Virtual Testing of Full Scale Wind Turbine Nacelles

Wind energy conversion systems have experienced a steady growth in size through their commercialization and use in utility scale power production. As wind turbine size increases, so too must the devices used to test them. Modern wind turbine test benches are larger and more complex than ever before and are impressive dynamic systems in their own right. Because these test benches are so few in number, and each one is slightly different, each bench must be studied individually. SIMPACK is being used along with other modern engineering tools to understand and fully utilize these modern, monster machines.

INTRODUCTION

Clemson University's Wind Turbine Drivetrain Testing Facility (WTDTF) is located at the South Carolina Electric & Gas (SCE&G) Energy Innovation Center (EIC) in North Charleston, SC, USA. The WTDTF houses two wind turbine dynamometer test benches, one rated at 7.5 megawatts (MW) (Fig. 1) and the other rated at 15 MW. These test benches are designed to rotate full-scale nacelles while applying non-torque loads (thrust force, vertical force, shear force, pitch moment, and yaw moment). Additionally, the Duke Energy eGRID (electric Grid Research Innovation and Development) center, also located at the EIC, is designed and built to load the nacelle electrically with the facility's 15 MW hardware-in-the-loop (HiL) electric grid simulator.

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The single biggest challenge to studying system-level wind turbine behavior is the stochastic nature of its natural driving force — the wind. Wind profiles corresponding to many of the design load cases are generally rare events, and if you are lucky enough to experience one in the field with a prototype turbine, you'll never see one just like it again. These test benches allow

Fig. 1: Clemson University's 7.5 MW test bay showing the drive motor, gearbox, load application unit, and nacelle

