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NRT Design Verification Test Plan

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Prepared by
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Abstract

The National Rotor Testbed (NRT) design verification experiment is the first test of the new NRT blades retrofitted to the existing Vestas V27 hub and nacelle operated at the Sandia Scaled Wind Farm Technology (SWiFT) facility. This document lays out a plan for pre-assembly, ground assembly, installation, commissioning, and flight testing the NRT rotor. Its performance will be quantified. Adjustments to torque constant and collective blade pitch will be made to ensure that the tip-speed-ratio and span-wise loading are as close to the NRT design as possible. This will ensure that the NRT creates a scaled wake of the GE 1.5sle turbine. Upon completion of this test, the NRT will be in an operational state, ready for future experiments.

Table of Contents

Figures

Tables

NOMENCLATURE

Abbreviation	Definition
DOE	Department of Energy
NRT	National Rotor Testbed
SNL	Sandia National Laboratories
SWiFT	Scaled Wind Farm Technology

APPROVALS

The following test plan may not be implemented until the following individuals approve by signing and dating below. Please sign using Adobe Reader or Acrobat.

NRT Principal Investigator Christopher L. Kelley	Wake Dynamics Principal Investigator Brian Naughton
SWiFT Program Lead Timothy Riley	SWiFT Testing Engineer Brandon Davis

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1. Introduction

The National Rotor Testbed (NRT) was designed to study wind turbine wakes, the interaction of wakes on wind plant performance, and to validate Computational Fluid Dynamics (CFD) codes. These three goals are summarized in the National Rotor Testbed Requirements SAND Report [1]:

> "Design, build, and test a scaled wind turbine rotor capable of reproducing the wake characteristics observed in utility-scale turbines; verify scaling capability.
>
> Utilize data in conjunction with high-fidelity models through formal and systematic Verification and Validation (V&V) process developed within the A2e initiative.
>
> Complement other A2e experimental campaigns in the wind tunnel and utility-scale wind farms to understand the impact of scaling on rotor aerodynamics."

It was decided that new blades should be retrofitted to the existing V27 turbines at SWiFT such that a scaled wake is produced. In this way, the NRT produces the same axial velocity field as a commercial size turbine, the GE 1.5sle, and the wake is relevant to commercial wind farm research.

The purpose of this experiment is to ensure that the NRT operates safely and consistently with its design of creating a scaled wake. The test objectives will leave the NRT in an operational state for future wake research and producing data for validation of CFD codes.

Inevitably, the NRT as manufactured will have differences with its theoretical design due to a host of realities: manufacturing tolerances, assembly tolerances, 3D aerodynamic effects, atmospheric turbulence and shear, blade roughness, and airfoil trailing edge thickness to name a few. The rotor torque constant and collective blade pitch are the two key parameters that can be adjusted to make the rotor perform as designed after it is installed on the A1 nacelle. The adjustment procedures are described in this test plan.

The following test plan is a guide for conducting the NRT design verification experiment. Section 2 discusses three primary test objectives of pre-assembling, assembling, commissioning, and flight testing the new NRT. Section 3 describes the roles and responsibilities of the team members. Section 4 goes over the new hazards associated with installing the NRT. Section 5 lays out a timeline estimate associated with the three test objectives. Section 6 examines the test configuration equipment. Section 7 goes over the procedures necessary to assemble, commission, and fly the NRT rotor, and in cases where the procedures are highly detailed, refers the reader to external documents. Finally, Section 8 shows the reporting requirements that will take place during the test to ensure the NRT design verification experiment is on track to meet its test objectives.

2. TEST OBJECTIVES AND SUCCESS CRITERIA

The experiment has three test objectives: to first assemble the NRT, second to commission the NRT to operate in power production mode, and third to flight test. The secondary objectives are optional but would enhance the capabilities of SWiFT test site for future experiments. The test objectives are summarized in Table 1.

Table 1. Test objectives and success criteria.

Primary Test Objectives
PTO1: Pre-Assembly
Success Criteria: All blades were painted, their surface roughness quantified, and the blades were balanced to their final mass and their center of mass locations were quantified. In addition, the management of change is completed and the analysis and simulations for safe operation of the NRT are completed.
PTO2: Assemble NRT
Success Criteria: NRT blades were attached to hub, blade-to-blade pitch angles were matched, and blade/hub data quality is verified
PTO3: Rotor Modal Test
Success Criteria: Rotor modes are measured and documented with the rotor on the nacelle
PTO4: Commission NRT
Success Criteria: NRT safely operated in power production mode, rotor was attached to A1 nacelle, torque constant is changed in speed controller, data quality for turbine and blade sensors was verified
PTO5: Flight Test of NRT
Success Criteria: Calibrated tilt angle, azimuth sensor, yaw encoder, tower strain, blade strain, and blade pitch. Rotor was operated at tip-speed-ratio equal to 9, fine pitch adjusted to match NRT design thrust loading
Secondary Test Objectives
STO1: Measure power curve and final loading data for a month of operation
Success Criteria: Quality data was collected and statistically converged
STO2: Perform wake measurements to verify blade loading produces intended velocity field
Success Criteria: Axial velocity profile is consistent with blade loading
STO3: Operate NRT in Region 3
Success Criteria: NRT safely operated in Region 3 and quality data was produced that describes blade pitch schedule
STO4: Increase NRT maximum operational speed to 52 rpm
Success Criteria: NRT safely operated at higher speeds avoiding tower and rotor resonance and quality data collected was sufficient to integrate into controller to prevent dwelling at modes
STO5: Unattended Operation
Success Criteria: The NRT rotor is certified to operate safely without human observation

3. ROLES AND RESPONSIBILITIES

The following tables describes the roles and responsibilities of the personnel that will be involved in all stages of the test plan.

Table 2. Roles and responsibilities.

