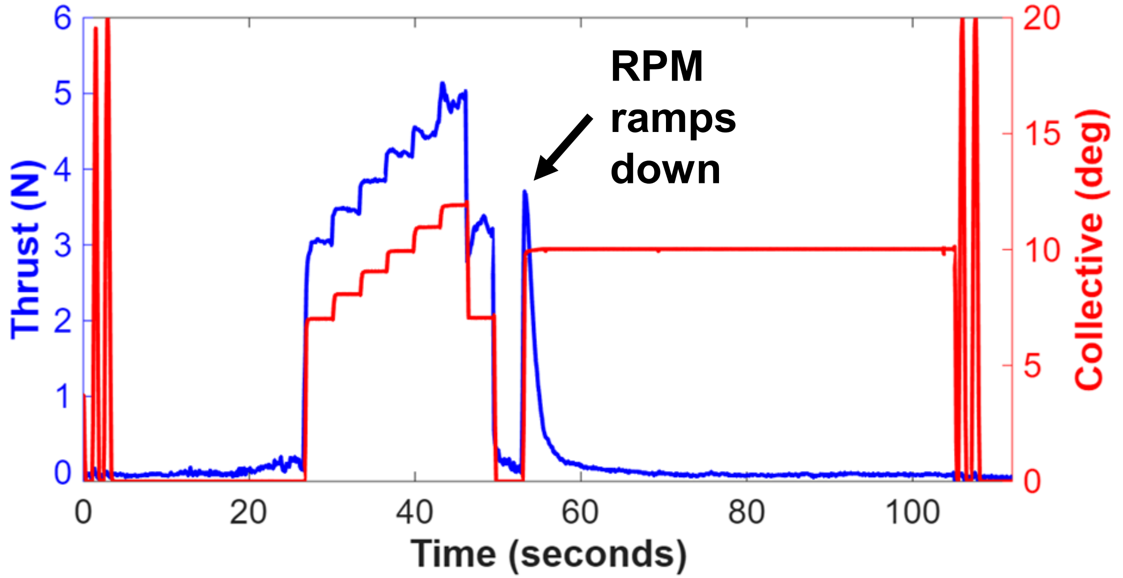
Data Collection and Safety Monitoring

- Each run lasted no more than ~60 seconds due to motor heating limitations
- Data collected on multiple systems
  - Helicopter control (RPM and collective)
  - Force/torque (thrust/power)
  - Accelerometers
- Safety and diagnostic monitoring
  - Microphone
  - Video

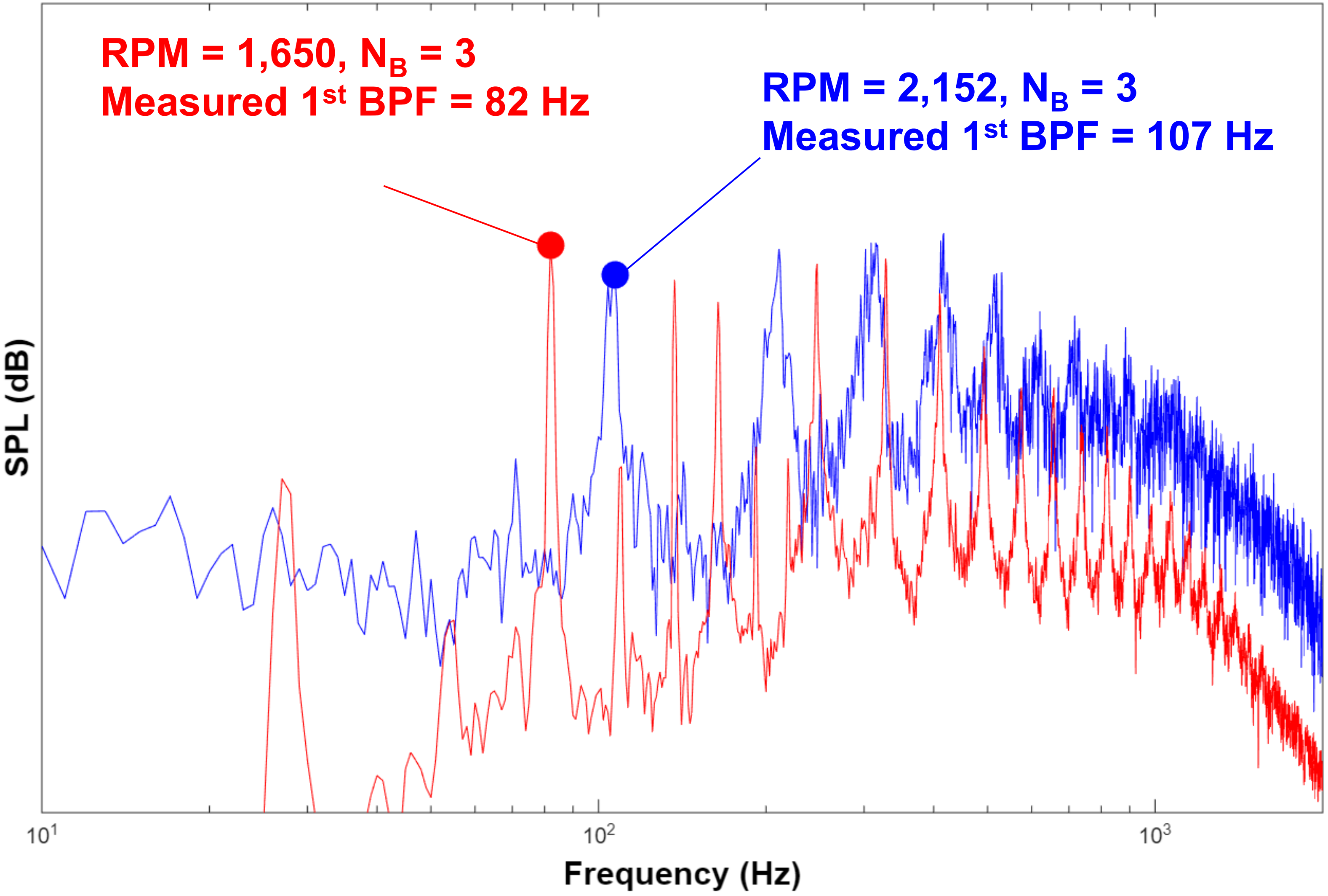


Safety Monitoring: Microphone

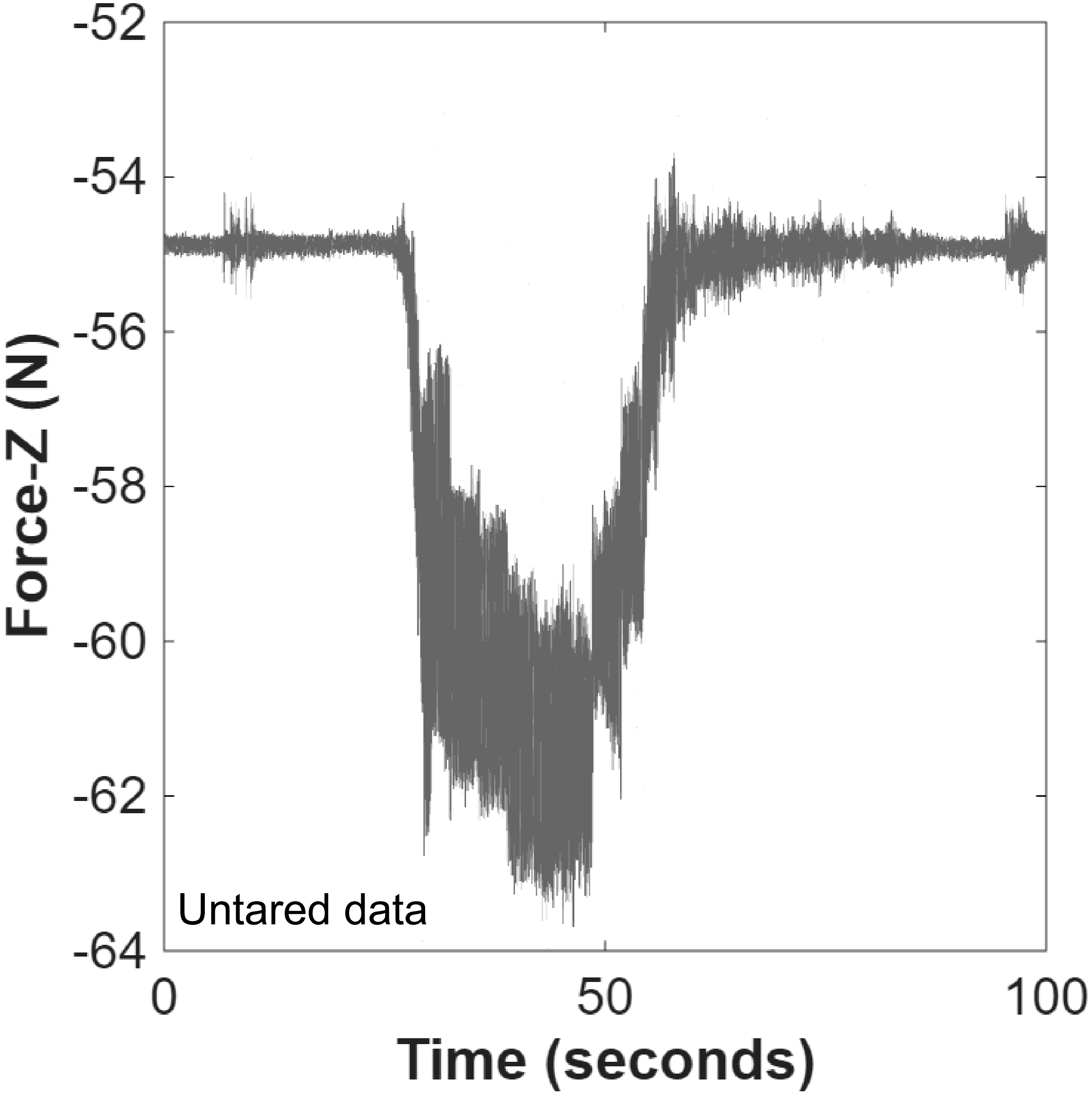
- Single microphone installed beneath rotor for safety monitoring
- Acoustic spectra of measurements processed and used to identify and validate RPM through blade pass frequency (BPF)