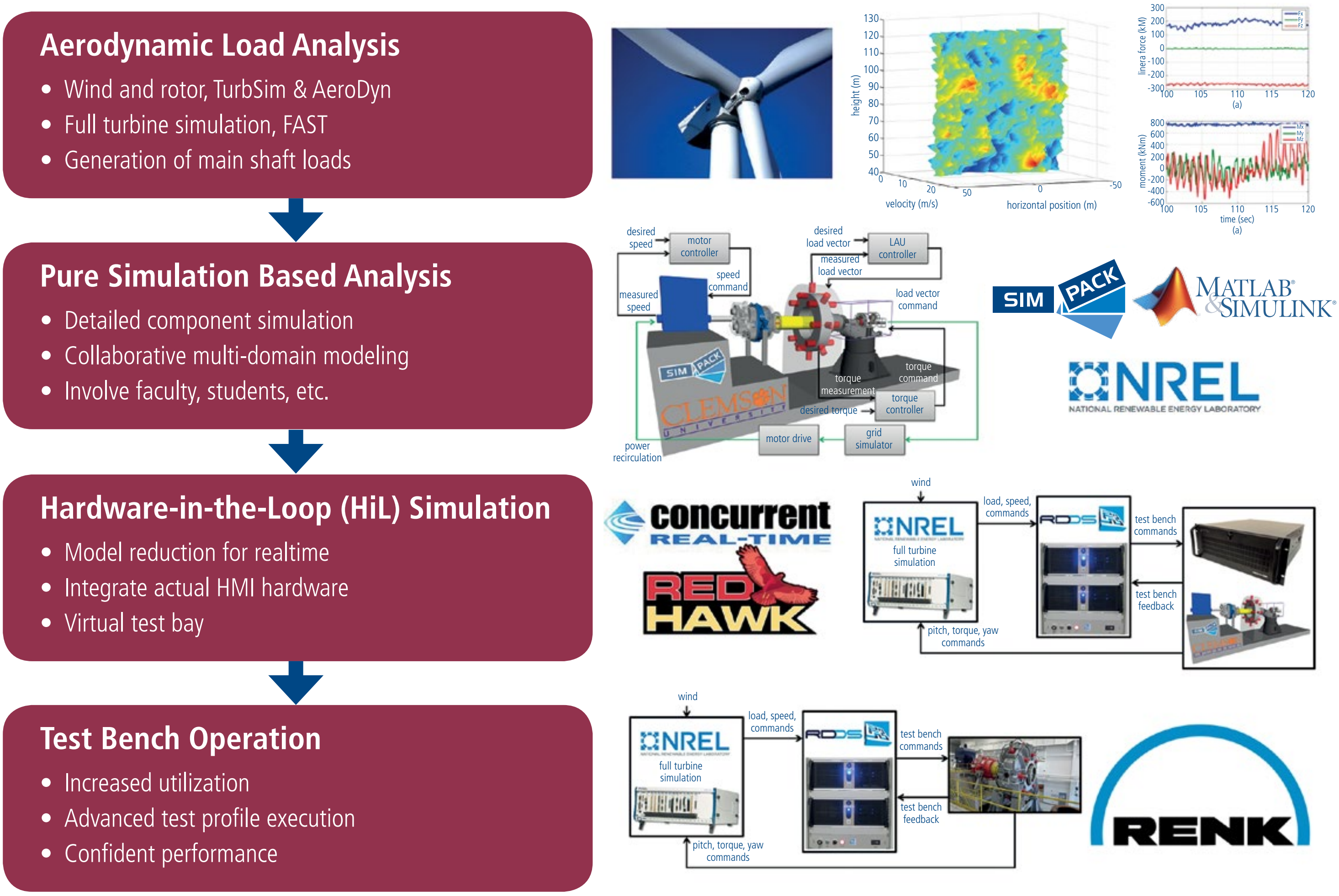

Fig. 2: Various modeling and simulation activities are underway including aerodynamic load analysis, pure simulation based analysis, and HiL simulation. All of these activities directly support the physical testing that is carried out on the test benches.

for engineers to controllably and repeatably apply full-scale loads to the nacelle.

PROBLEM

The facilities at the EIC offer tremendous testing capability for both the onshore and offshore wind industry. Additionally, the facilities offer many research and development opportunities for students and faculty at Clemson University and partner universities. Unfortunately, these systems are limited resources as they are very expensive to operate and can be dangerous if not used properly.

SOLUTION

To help mitigate these shortcomings, Clemson University is constructing a multibody, real-time simulation laboratory. The simulation lab will serve as an intermediary between purely simulation based analysis and physical testing (Fig. 2). The lab consists of two primary pieces of equipment. The first is a duplicate test control computer from RENK Test Systems referred to as the RENK Dynamic Data System (RDDS). The second is a real-time simulation computer from Concurrent Real-Time. The test control computer is the human-machine interface to the test rig and is where the test engineer programs the test profile, executes the test, and monitors the behavior of the test bench.

The real-time simulation computer is for running dynamic models of the test benches, which interact with the duplicate test control computer in real-time. The Concurrent system is a 2.9 GHz Xeon E5 8-core machine with EtherCAT and reflective memory I/O in addition to typical A&D I/O. The machine runs RedHawk Linux, an industry-standard, real-time, low-latency operating system perfectly suited for such a demanding application. The actual simulations are managed by Concurrent's SIMulation Workbench, a complete framework for developing and executing real-time HiL simulations. This tool allows for the SIMPACK model to be relegated to specific CPU cores, isolating it from other models or processes and ensuring deterministic behavior. This tool also handles the I/O mapping between the simulation models and the I/O hardware.

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The simulator accepts input signals from the test control computer, simulates the dynamic response of the test bench, and provides feedback to the test control computer. This is essentially a virtual test bench, which offers engineers the ability to evaluate proposed test profiles, troubleshoot unexpected behavior, and train personnel without ever having to use the physical test bench. Additionally, the lab will have controllers, I/O hardware, and data acquisition hardware so that engineers can replicate test-floor configurations in a laboratory setting.