Title	Name(s)	Responsibilities
Wake Dynamics Program Lead	Brian Naughton	• Manage planning and execution of experiments at SWiFT • Coordinate with SWiFT Program Lead on operations and maintenance of SWiFT in conjunction with this experiment • Manage budget and status updates to customer
NRT Experiment Principal Investigator	Christopher Kelley	• Create test plan • Oversee all tasks in experiment • Compare experimental performance to design • Advise on torque and pitch adjustments • Document and report results
SWiFT Program Lead	Timothy Riley	• Coordinate staffing at SWiFT site during experiment • Ensure ES&H compliance
SWiFT Controls Lead	Jonathan Berg	• Implement turbine controller adjustments • Operate turbine
SWiFT Testing Engineer	Brandon Davis	• Plan NRT lift and installation • Troubleshoot commissioning • Document testing procedures • Ensure ES&H compliance
SWiFT Site Supervisor	Dave Mitchell	• Coordinate NRT lift and installation • Lead safety briefings • Operate turbine
NRT Structural Lead	Joshua Paquette	• Develop and implement NRT Management of Change (MOC) evaluation • Review and confirm safe structural response of NRT rotor
SWiFT Technicians	Miguel Hernandez Greg Salas	• Assemble rotor including rigging, hoisting, and forklift • Operate turbine
Modal Test Contractor	ATA Engineering	• Perform rotor modal testing • Report summarizing results

4. UNIQUE HAZARDS

The following table provides a summary of hazards that are unique to this test. The issues are all addressed in the NRT Management of Change (MOC) document [2].

Ground Assembly Hazards	Description
Blade strike against ground while on blade assembly stand	The NRT blade has a different planform shape than the V27. It has been checked that when the NRT blades are affixed to the hub on the blade assembly stand, the blade misses the corner of the concrete octagon by as little as 17”, and the maximum chord clears the ground by 7.5”. However due to uneven terrain, care should be taken when pitching the blades on the hub on the blade assembly stand.
Commissioning Hazards	Description
Changes to commissioning procedures	A revised commissioning document will be created to reflect changes unique to the NRT **Sections with parameter changes needed in commissioning manual:** 6.3.1.5, 6.3.1., 6.4.1.4, 6.4.3, 6.5.1.4, 6.6.3, 6.6.7
New torque constant	Reducing the torque constant means the rotor will spin at a higher speed for a given wind speed, compared to the V27.
Pause blade pitch	The rotor could spin too fast in pause by reusing the V27 pause pitch position
Startup speed/pitch	The rotor speed and blade pitch to transition from startup to run may need to be adjusted
Hydraulic pressure/twisting moment	It should be verified that the hydraulic pressure is sufficient to return the turbine blades to feather because the NRT has slightly higher blade pitching moment than the V27
Flight Test Hazards	Description
New blades	New blades have different structural and aerodynamic properties. Different vibration modes and dynamic forces will exist. IEC design load simulations are performed to show safe operation of the NRT
Supplemental Test Hazards	Description
Flutter	Flutter analysis will be performed to verify that increasing the rotor speed above 43.9 rpm will not lead to flutter.
Tower/rotor resonance	Torque control to prevent dwelling at the first rotor mode in operational range will be implemented if the NRT operational speed is increased above 43.9 rpm

5. SCHEDULE

An initial estimate of the testing schedule shows at least 6.5 months (26 weeks) of work starting with a safety review and ending with the NRT producing a scaled wake as close to the design as possible for rotor speeds up to 43.9 rpm.

Table 3. Test schedule.

Dates	Description
Week 1—5	**Safety review and Pre-assembly** A readiness review will be performed to ensure that the proper safety considerations have been made for the assembly, installation, and flying of the new NRT blades. The Pre-assembly involves painting the blades, quantifying surface roughness, and a final weighing
Week 6—10	**Ground assembly of rotor** The blades will leave building 350 for assembly to the hub. Crank arm positions will be adjusted to ensure each blade has the correct pitch and the backlash angle will be measured. Blade sensor data will be verified before installation
Week 6—15	**Commissioning and rotor installation** The commissioning process will be carried out so the NRT can safely operate and produce power. Some commissioning tests occur before the rotor is installed, and some occur after. An initial torque constant change will be made to the controller.
Week 13—14	**Rotor Modal Testing** ATA Engineering performs a modal test of the assembled NRT rotor and a provides a report summarizing their findings. The rotor modes will be used to verify there are no resonances in the initial 0-44 rpm operating speed range. The results can also inform a more accurate FAST structural model, and rotor speeds to avoid if the NRT is operated up to 52 rpm.
Week 16—26	**Flight test** The flight test will bring the NRT to its final operational state with performance as close as possible to the NRT design. Torque constant and collective blade pitch adjustments will be made so that the NRT has a tip-speed-ratio equal to 9 and thrust loading distribution matching its design. Slow rolls of the turbine in pause will also allow for the final calibration of the strain gauges, and a collective blade pitch calibration will take place.
Week 27—	**Supplemental tests** Supplemental tests will be used to enhance functionality of the NRT. For example, flow visualization could be performed to explain any efficiency differences with the NRT design, and a full IEC power curve could be measured.

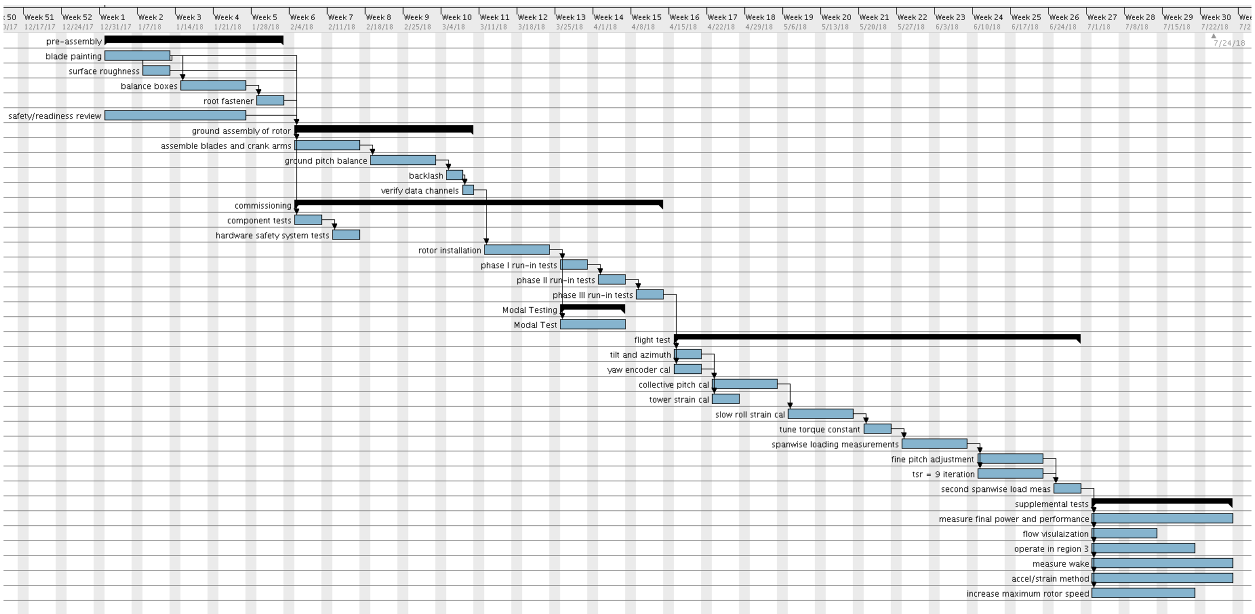

Figure 1. NRT Design Verification Experiment Gantt Chart.