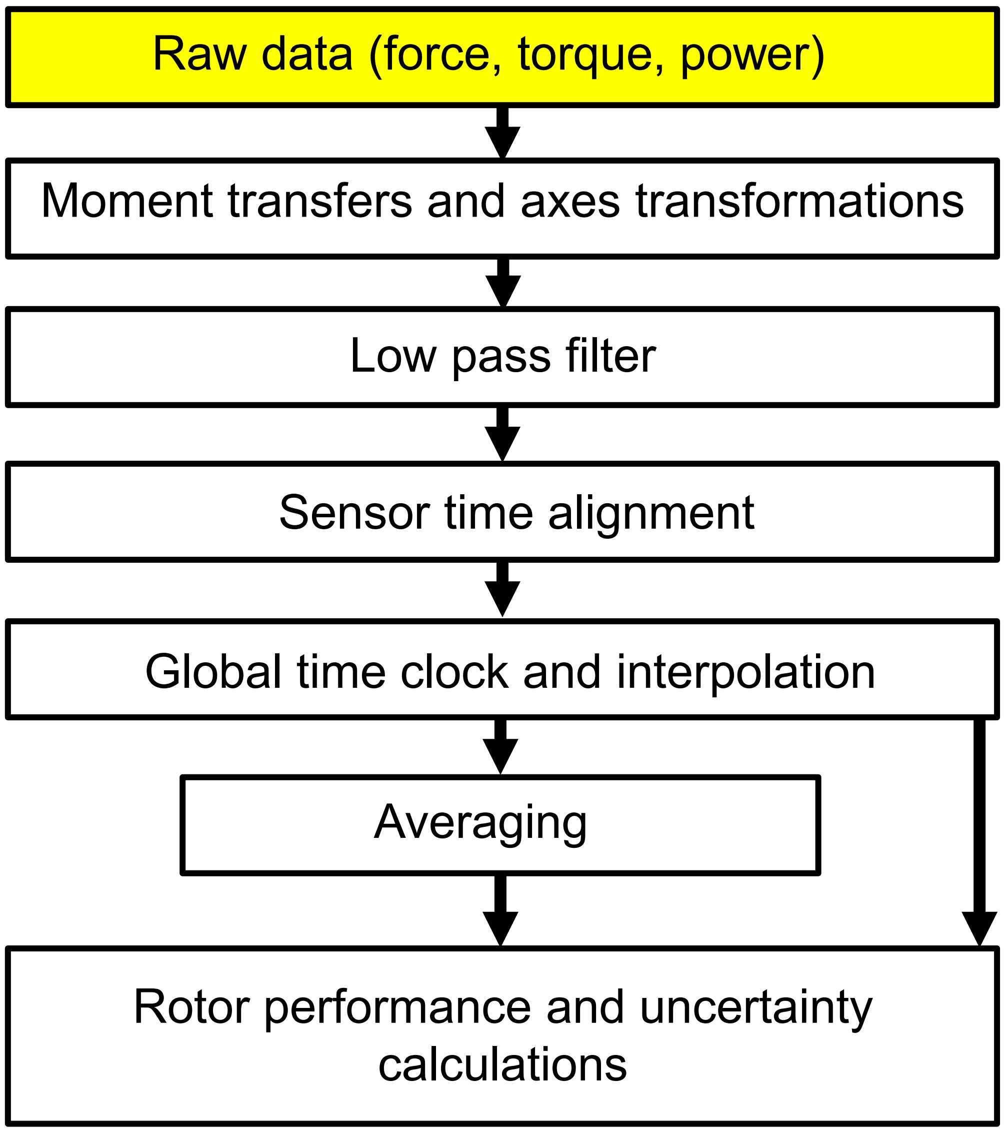
$$BPF\ (Hz) = \frac{RPM\ *\ N_B}{60}$$

N_B = Number of blades



Data Processing





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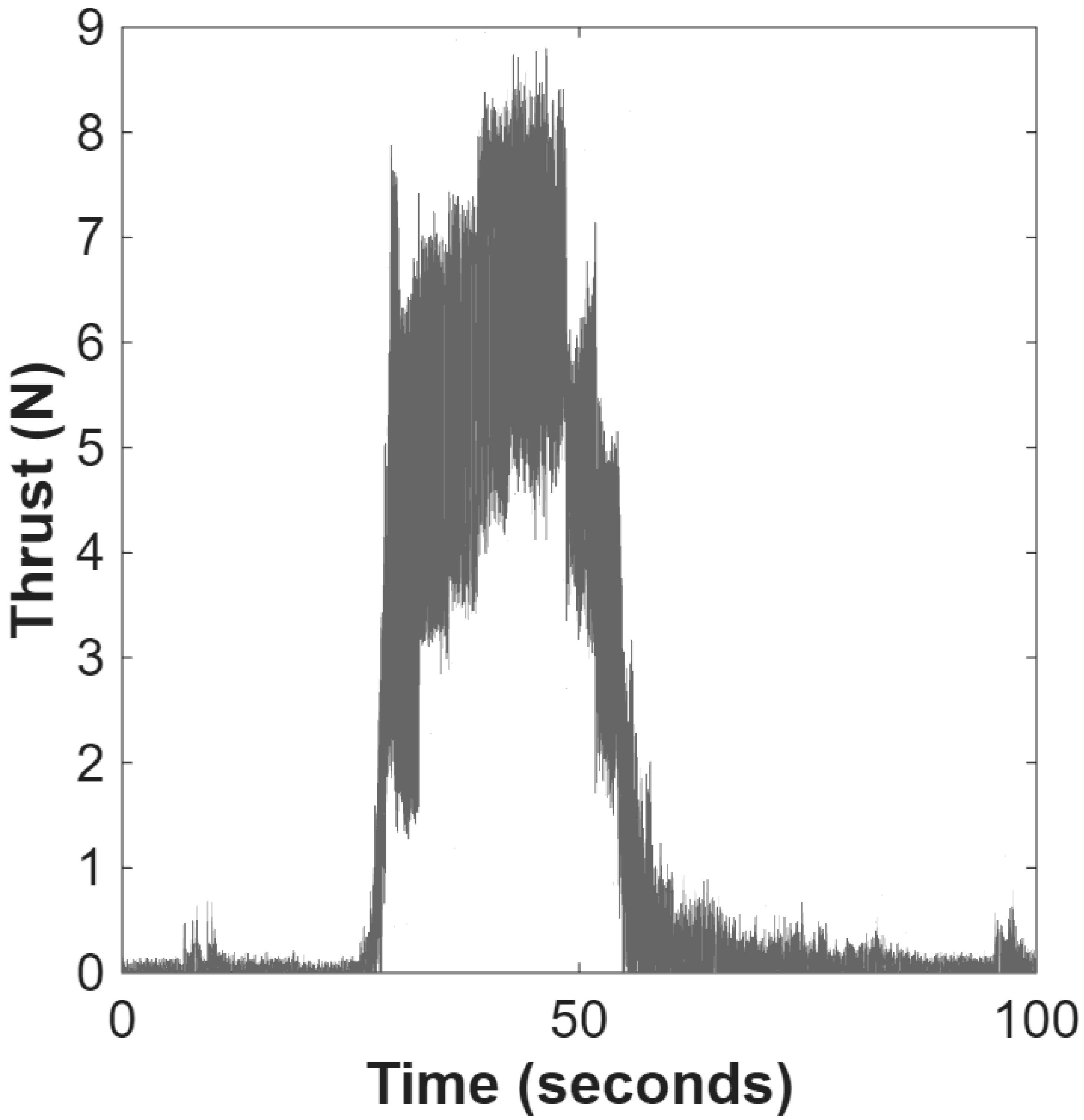
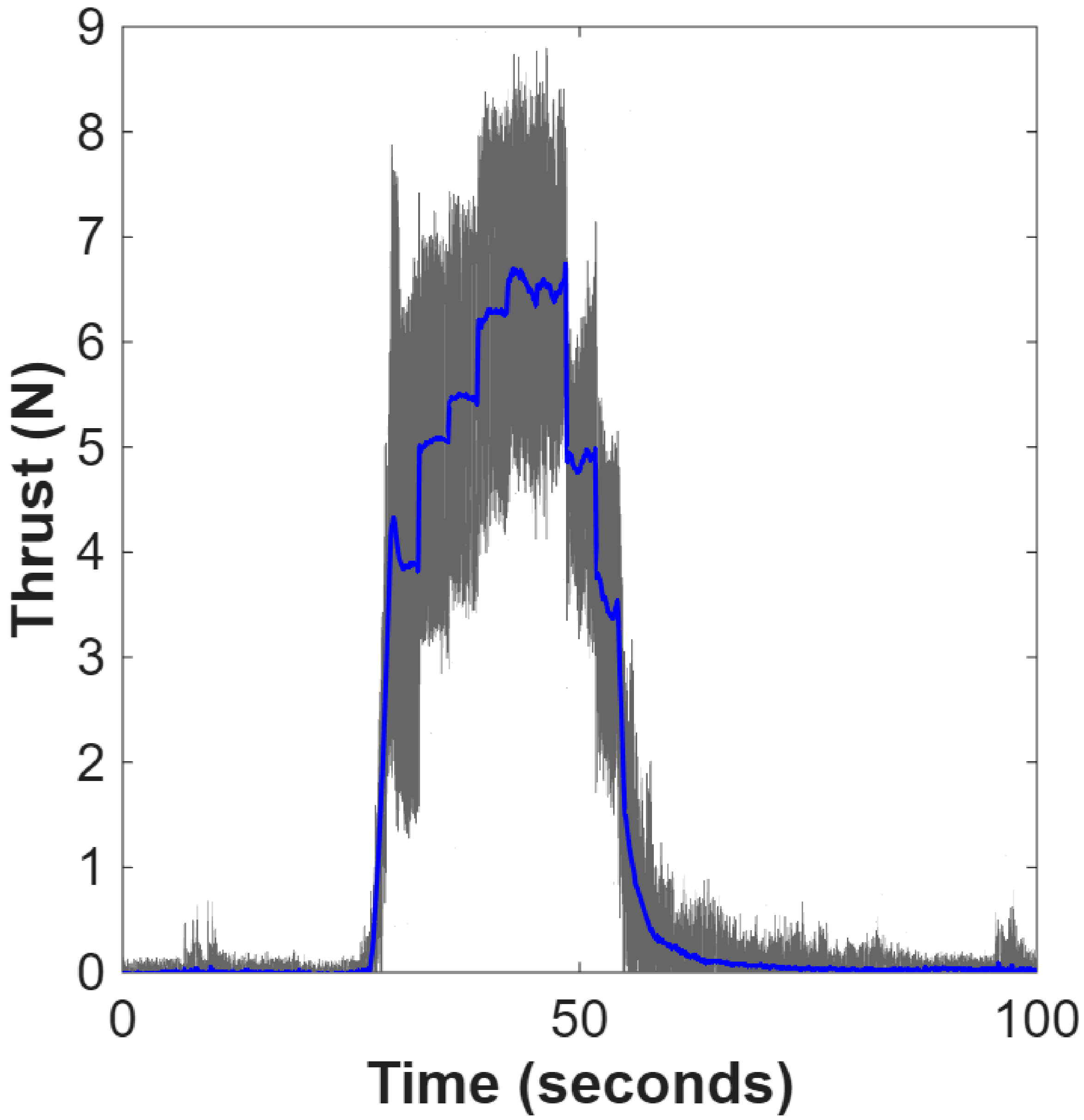