Although the testing facility is a Clemson University facility, it is not a typical university lab. The equipment is large, expensive, and potentially dangerous, making it difficult for students and faculty to engage with the facility. The simulation lab makes the dynamics of the test benches accessible to students and faculty with zero risk compared to using the actual test bench.

The laboratory is designed specifically to replicate and study the dynamic behavior of the complete test bench, including both the device under test (DUT) and the test equipment (hardware and software). Many other researchers and manufacturers have studied the dynamic responses of wind turbines. This lab is focused on understanding the dynamic response of the complete test bench system, including the nacelle.

SIMPACK MODEL

To better understand the dynamic response of the complete test bench, multi-body and dynamic models of the test benches have been created in SIMPACK and Simulink®. The complete test bench includes the DUT in addition to the test equipment. Components modeled in SIMPACK include the drive motor, high-speed couplings, 7.5 MW reduction gearbox, low speed shaft, load application unit disk, and nacelle, including main bearing, gearbox, and generator. The dynamic character of the DUT will significantly influence the overall system response, and therefore, must be included in the modeling effort. Clemson University has been working with its first customer, General Electric, to develop representative dynamic models of their wind turbine nacelle, also in SIMPACK.

"The system model is divided into naturally occurring subsystems in both SIMPACK and Simulink."

Many of the component models have multiple versions with varying levels of fidelity allowing the complexity of the overall model to be aligned with specific modeling goals. For real-time applications, for instance, stiff elements are modified such that all natural frequencies of the full model fall well below 500 Hz in order to achieve the desired fixed time step of 1 ms. Additionally, the number of states is kept reasonable and in line with the real-time hardware's computational capabilities.

The system model is divided into naturally occurring subsystems in both SIMPACK and Simulink. Senders, Receivers, and Substructures are heavily used in SIMPACK making the model easy to reconfigure and work on. For example, there are three versions of the 7.5 MW reduction gearbox. The low fidelity version is intended for real-time applications. It uses linearized gear elements, neglects bearing stiffnesses, and has a simplified construction of a rather complex input stage. At the other end of the spectrum, is the high fidelity gearbox model which includes SIMPACK's 225 Gear Pair Force Element, bearing stiffnesses, and a load balancing mechanism found on the input stage's parallel shafts. The medium fidelity model is somewhere in between. However, all the gearbox models have the same input, output, and support Markers