6. CONFIGURATION

The configuration section discusses equipment out of the ordinary necessary on site, and personnel needed for specific tasks during the experiment. All phases of this experiment will require the METa1 meteorological tower and the WTGa1 wind turbine to be fully operational. The other turbines at the site can be operated as needed with advanced consultation with the PI to avoid potential conflicts such as wake interaction.

6.1. Personnel and Special Equipment

During ground assembly, the SWiFT site should be prepared to move rotor hubs and blades from building 350 to the WTGa1 assembly pad. A telehandler will be necessary to install blades onto the hub for ground assembly.

During commissioning, a turbine operator will be required to perform the component and hardware safety system tests. In addition, the assembled rotor is lifted onto the A1 nacelle halfway through the commissioning procedure. A crane will need to be on site for this work. The SWiFT Site Supervisor and the SWiFT Testing Engineer will oversee the NRT rotor assembly, lift, and installation on the A1 nacelle.

Flight testing requires a turbine operator. In addition, special controller modifications will be implemented by the SWiFT Controls Lead including the torque constant and fine blade pitch settings. The collective blade pitch calibration will require a boom-lift to measure the blade pitch with the rotor installed. The NRT PI will complete the calibration of the blade strain gauges during the slow roll test. He will also assist in calculating the measured strains and transformations to thrust moments. The NRT PI will then analyze the thrust loading and advise the SWiFT Controls Lead on how to modify the collective blade pitch or torque constant.

7. PROCEDURES

This section presents the major test procedures that will be used to achieve the test objectives.

7.1. Pre-Assembly

The pre-assembly includes preparing the NRT blades for ground assembly including painting the NRT blades, surface roughness measurements, and mass and balance measurements. In addition, the management of change will be completed with IEC design load case simulations to verify the NRT will safely operate.

7.1.1. Blade Painting and Surface Finishing

The NRT blades will be painted according to the NRT paint scheme document. The painted surface will be mildly sanded or polished to remove orange peel from spraying. Refer to the following Surface Roughness section for a description of roughness requirements.

7.1.2. Surface Roughness

Following any painting and finishing of the blade, and before installation of the rotor onto the nacelle, the surface roughness of the blade should be quantified by a profilometer. The surface roughness should be sufficiently low that is of equal or better quality than the V27 blades, and have minimal roughness to affect aerodynamic performance, whichever is stricter.

NACA recommended roughness not exceeding 0.0001c based on wind tunnel tests. The NRT at 86% radius (where maximum thrust occurs) has a chord of 23.5 inches. Therefore, the painted and polished surface of the NRT blade should have an average roughness below 0.0023" or 58 μm to not affect aerodynamic performance.

The NRT will have an average surface roughness equivalent or better than the V27 blade, $R_a \leq 0.243$ μm and $R_z \leq 1.32$ μm. Twenty roughness measurements will be taken on the suction surface at maximum chord (x = 2.875 m) and 20 measurements at maximum thrust (x = 10.81 m) all at the half-chord location, 10 in the chordwise direction, and 10 in the span direction using the Starrett SR-160 profilometer. The average of all 40 measurements will quantify the overall NRT blade surface roughness. Therefore, matching the V27 roughness is stricter than the aerodynamic requirement. Record surface roughness measurements in the Test Results Summary Report document.

7.1.3. Mass and Balance

A measurement of each blade's mass and center of mass location will be performed. The balance boxes should be used to adjust mass differences between blades. Record the final blade masses and center of mass locations in the Test Results Summary Report document. Escalera and Wetzel specified a tolerance 0.3% maximum difference between the three blades' static moment [3].

7.1.4. Root Fastener Test

To ensure the NRT root fasteners are safe to fly and free of manufacturing defects, all bolts in all blades shall be tested to 54 kN of tension. This corresponds to the maximum loading on a single bolt from FAST simulations. In addition, the root fasteners of NRT 000 blade, which was statically tested to failure at NREL, shall be tested to 3 times the ultimate load.

7.2. Safety Review

A safety readiness review and management of change will take place prior to rotor commissioning. The management of change addresses the hazards proposed in this test plan associated with flying new blades on an existing nacelle. Dynamic load simulations will be performed in FAST to ensure no unsafe tip deflections or dynamic loading takes place, or that the machine exhibits any unexpected stops or shutdowns using the V27 controller.

7.3. Ground Assembly

The ground assembly ensures that the blade sensors and associated hub hardware are fully functioning and that the NRT blades are installed on the hub in the proper orientation. Careful geometric alignment of the wind turbine blades ensures that all three blades have the same pitch setting when assembled. The ground assembly includes the following tasks.

- Assemble NRT blades on A1 hub
- Ground blade pitch balancing – see Section 7.3.1
- Backlash measurement – see Section 7.3.2
- Verify strain, temperature, and accelerometer data in each NRT blade

Prior to this experiment, the blades sensors have been calibrated and tested according to [4], but the data channels should be again verified during ground assembly for data quality before installing the rotor on the nacelle.

7.3.1. Ground Blade Pitch Balancing

It is important that each blade has the same pitch angle when rigidly attached to the pitch arm assembly and pitch ram. The following general steps should be followed.