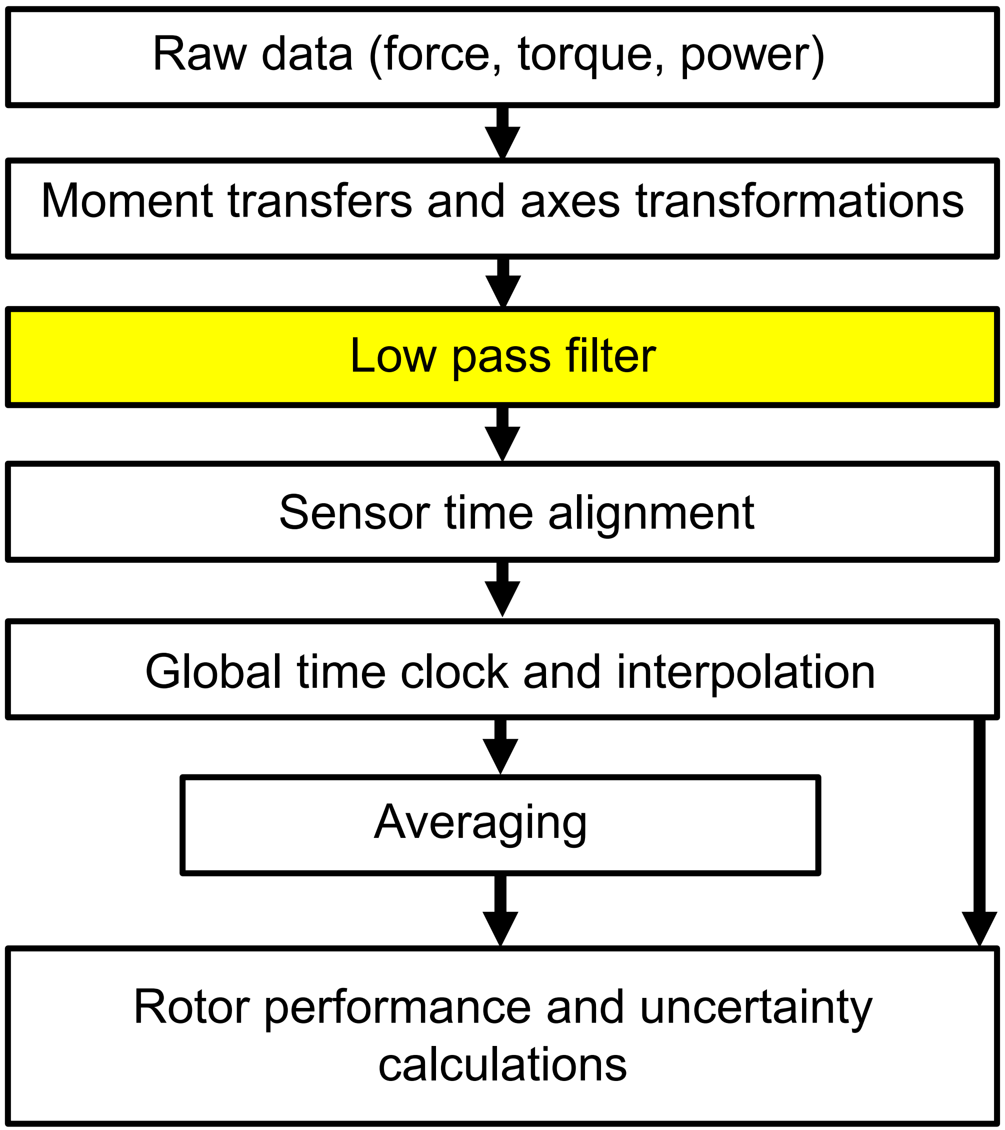


- Raw data (force, torque, power)
- Moment transfers and axes transformations
- Low pass filter
- Sensor time alignment
- Global time clock and interpolation
- Averaging
- Rotor performance and uncertainty calculations