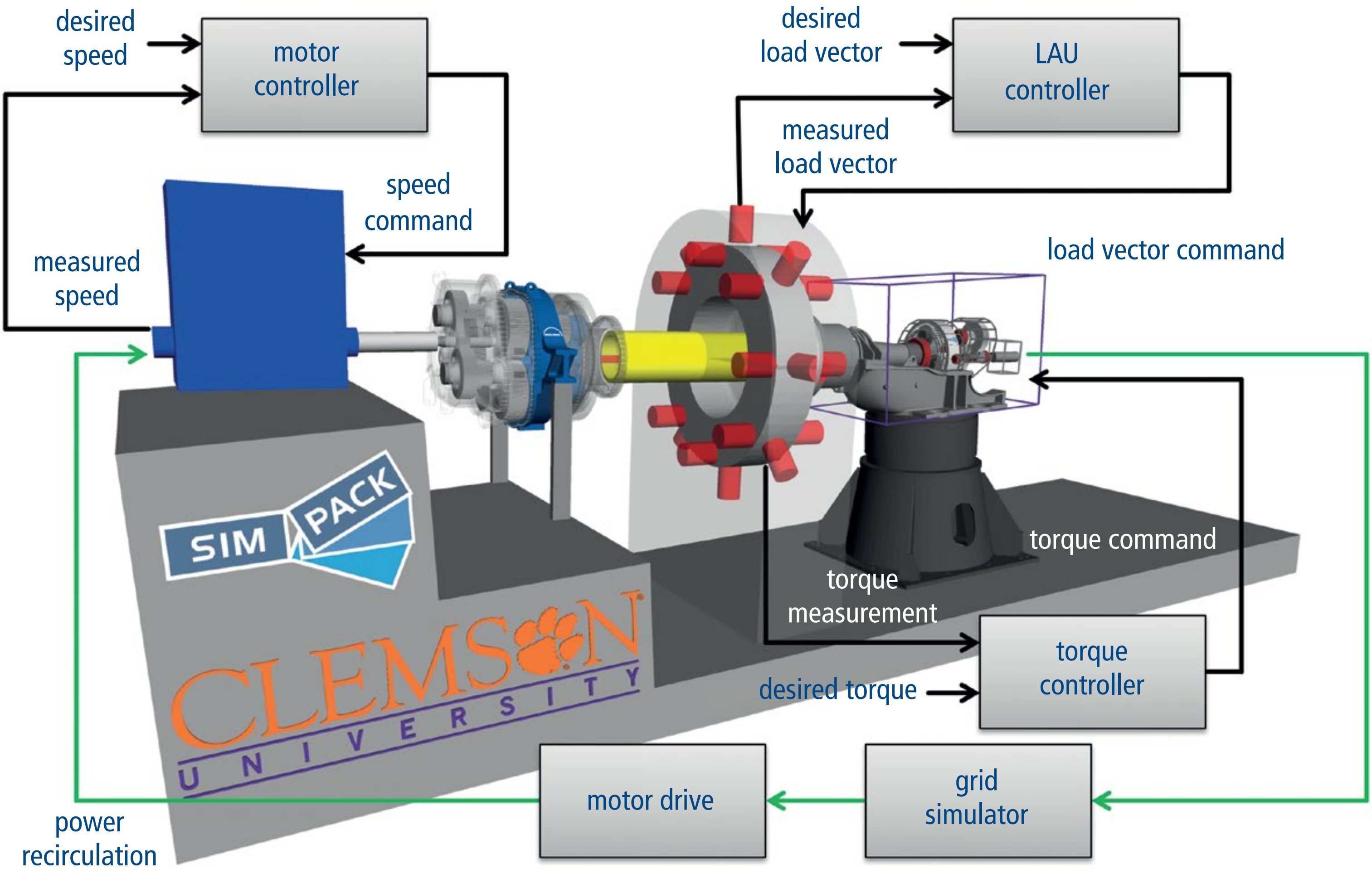

Fig. 3: Integrated test rig model showing the multi-body and non-multi-body models and how they interact with one another