- Assemble NRT blades on A1 hub at the A1 assembly stand on the ground. The blade, bearings and torque plate are first assembled. Then the blade/bearing assembly is attached to the hub
- Rigidly affix the pitch yoke to the interior of A1 hub through the mounting tabs, ensuring the yoke is centered in the hub and flat against the hub body.
- Place NRT blade saddles on blade 1
- Place digital level on each saddle, manually twisting the blade pitch to get the level reading as close to 5° for all saddles. The 5° puts the leading edge below the trailing edge on the assembly stand. This corresponds to a -5° pitch angle with the yoke bottomed out on the hub. The manual pitching motion will be rotating the blades in the bearing, and the pitch plate spindle will rotate freely with respect to the crank arm. It will be easier to use the chain fall to make small angular changes to the blade as opposed to a motorized crane.
- Lock blade 1 crank arm position by tightening clamping screws to pitch plate spindle

- Repeat level measurements and pitch adjustments on NRT blades 2 and 3, leaving all three blades measuring as close to 5° as possible. Leading edge below trailing edge as viewed on assembly stand.

7.3.2. Backlash Measurement

Due to gaps around the pins and linkages of the pitch crank arm assembly, there will be a certain amount of play or backlash. This step will quantify the amount of backlash.

- With a blade assembled to the hub, lock the spider to the hub base using the three spider bolts
- Place the digital level on the flat of the crankarm clamp
- Affix the 7.55 m saddle to the blade
- Use the saddle to apply torsion to the blade by hand, one person pushing up the other down
- Record the angle change of the crankarm
- Repeat torsion in opposite direction and measure angle

7.4. Commissioning and Installation

The commissioning process ensures that mechanical systems and hardware safety systems are functioning. The details of commissioning are detailed in "Sandia SWiFT Facility Site Operations Manual (SAND2016-0746) Volume 6: Turbine Commissioning" [5, 3]. A few parameters in the commissioning tests will be changed for the NRT rotor. These changes are addressed in the Management of Change (MOC) document [2] and the commissioning document. After component tests and safety system tests, the NRT rotor can be installed on the nacelle. Next, the new torque constant should be changed to 2.506×10^{-4} Nm/rpm^2. The commissioning procedure then resumes for run-in tests with phases I—III, to bring the turbine into a fully operational state.

7.5. Modal Testing

After the rotor installation and in parallel with commissioning, ATA Engineering will perform a full modal test of the NRT rotor/tower system. They will also provide a report summarizing their findings in a format similar to their previous report on the V27 modal testing [6]. These quantities will be analyzed by the NRT structural lead to ensure that rotor will safely operate in the 0—44 rpm range without any dangerous resonances. The reported modes can also be used to update the accuracy of the NRT FAST wind turbine model. In addition, the analysis will inform a future speed increase to operate the NRT up to 52 rpm and avoid the measured resonances.

7.6. Flight Test for Design Verification

The following tests occur once the NRT rotor has been commissioned to operate and produce power. First, the collective blade pitch will be calibrated. Next, the strain gauge calibrations will be completed with slow, paused rotation of the turbine. The torque constant will be adjusted to bring the tip-speed-ratio as close to 9 as possible. The collective blade pitch will be finely adjusted to achieve the designed thrust loading.

7.6.1. Tilt and Azimuth Calibration

The tilt and azimuth measurement tests will quantify the rotor shaft tilt and calibrate the azimuth sensor. The following procedure should be followed. Wind speeds shall be below 2 m/s at hub height, and the rotor should not spin faster than 1.8 rpm in pause.

- Take tilt and azimuth measurements on turbine according to "On Turbine Tilt, Azimuth, and Pitch Calibration" [7]
- Analyze azimuth data output compared to digital level readings and adjust controller azimuth offset

7.6.2. Yaw Encoder Calibration

A total station shall be used to measure the alignment of the nacelle. Simultaneously the nacelle heading will be measured through the CompactRIO. Following analysis of the data, a new offset value will be set in the turbine controller.

7.6.3. Tower Strain Calibration

Using the known mass properties of the nacelle and new rotor, a slow yaw of the nacelle will calibrate the tower strain. Command the wind turbine to yaw a clockwise and counter-clockwise revolution. The overhanging bending moment of the nacelle is transmitted to the tower strain gauges.

7.6.4. Collective Blade Pitch Calibration

The collective blade pitch calibration ensures that when the controller commands the blade pitch to run at 0°, the blades are truly at 0° with respect to the rotor plane. The following procedure should be followed.

- Take blade pitch measurements on turbine according to "On Turbine Tilt, Azimuth, and Pitch Calibration" [7]
- Compare controller pitch to digital level angle. Controller range should be adjusted to measured level range.
- Perform least squares fit of pitch linkage kinematic equation to digital level data to solve for 3 pitch linkage lengths that minimize error. Increase weighting of fit at 0° pitch.
- Update pitch linkage lengths in turbine controller kinematic equation
- Command controller to 0° and confirm with blade saddle and level that pitch is actually 0°.

7.6.5. *Slow Roll Strain Calibration*

The slow roll strain test objective is to finish the calibration of all three NRT blades strain gauges. By measuring strains as a function of rotor azimuth and using the known mass and center of gravity location, the strain due to gravity can be separated from the aerodynamic strains. The aerodynamic strains are important to the fine pitch tuning and span-wise load verification tests.

Strain gauge data shall be collected with the NRT operating in pause in low wind speeds. Hub height wind speeds less than 2 m/s are considered low, the rotor shall not spin faster than 1.8 rpm in pause, and at least one hour of data should be recorded. This data should then be used to finish the transformation process from blade strains to aerodynamic thrust moments by Jonathan White. This test will also serve as data channel verification for all blade sensors. The processing capability is necessary for the fine pitch tuning and span-wise load measurement tests.