Data Processing





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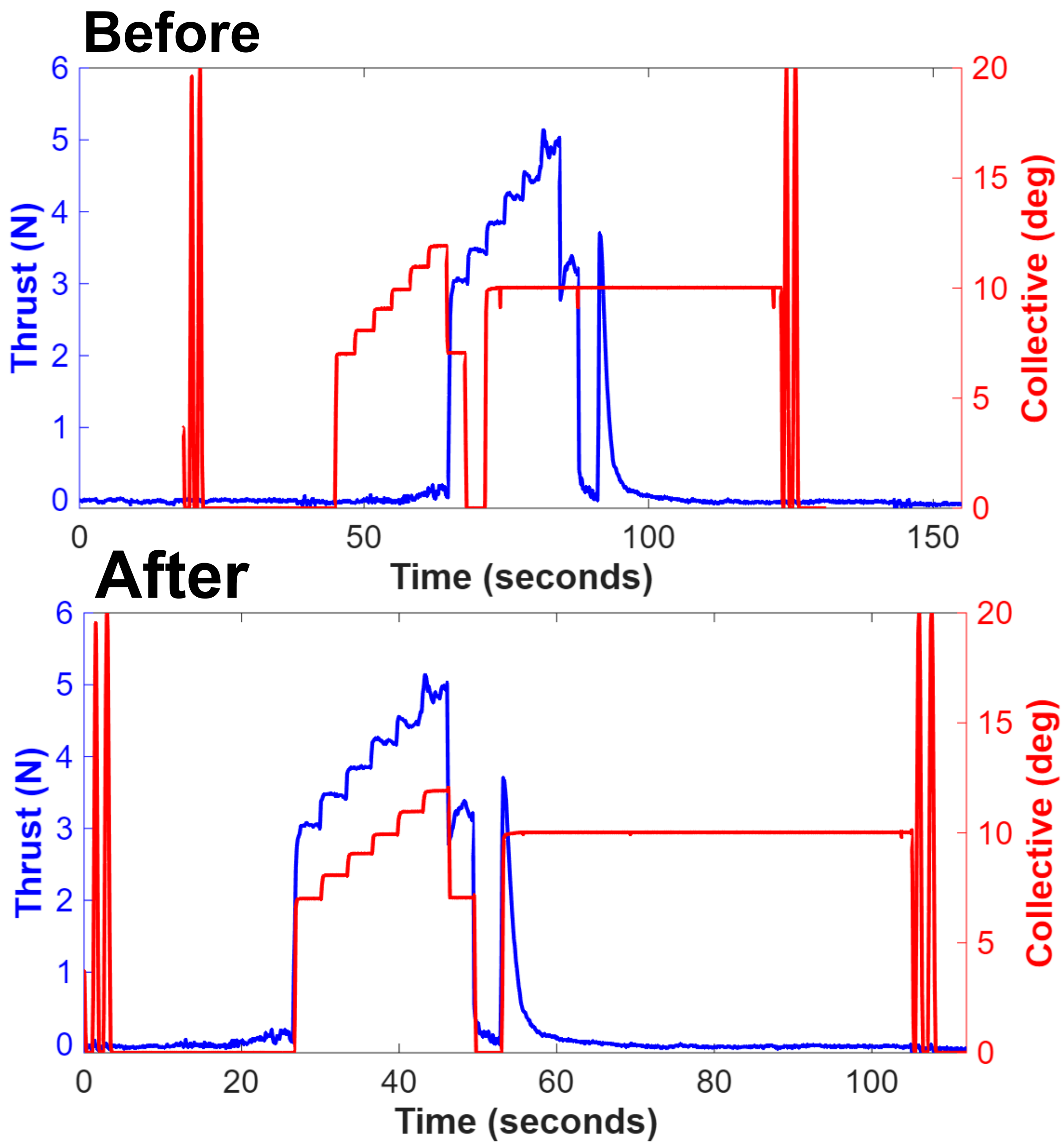

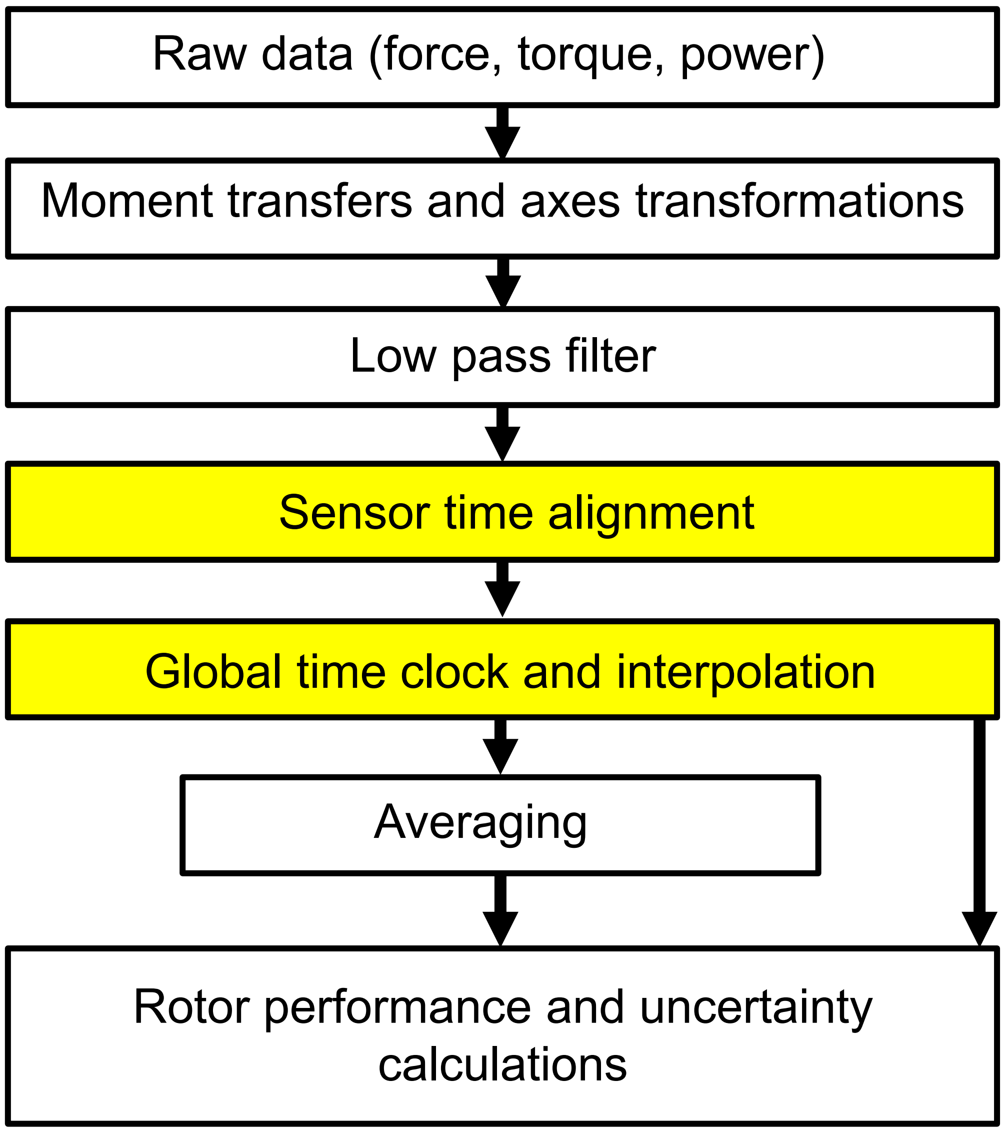

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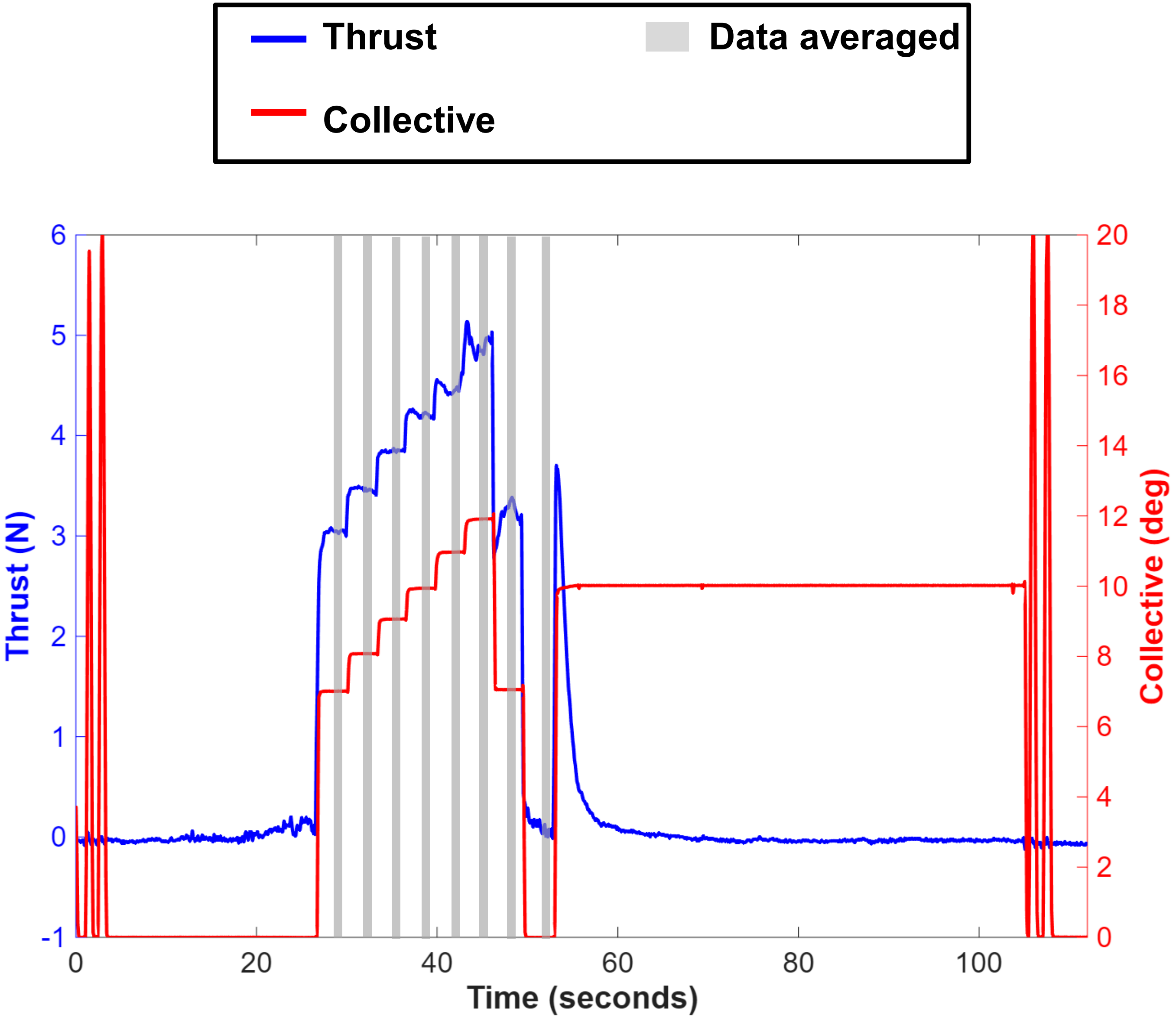