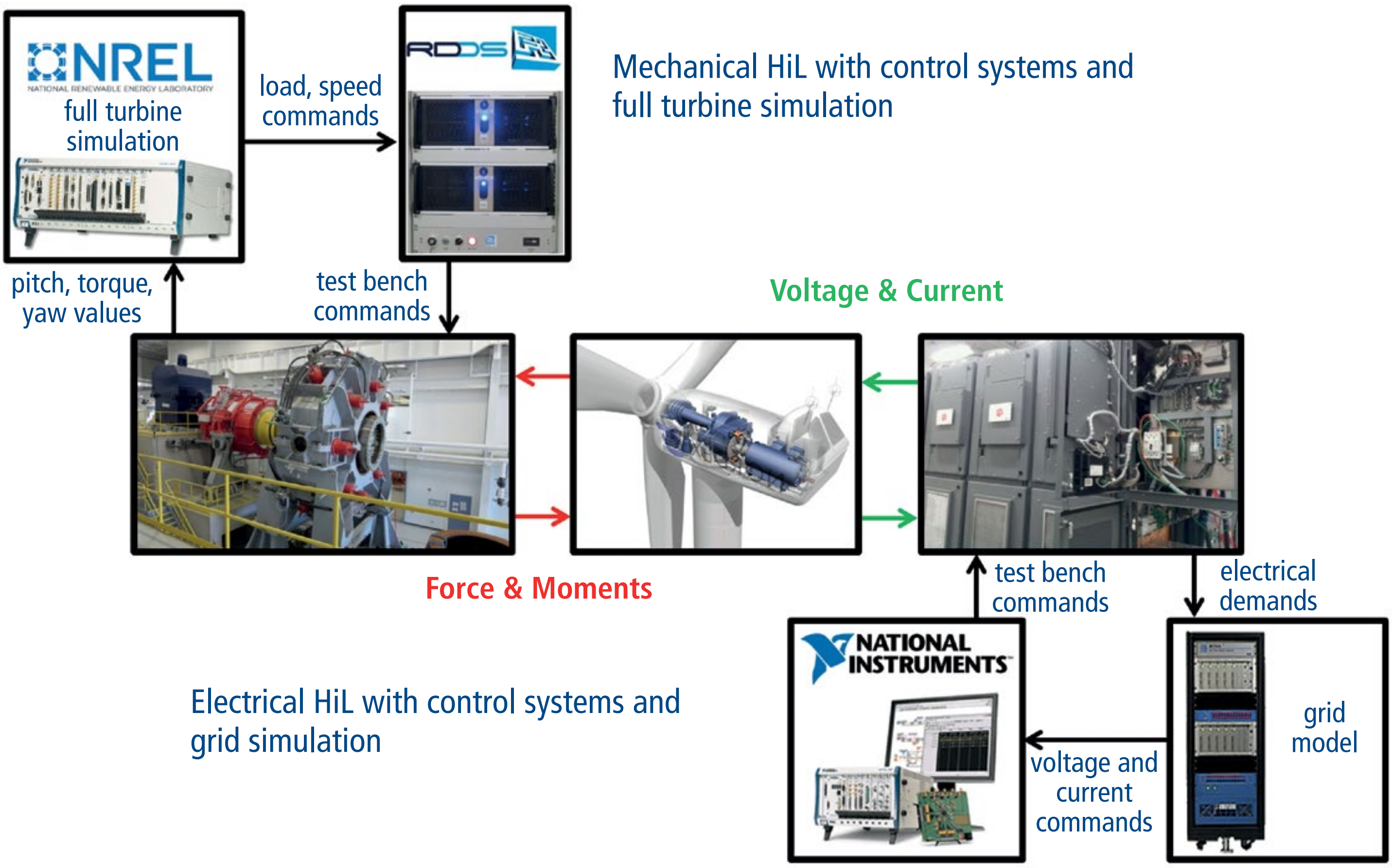

Fig. 4: Diagram of advanced testing topology showing both mechanical and electrical hardware-in-the-loop configurations

making it easy to reconfigure the model for high and low fidelity simulations. In addition, the modular nature of the developed models makes it easy to add fidelity locally. For instance, engineers can combine lower fidelity drive side models with higher fidelity nacelle models to study internal nacelle behavior while reducing computational effort. The fully reduced multi-body model has 23 states while the high fidelity model currently has 68 states.

Another advantage of the modular construction is the ability to reuse modeling elements. The 7.5 and 15 MW test benches are similar in design and construction, and some of the multi-body elements are being used for both the 7.5 and 15 MW benches. Finally, the Simulink portions of the models have been parameterized so that they can be coupled with the 15 MW multi-body model as well. Development of the 15 MW test bench model is on track to take only a fraction of the time that was needed to develop the 7.5 MW model.

> ***"The ultimate goal is to replicate a nacelle's response to full-scale mechanical and electrical loads in a controlled and repeatable environment."***

OTHER MODELS

In addition to multi-body systems, the test benches include hydraulic, electric, and control system models all functioning simultaneously to produce an overall system response.

The drive motors are controlled with industry standard motor drives, which implement a pro-portional-integral (PI) control scheme with anti-windup protection (when in speed control mode). Servo-valves are responsible for directing 5 MW of available hydraulic power to manipulate the two LAUs. The servo-valves themselves are controlled by a custom designed, multi-input, multi-output control system implemented in RDDS. The generator in the nacelle can be controlled from RDDS for standard dynamometer configuration or can be controlled by the nacelle's on-board control systems for simulated nacelle operation.