7.6.6. *Torque Constant Tuning*

During commissioning the high-speed shaft torque constant should be changed to 2.5162×10^{-4} Nm/rpm^2. This should bring the NRT close to the desired tip-speed-ratio of 9. During the flight test, the NRT will be operating at a wind speed in region 2 (wind speeds above cut-in and below 6.9 m/s) but will not be exactly achieving a tip-speed-ratio of 9. A small adjustment of the high-speed shaft torque constant can be made to slow down or speed up the turbine at a given wind speed. This can be for any wind speed in region 2, but low turbulence intensity is preferred, $TI <$ 7.5%. The equilibrium rotor speed is found by equating generator power to aerodynamic power,

$$k\Omega^3 = \frac{1}{2}\rho U_\infty^3 \pi R^2 C_P \eta.$$

For the same wind speed, and negligible changes to C_P near the design tip-speed-ratio, the torque constant is proportional to the cubic-inverse of rotor speed,

$$k \propto \frac{1}{\Omega^3}.$$

This relationship is useful to tune the torque constant. For example, if the tip-speed-ratio is 5% low when the NRT is initially flown, the rotor speed should be increased by 5%, and the torque constant should be decreased by the factor $\frac{1}{1.05^3} = 0.86$. This will let the rotor spin 5% faster at the same wind speed and achieve the desired 5% higher tip-speed-ratio. Conversely, if the tip-speed-ratio is 5% high, the rotor speed should be reduced by 5%, and the torque constant should be increased by the factor $\frac{1}{0.95^3} = 1.17$.

7.6.7. *Fine Pitch Tuning*

Once the NRT torque constant has been tuned to achieve a tip-speed ratio of 9, the machine should be operated to collect strain data. From these measurements, the fine pitch setting of the controller in region 2 can be adjusted to achieve the designed thrust loading. This can be for any wind speed in region 2 (wind speeds above cut-in and below 6.9 m/s), but low turbulence intensity is preferred, $TI < 7.5\%$.

The desired root thrust bending moment coefficient is 0.1738. The root thrust pitch sensitivity is -0.0145 $C_{M_T}/°$. If for example, the measured $C_{M_T} = 0.20$, the collective pitch should be increased 1.8°. Ideally, this will bring the correct loading to all 4 span stations. This will be an adjustment to the operating set point in the pitch controller.

If one blade pitch adjustment brings some stations closer to their correct loading distributions but not at other stations, it is not clear which stations should be properly adjusted or are more important to the wake. The root at least ensures the average thrust force loading over the whole rotor is correct. In addition, blade-to-blade moment differences may appear. If it is deemed important, the rotor could be deconstructed, and individual blade pitch can be adjusted as appropriate.

Any pitch adjustment will change the tip-speed-ratio slightly. Therefore, an additional torque constant tuning should take place following a fine pitch adjustment.

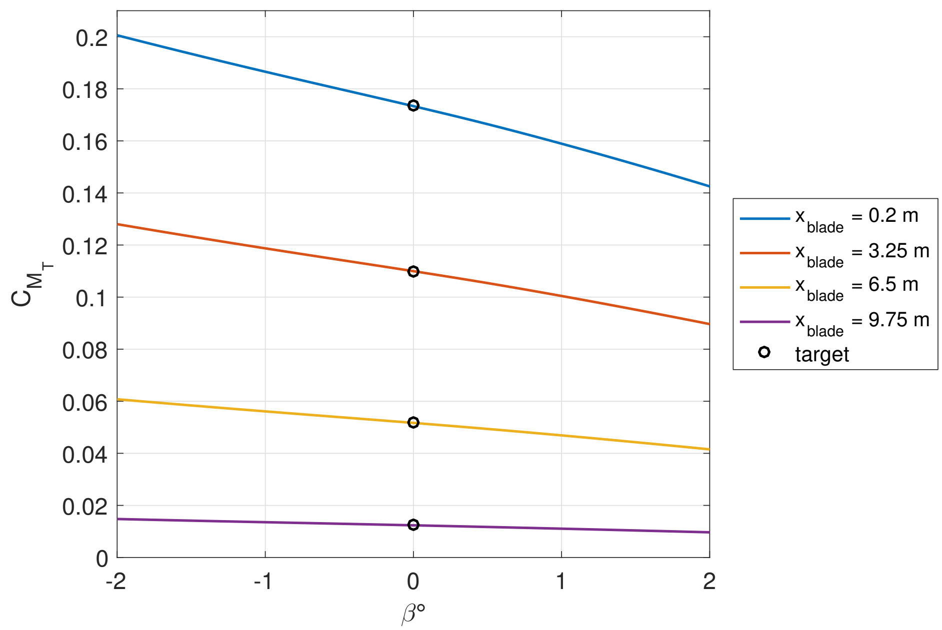

Figure 2. The effect of blade pitch on root thrust bending moment coefficient.

7.6.8. Span-wise Load Verification of Circulation (Thrust Loading)

To check that the NRT has the designed blade loading, the thrust moment coefficient measured from the distributed strain gauges should be checked in region 2 wind speeds (4—6.9 m/s) with low turbulence, $TI < 7.5\%$. The scaled design need only to match the thrust loading that is tabulated in Table 4. Force coefficients should be scaled by the density ratio, $\frac{\rho_0}{\rho_{exp}}$, where ρ_0 is the average SWiFT air density, 1.078 kg/m^3, when comparing to values in the table.

Table 4. Moment coefficients to match design NRT span-wise loading.

C_{M_T}	x_{blade} (m)
0.1738	0.20
0.1102	3.25
0.0518	6.50
0.0124	9.75

C_{M_E}	x_{blade} (m)
0.0155	0.20

The moment coefficients along the blade span in region 2 are plotted below and hold for any wind speed in region 2. Additional details of the force, moment, and coefficient formulas are summarized in Appendix A1.

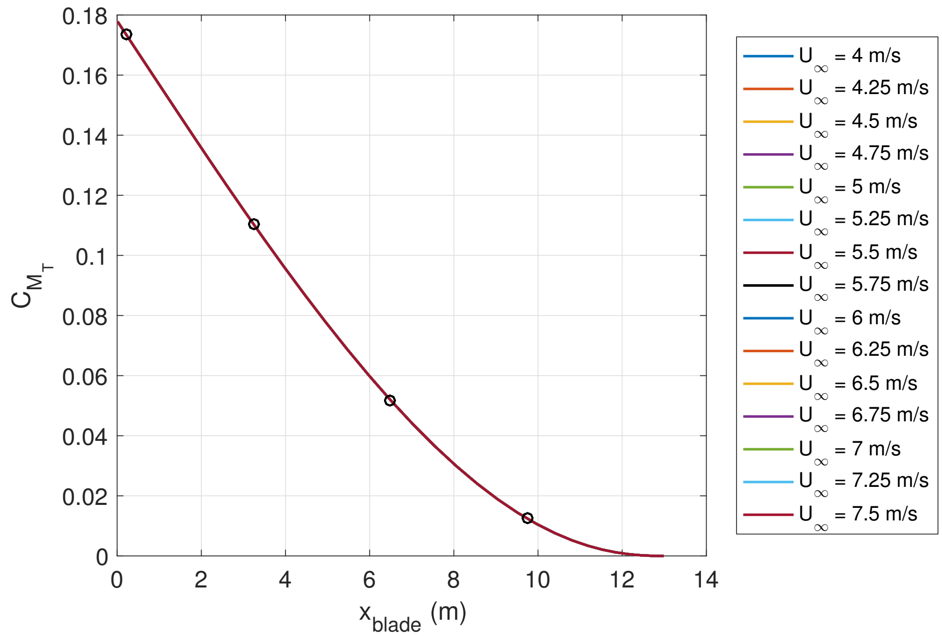

Figure 3. Thrust moment coefficients along NRT span for any wind speed in region 2.