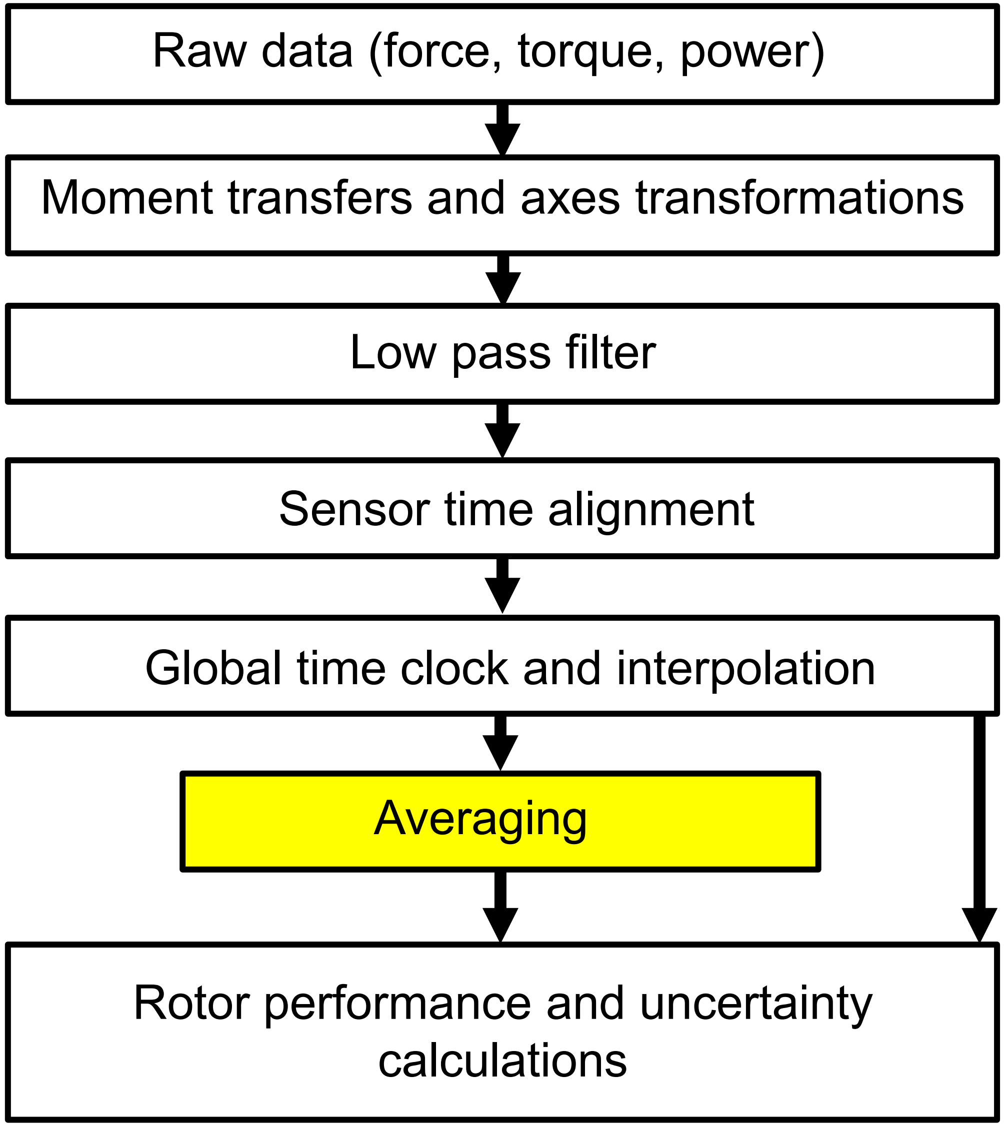

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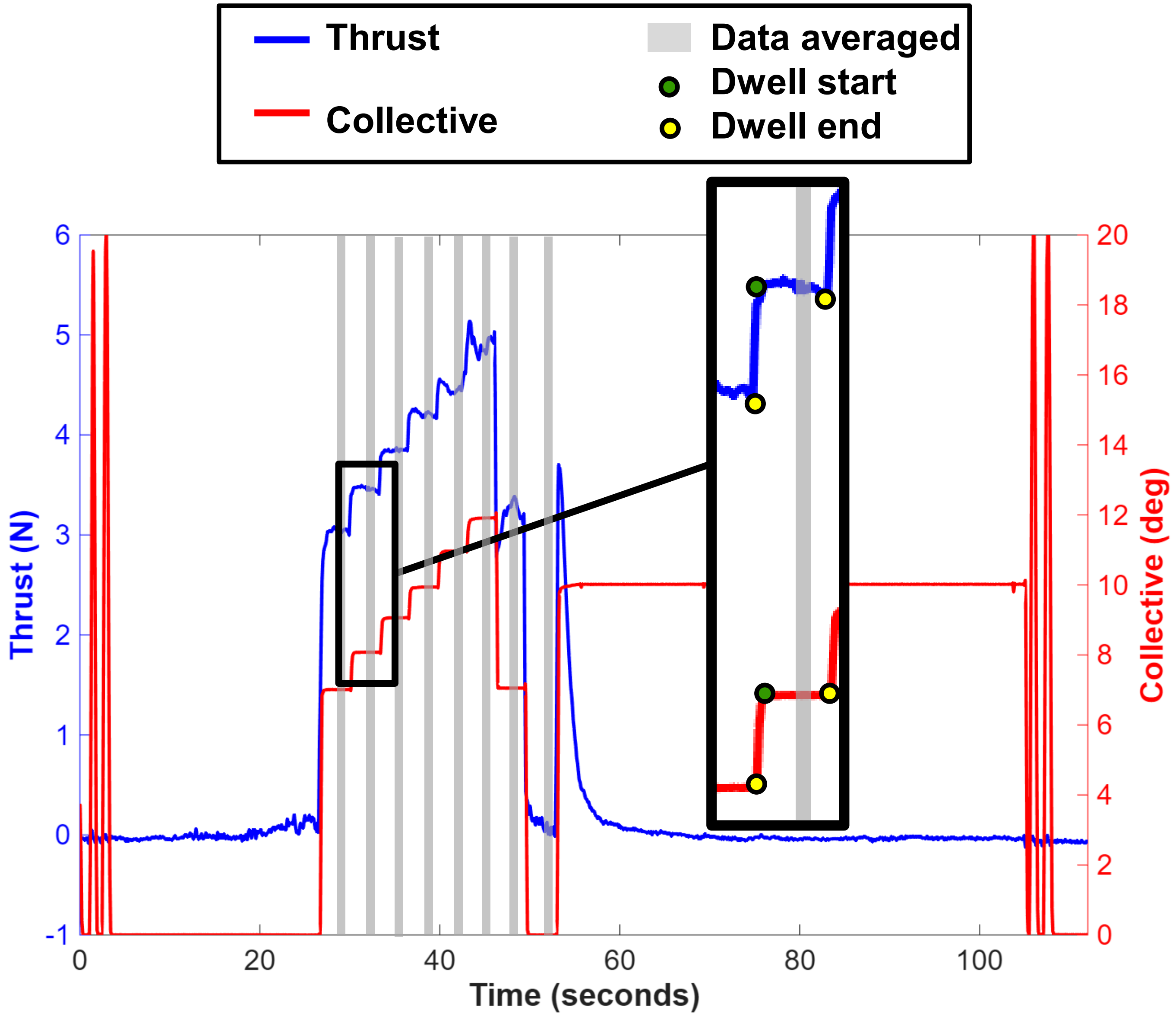
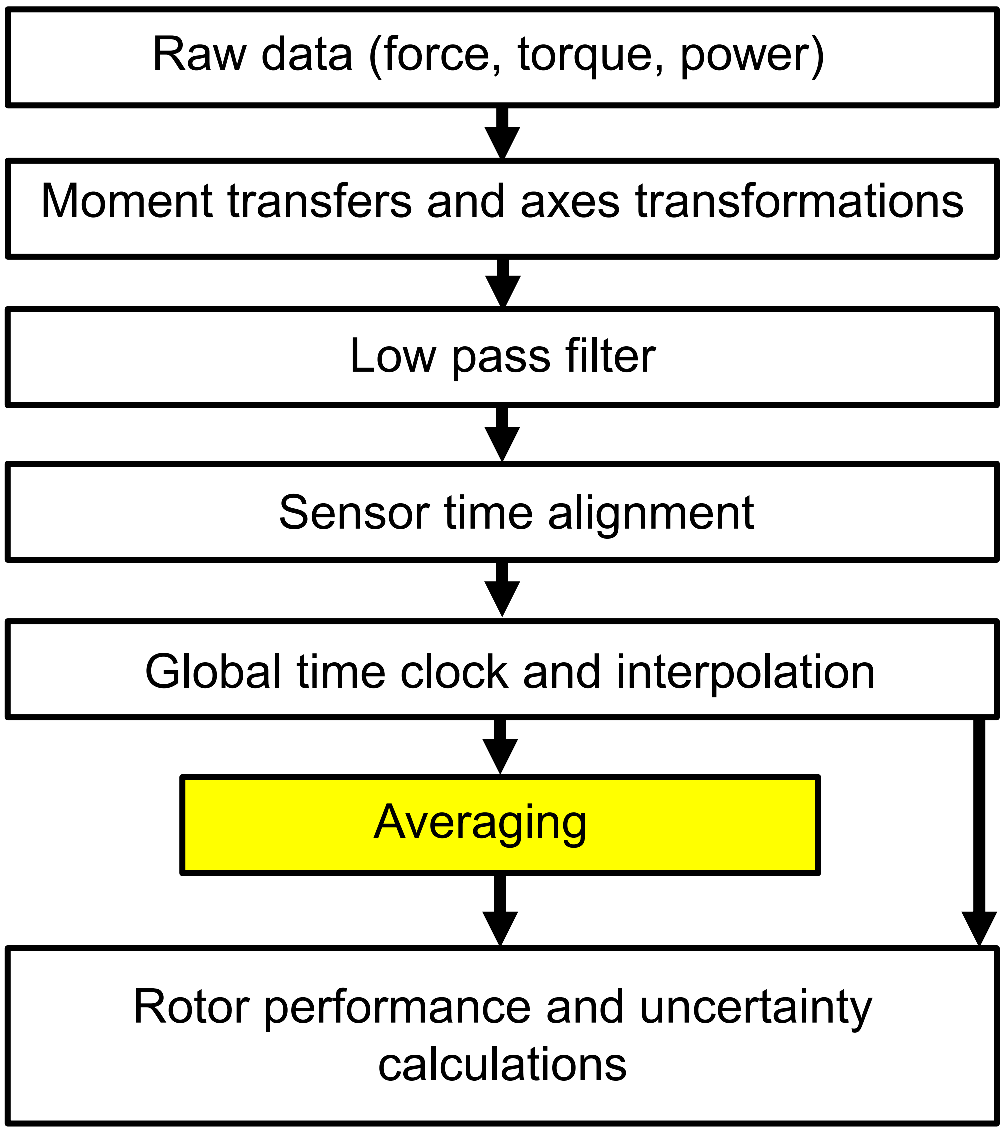