The governing equations for these various subsystems were developed analytically and coded in Simulink. These models interact with the SIMPACK model using SIMPACK's co-simulation feature or the S-function model export feature. The complete model

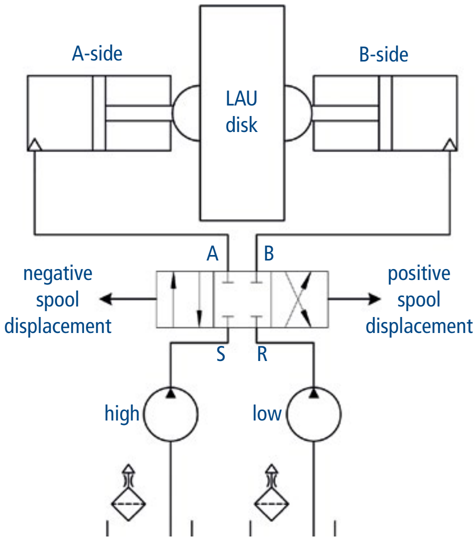

Fig. 5: Diagram showing the hydraulic control configuration: Each pair of horizontally opposed actuators is controlled by a single valve

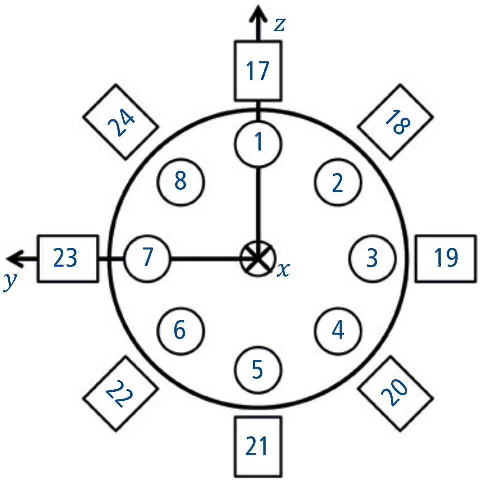

Fig. 6: Diagram showing the orientation of the hydraulic actuators around the LAU disk. Actuators 9–16 are opposite actuators 1–8.

couples the behavior of the multi-body and non-multi-body systems as shown in Fig. 3.

ULTIMATE GOAL

The ultimate goal is to replicate a nacelle’s response to full-scale mechanical and electrical loads in a controlled and repeatable environment. Replicating such a response requires two hardware-in-the-loop simulations operating simultaneously — one mechanical and one electrical. Fig. 4 shows how the two simulation loops interact with the DUT. This is an advanced testing strategy and making it a reality is challenging.

Engineers at eGRID are currently developing dynamic models of the facility’s power systems and future goals include coupling the mechanical (WTDTF) and electrical (eGRID) models to form a single, facility-level, dynamic model. The availability of such a model will help to make this testing strategy a reality.

LOAD APPLICATION UNIT SUBSYSTEM

Already, the dynamic models have been used to investigate the effectiveness of advanced, non-linear control algorithms in controlling the LAU. The LAU is a multi-input, multi-output, over actuated, non-linear system. Each pair of horizontally opposed hydraulic cylinders is actuated by a single servo-valve (Fig. 5).

The configuration creates what is essentially a double acting cylinder allowing for linear force actuation in both directions along the cylinders’ line of action. There are 12 pairs of cylinders (24 in total) situated around the LAU disk as shown in Fig. 6.

The tip of each piston is fitted with a hydraulic slide bearing, allowing the disk to slide past each piston regardless of the disk’s orientation in space (Fig. 7).

These actuators allow the LAU to apply forces and bending moments in the non-torque directions. By applying these types of forces and moments, engineers can replicate the effects of gravity and asymmetrical wind loading to study the nacelle's response.