7.7. Supplemental Tests

There is flexibility in the final phase of the experiment depending on schedule and research priorities after approximately 26 weeks of testing in which the NRT is now performing as designed. One possible test would involve a new MOC process to increase the NRT maximum rotor speed from 43.9 rpm to 52 rpm. An increase in rotor speed would increase the wind speed range over which the NRT operates in region 2, producing a scaled wake. This would increase the rate of data collection for future wake experiments. The MOC process could also be used to certify the NRT to operate into region 3 with blade pitch power control and unattended operation.

If the NRT is underperforming with respect to power and efficiency, flow visualization could be performed to better understand 3D flows not modelled in its design.

Another supplemental test that would be to measure the wake after the blade loading has been matched to design. This would be the final step to verify the scaled wake is being created by the NRT rotor and the velocity deficit matches the GE 1.5sle.

The ability to measure strain from accelerometers could be implemented based on the data collected during the spanwise loading measurement tests. This would increase the experimental data processing capability of the group.

Finally, the NRT could be brought into unattended operation mode and left to produce power for a longer campaign to measure the NRT power curve with IEC standards.

8. REPORTING

The Reporting section describes which sensors and data channels are necessary for each test and summarizes the process of data verification and upload to the NRT experiment collaborative drive.

8.1. Sensors and Data Channels

Throughout this experiment various data channels and sensor readings should be recorded for calibration and analysis. Table 5 summarizes the required sensors and data channels for each test and should be used as a general checklist. Within the table, level refers to the digital level which records and transmits data over Bluetooth. Met tower wind speed is the sonic anemometer at hub height on the A1 meteorological tower. Strain gauges refer to all the strain gauges in the NRT blades that are recorded to the hub and transmitted wirelessly following an experiment. Controller pitch, rotor speed, and azimuth are all data channels recorded by the CompactRIO in the A1 turbine.

Table 5. Necessary data channels for each test.

Test	Required Sensors
Surface roughness	Profilometer, tape measure
Mass and balance	Load cell, tape measure, laser guide
Ground blade pitch balance	Digital level and blade saddles
Backlash	Digital level
Verify data channels	Blade sensors
Tilt and azimuth	Digital level, met tower, rotor speed, azimuth
Yaw encoder calibration	Yaw encoder, total station
Tower strain calibration	Yaw encoder
Collective pitch calibration	Digital level, blade pitch, azimuth
Slow roll strain calibration	Blade pitch, met tower, rotor speed, blade strains, azimuth
Tune torque constant	Met tower, rotor speed
Fine pitch tuning	Controller pitch, met tower, rotor speed, blade sensors, azimuth
Span-wise load measurement	Controller pitch, met tower, rotor speed, blade sensors, azimuth

8.2. Data Verification and Upload

Following each test, the necessary data channels will be uploaded to the collaborative drive folder "Design_Verification_Experiment." The data quality will be analyzed by an engineer. Most tests also require analysis of the data to calculate specific quantities which are a prerequisite for the following test. The engineer reviewing and analyzing data from each test will write a short summary report to be placed in the NRT experiment collaborative folder within the document existing template "Test_Results_Summary_Report.docx." For example, the slow roll strain test data will be copied to folder test_data/slow_roll_strain, analyzed, and checked for data quality. Only after the data is reviewed for quality can the next test proceed.

The turbine operator should keep a test log of daily activities relating to the NRT design verification experiment. As with the previous wake steering experiment, the turbine operator should record daily events and tests performed, observations, and site conditions. It is important to record the time when test starts and ends, so that the time range of data for analysis is easily identified.

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APPENDIX A1: SPAN-WISE LOADING FORMULAS

The designed thrust and edge forces along the blade were found from WT_Perf for the NRT design, integrated to derive the desired moments, and then normalized to a coefficient according to the following equations:

$$M_T(x) = \int_x^L \int_x^L F_T(\xi)\, d\xi\, d\lambda$$

$$C_{M_T}(x) = \frac{M_T(x)}{\frac{1}{2}\frac{\rho_{exp}}{\rho_0} U_\infty^2 \pi R^3}$$

$$M_E(x) = \int_x^L \int_x^L F_E(\xi)\, d\xi\, d\lambda$$

$$C_{M_E}(x) = \frac{M_E(x)}{\frac{1}{2}\frac{\rho_{exp}}{\rho_0} U_\infty^2 \pi R^3}$$

The reference density, ρ_0, is 1.078 kg/m^3 and is the average air density at SWiFT. The thrust force acts on the blade parallel to the axis of rotation. The edge force acts on the blade in the rotor plane and perpendicular to the pitch axis.