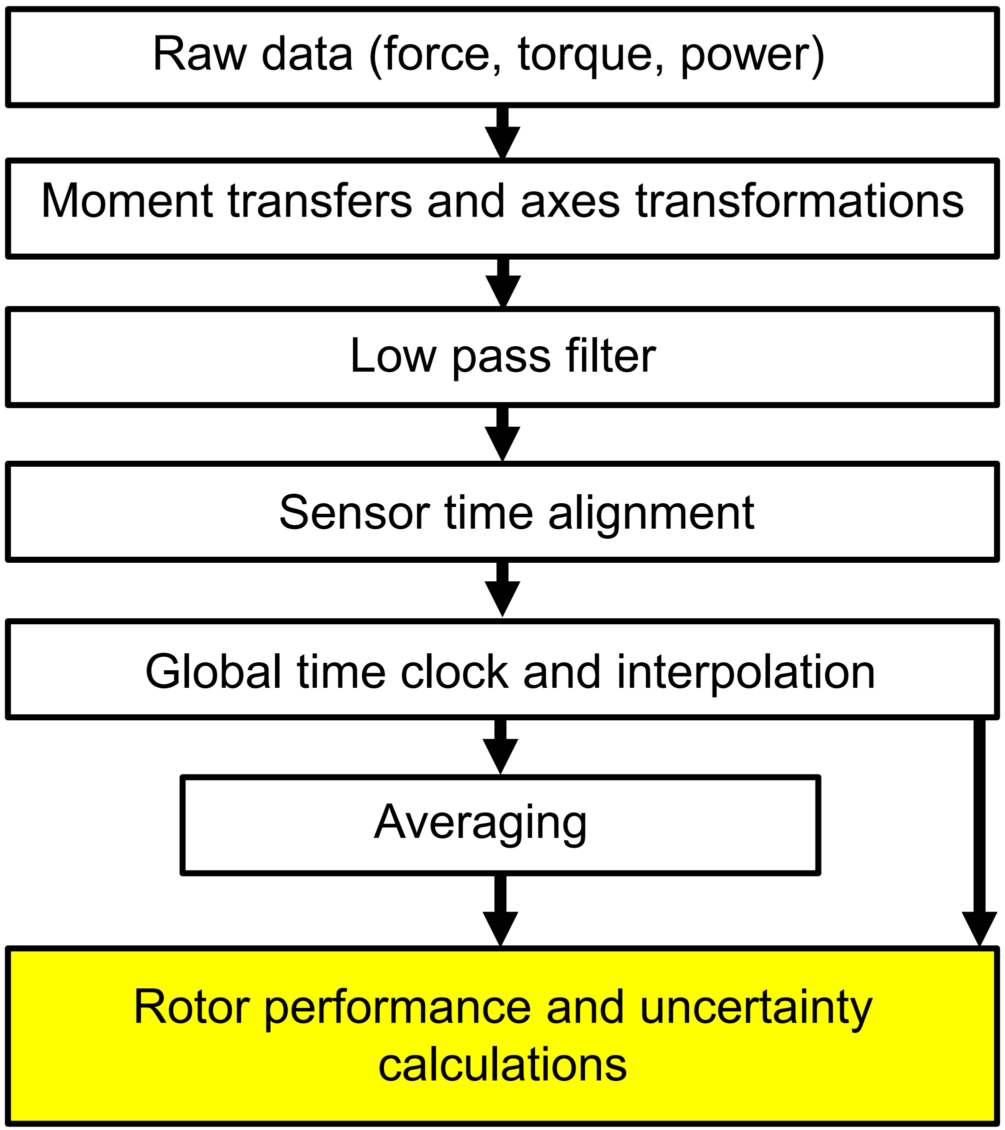


Data Processing

$$C_T = \frac{T}{\rho A(\Omega R)^2}$$

$$C_P = \frac{P}{\rho A(\Omega R)^3}$$

$$FM = \frac{{C_T}^{3/2}}{\sqrt{2}C_P}$$



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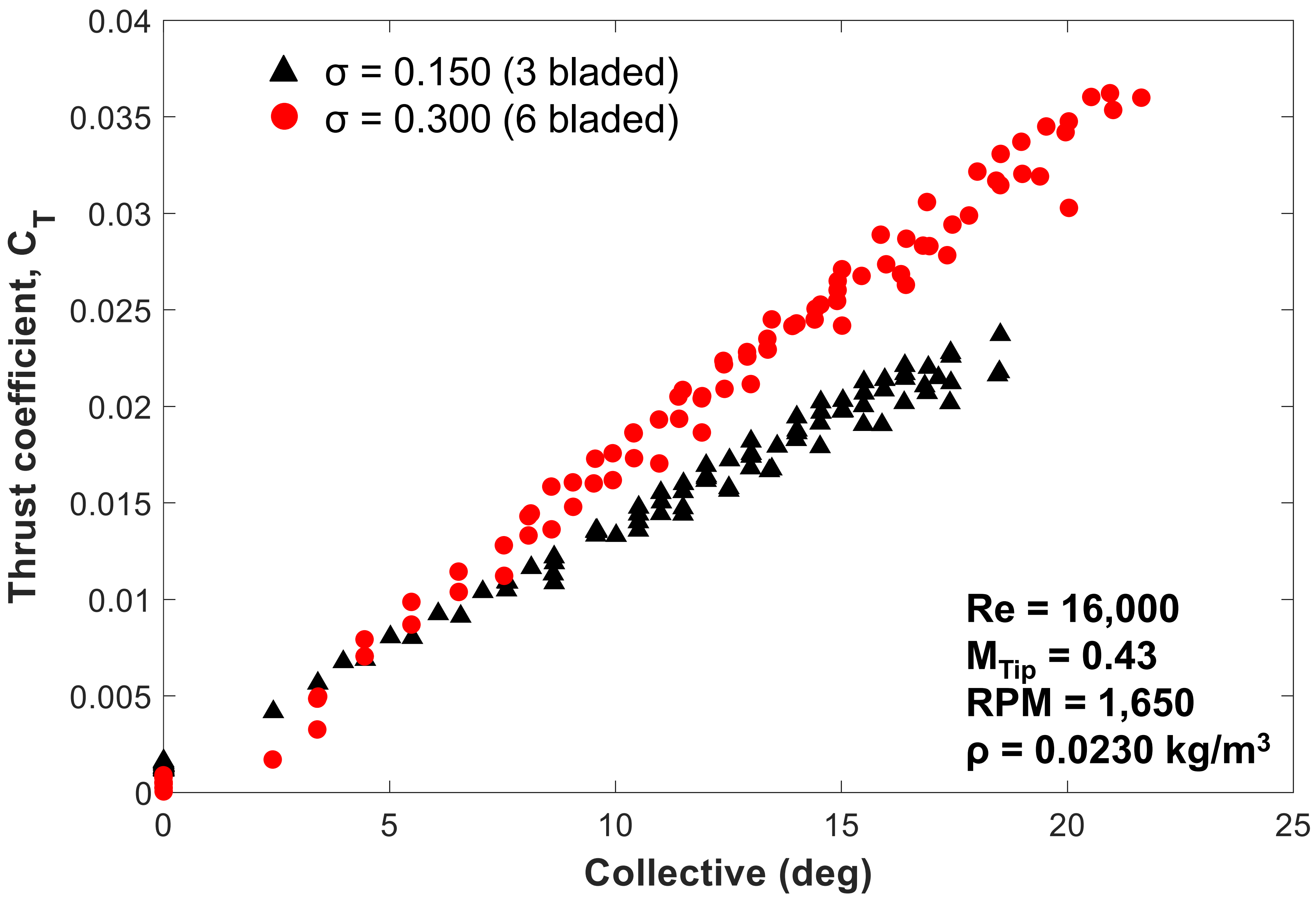
Results: C_T vs Collective (Low versus High Solidity)