“Clemson University has built a world-class wind turbine drivetrain testing facility for testing and proving the next generation of wind turbine technology.”

These physical systems modeled in SIMPACK and Simulink have been coupled with the control system algorithms to simulate a complete, system level response.

CONTROL SYSTEM DEVELOPMENT

In order to replicate the types of main shaft loads that a wind turbine experiences during normal and extreme wind conditions, the hydraulic actuators must be managed by an appropriately designed control algorithm. A typical starting point, as well as the default control algorithm being used for the 7.5 MW test bench, is a Proportional-Integral (PI) controller. The PI controller is an industry standard, is easy to implement, and has a long history of proven performance. Unfortunately, a PI controller introduces phase lag and is not well suited for multi-input, multi-output, non-linear systems. Fig. 8 shows the control performance of the default PI controller. The test profile (shown in blue) is 500 kN in the Fx and Fy directions (25 % of the 7.5 MW LAU’s rated capacity for linear force) and 500 kNm in the My direction (5 % of the 7.5 MW LAU’s rated capacity for bending moment) at a frequency of 0.5 Hz. This is considered a fairly aggressive profile because the 7.5 MW LAU was originally designed for static operation — this profile is dynamic.

Clearly, the system has some difficulty tracking the reference signal (especially in the Mz direction) although it is not immediately clear whether the difficulty is due to actuator limitations or control system limitations. An alternative sliding model controller was developed, tuned, and used to control the SIMPACK and Simulink test rig model and the results are shown in Fig. 9. The sliding mode controller demonstrates greatly enhanced tracking capability. This control strategy more fully utilizes the available bandwidth of the actuators to apply dynamic loads to the device under test.

CONCLUSION

Clemson University has built a world-class wind turbine drivetrain testing facility for testing and proving the next generation of wind turbine technology. Researchers at the WTDTF have been developing a simulation capability for analysis of the complete test system. This simulation capability incorporates multi-body models created in SIMPACK, dynamic models created in Simulink, real-time simulation hardware, and the actual test control computers. This capability allows engineers, researchers, and customers to study the response of both test benches in a safe, efficient, and cost effective manor.

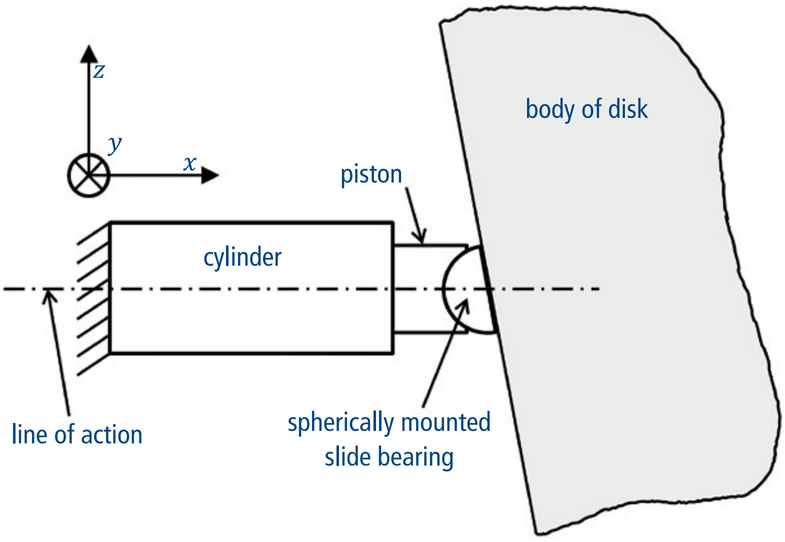

Fig. 7: Diagram showing the operation of the slide bearing: Each of the 24 cylinders is fixed while the disk is free to move; the piston and slide bearing accommodate this motion and maintain contact with the moving disk