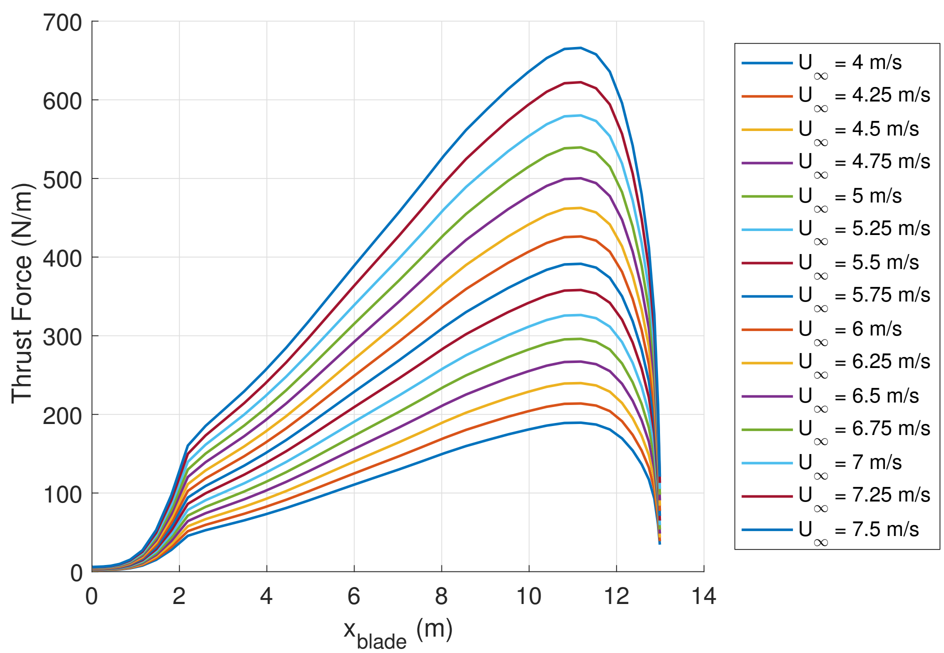

Figure 4. Thrust force across blade span for various wind speeds in region 2.

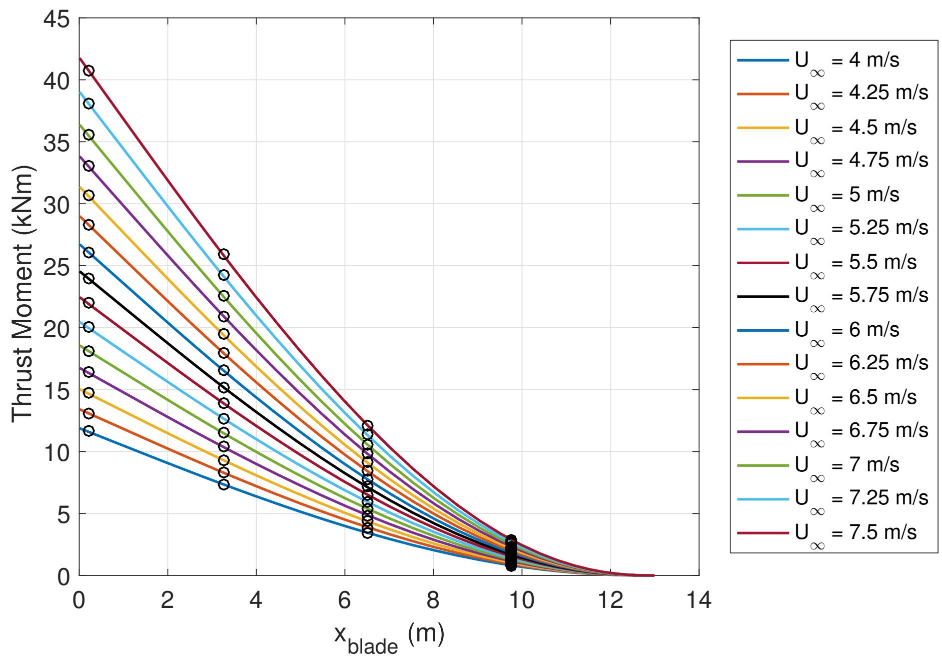

Figure 5. Thrust moment across blade span for various wind speeds in region 2.

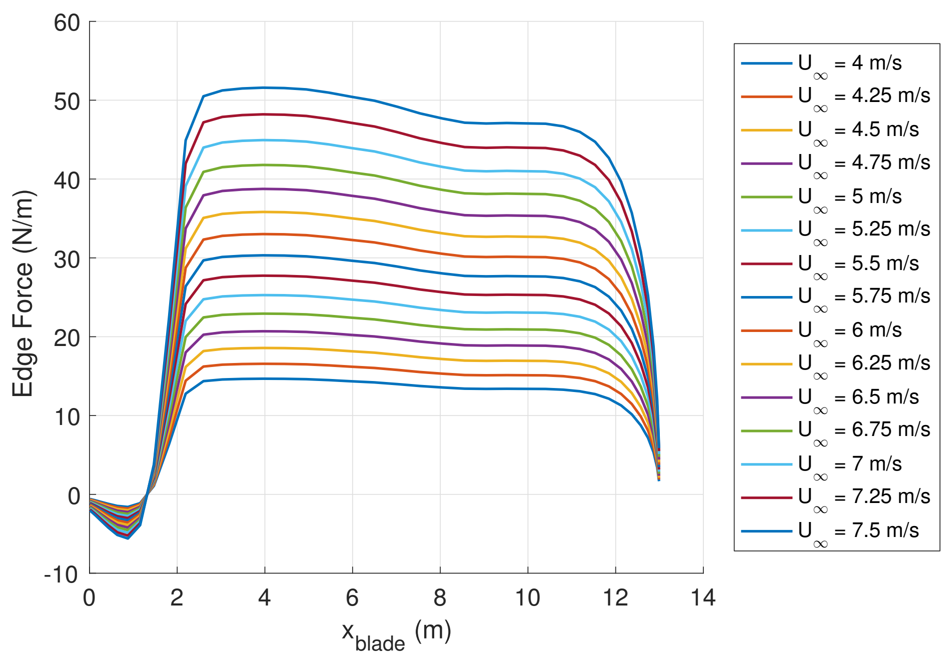

Figure 6. Edge force across blade span for various wind speeds in region 2.