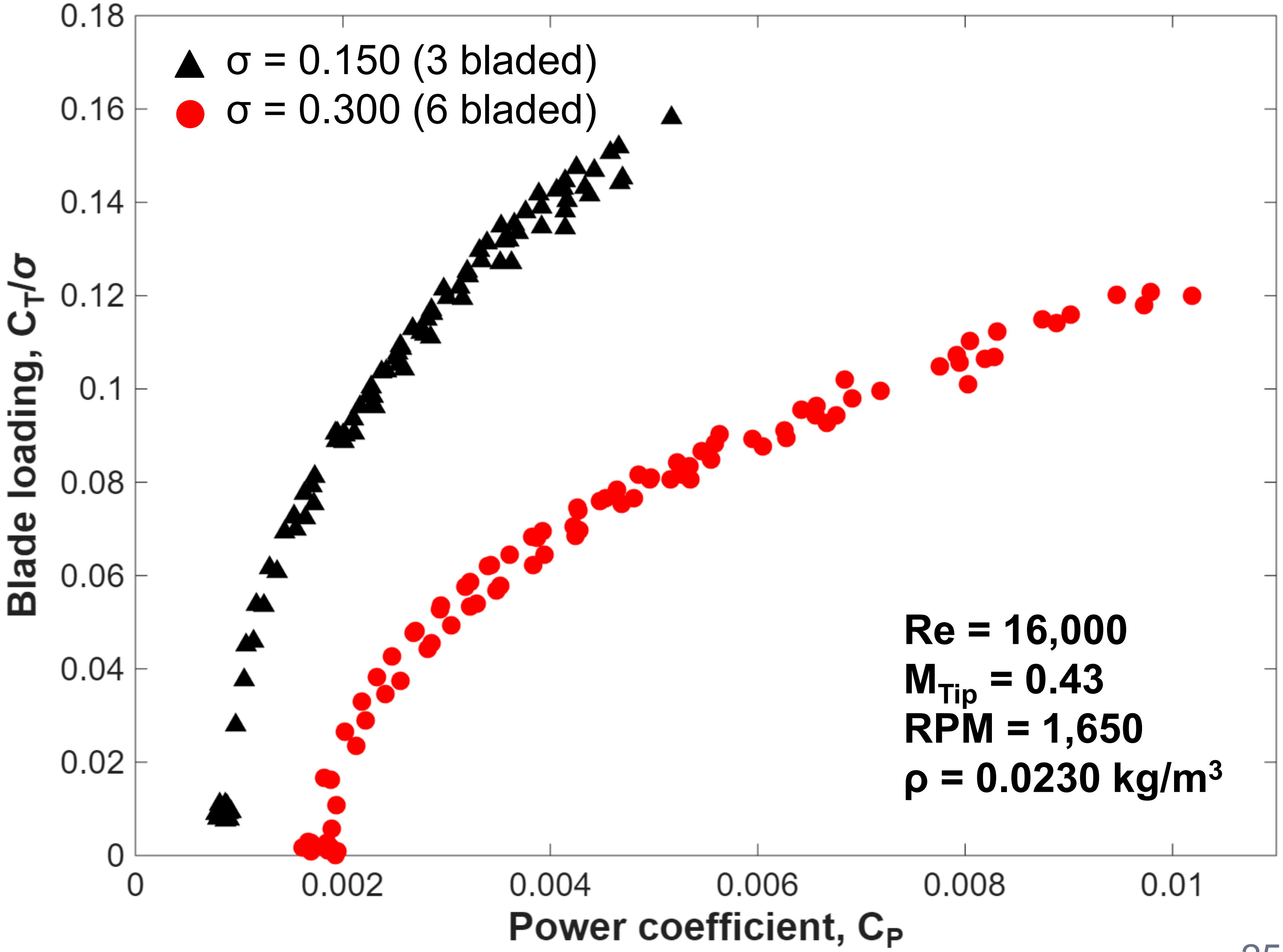
- More thrust capability with increase in solidity (number of blades)



Results: C_T/σ versus C_P (Low versus High Solidity)

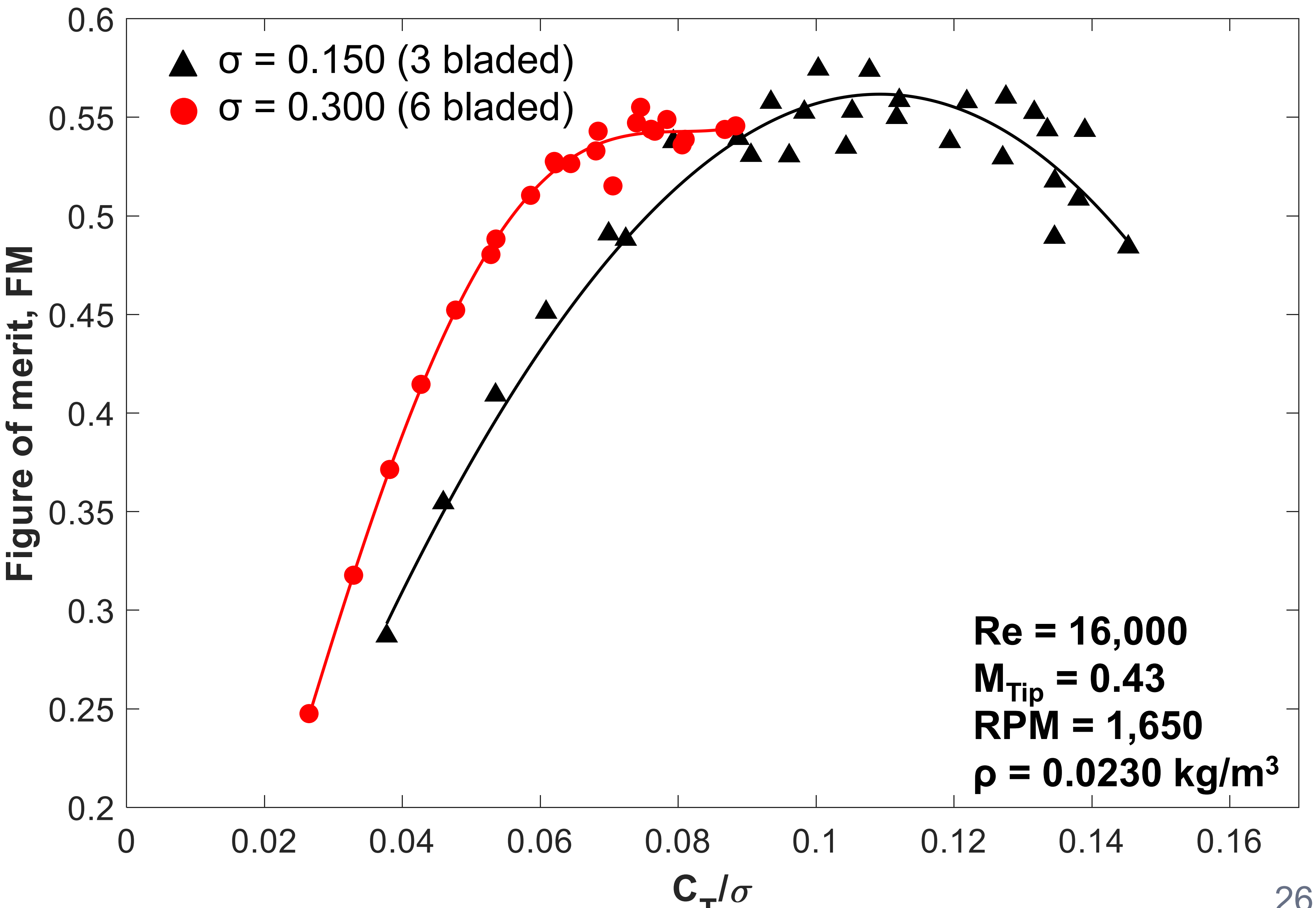
- Increase in solidity therefore increase in profile power