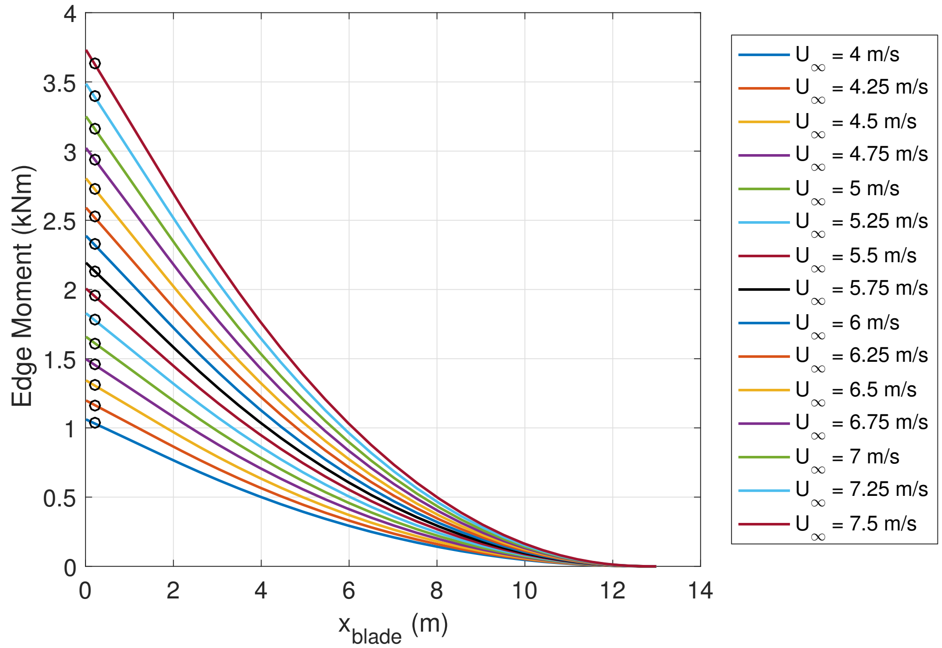

Figure 7. Edge moment across blade span for various wind speeds in region 2.

The strain gauges for flap strains are positioned at blade coordinates 0.20 m, 3.25 m, 6.5 m, and 9.75 m away from the root. Edge strains are measured 0.20 m away from the root. The flap and edge moment coefficients at these specific blade locations are tabulated below for region 2.

Table 6. Moment coefficients to match design NRT span-wise loading.

C_{M_T}	x_{blade} (m)
0.1738	0.20
0.1102	3.25
0.0518	6.50
0.0124	9.75

C_{M_E}	x_{blade} (m)
0.0155	0.20

Because the strain gauges do not measure exactly in the thrust direction, the flap moments from the strain gauges should be transformed to the thrust direction for comparison to the design values. The dimensionless force and moment coefficients do not change for different wind speeds in region 2 because the tip-speed-ratio and angles of attack remain constant. Verifying at one wind speed is sufficient. Small differences in moment coefficients for various winds in region 2 may appear due to Reynolds number effects.

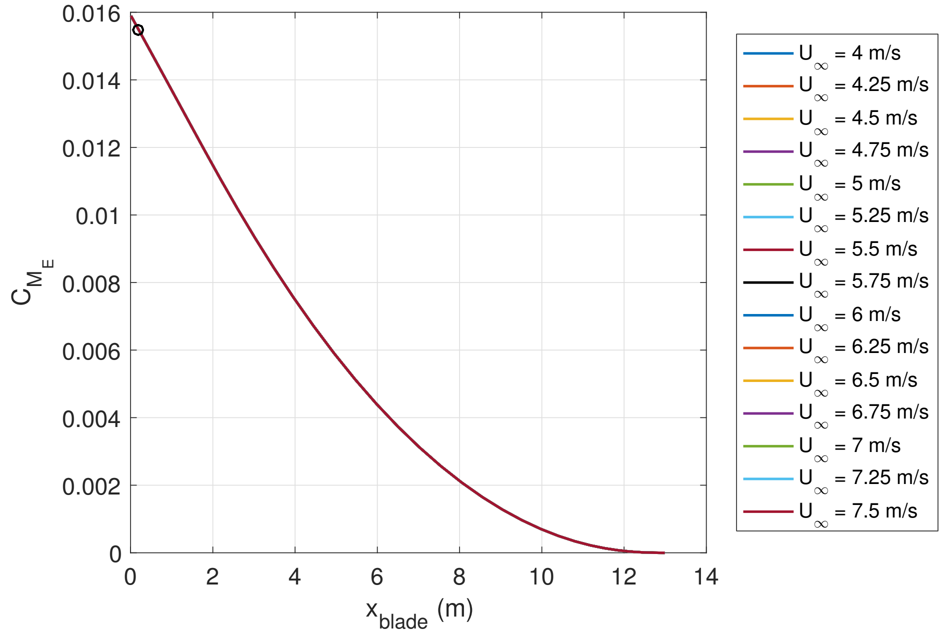

Figure 8. Edge moment coefficients along NRT span for any wind speed in region 2.

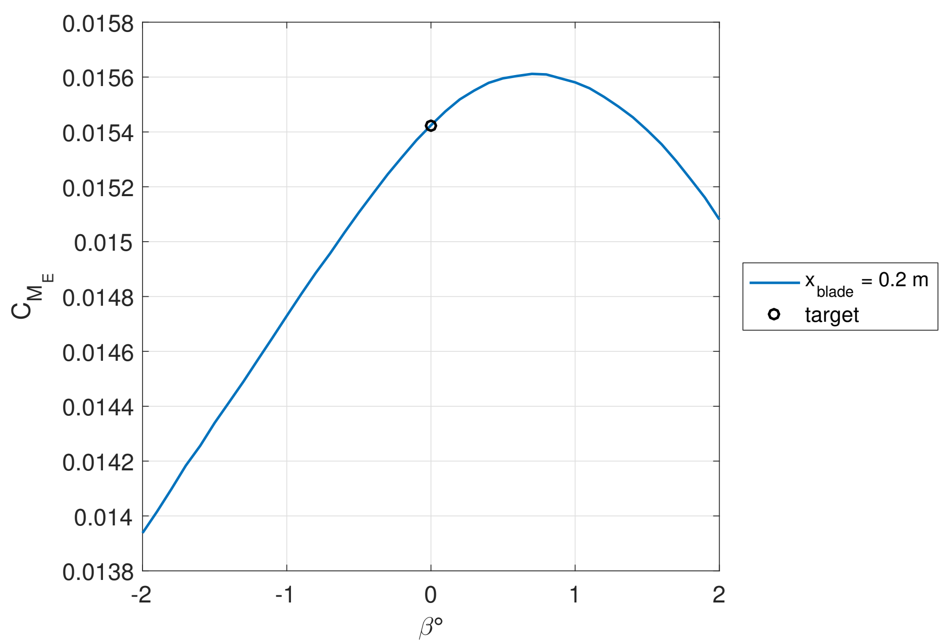

Figure 9. The effect of blade pitch on root edge bending moment coefficient.

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