- More blades, higher chance of blade vortex interaction



Results: FM vs C_T/σ (Low versus High Solidity)

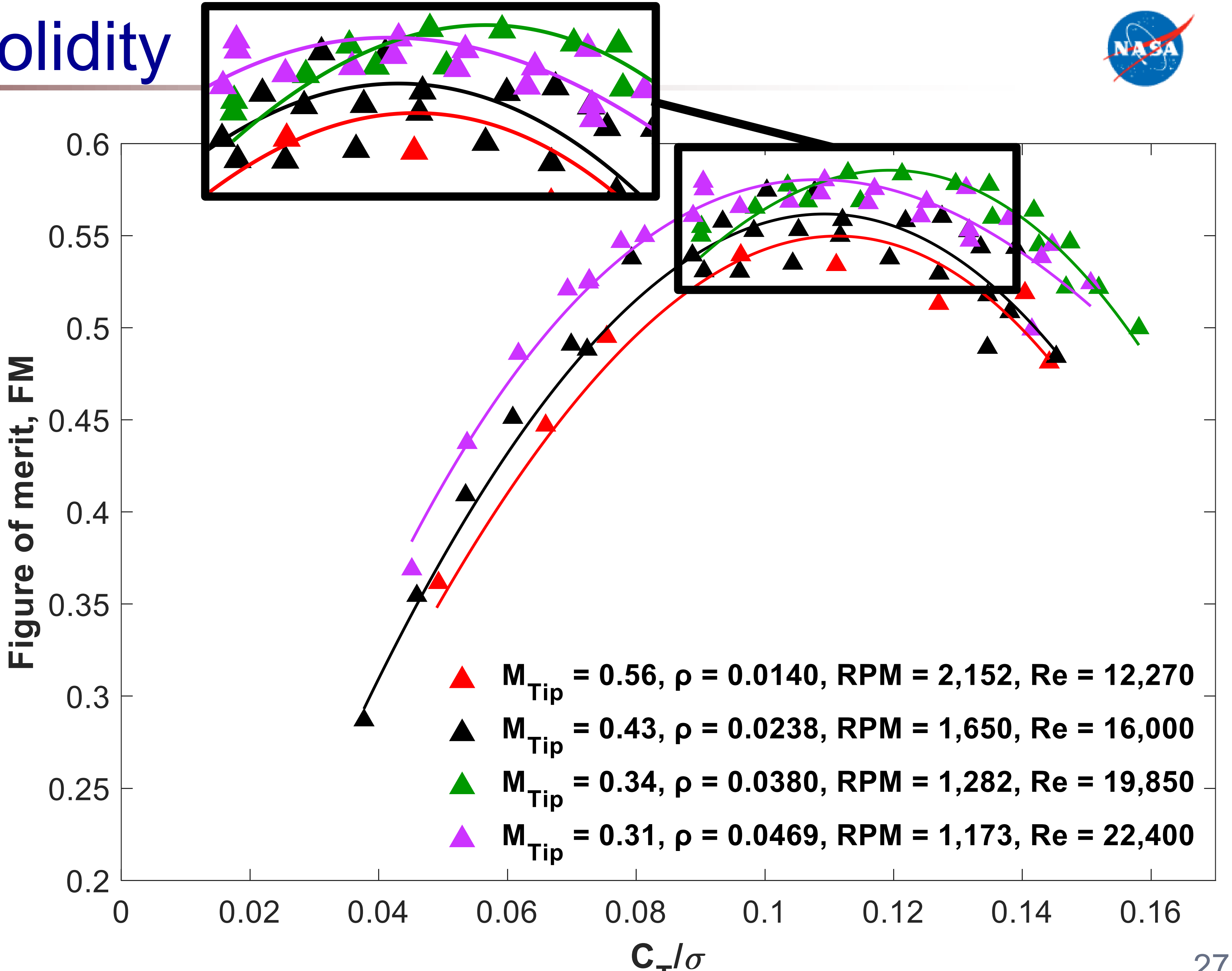
- Figure of merit (FM) shown to highlight efficiency of rotors
- 3-bladed rotor (low solidity) peaks at higher FM
- Peak FM occurs at a lower C_T/σ for 6-bladed rotor for given collective range



Results: Low Solidity

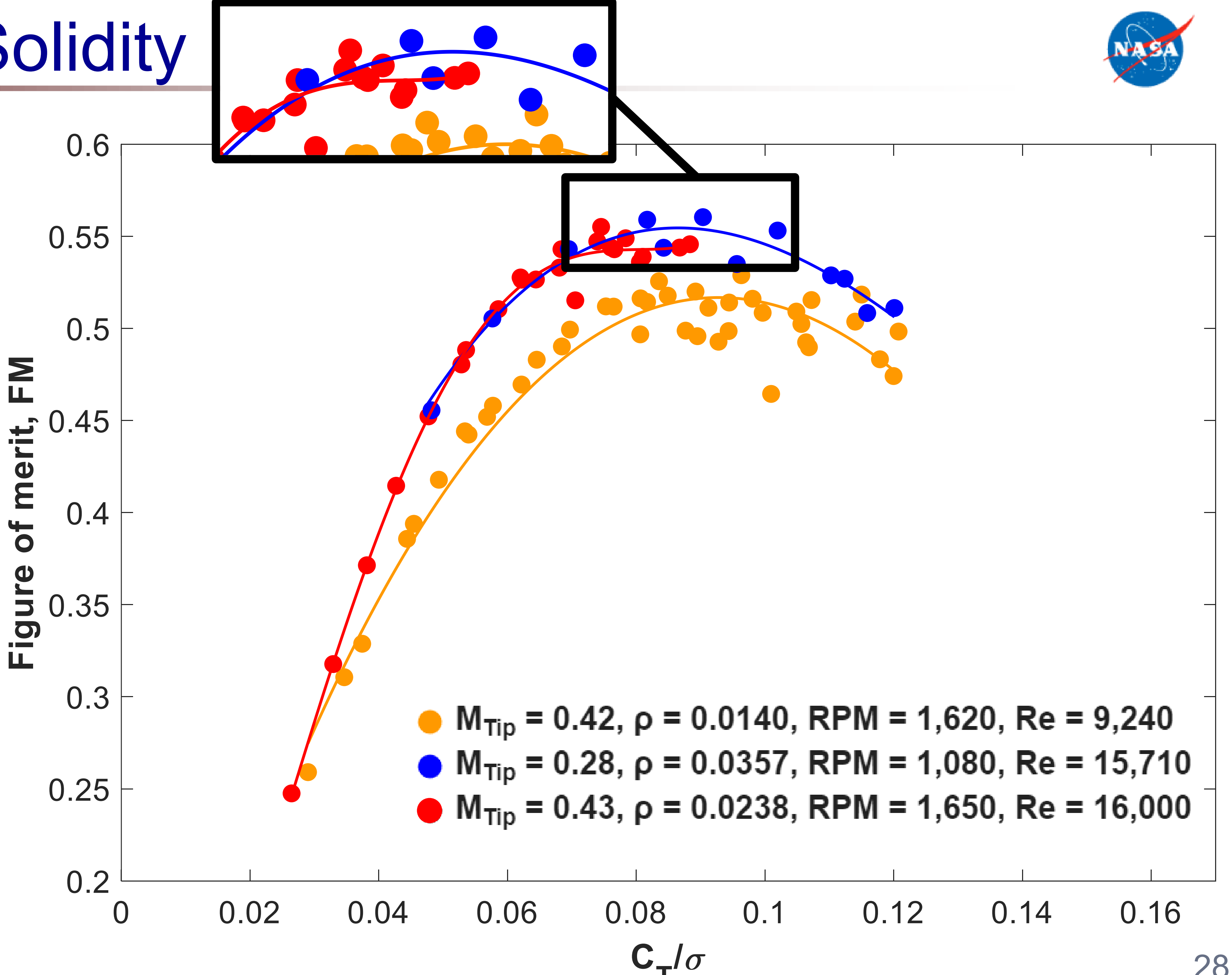
- FM increases with increase in Reynolds number

- Similar peak FM at Re of **19,850** and **22,400**



Results: High Solidity

- FM increases with increase in Reynolds number
- Further investigation underway for large scatter at **Re = 9,239**
- Peak figure of merit occurs at 0.56 at 0.09 C_T/sigma at **Re = 15,707**
- Increased efficiency with increased density



Summary and Conclusions

- HST campaign performed in the NASA JPL 25-ft Space Simulator for a low (3-bladed) and high solidity (6-bladed) rotor
- More thrust capability with increase in solidity (number of blades) for same collective
- Increase in solidity therefore increase in profile power
- Peak FM occurs at a lower C_T/σ for 6-bladed rotor for given collective range compared to 3-bladed rotor
- Further investigation of use of high solidity rotors is underway to understand discrepancies from current predictions

Results will aid in future Mars rotorcraft development by providing data for validation efforts

Acknowledgments

- NASA Ames Aeromechanics Office
- Ingenuity Mars Helicopter Team
- High Solidity Test Team
- Work was paid for by a combination of the Mars Exploration Program and SVTT

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Questions?

NASA