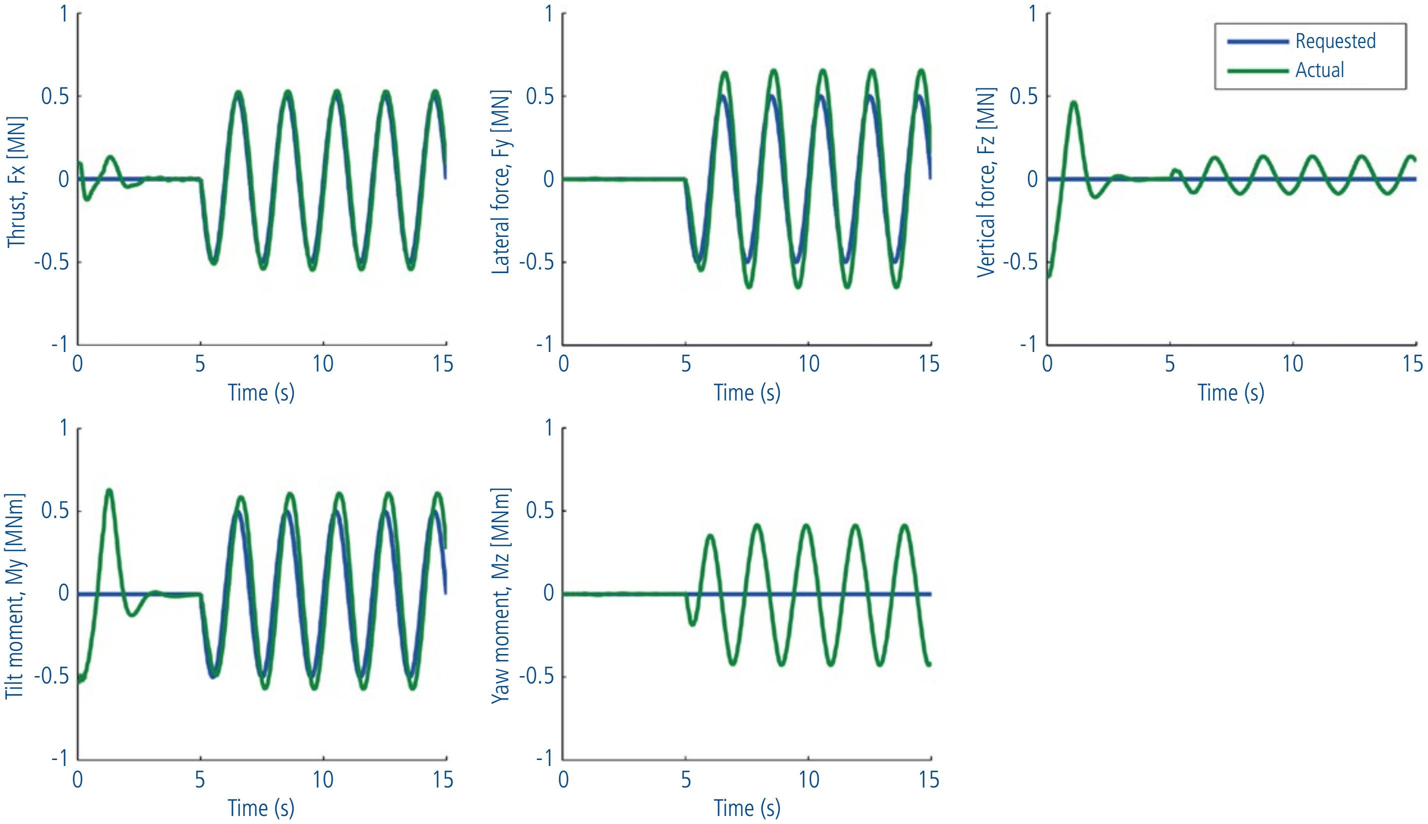

Fig. 8: Response of the LAU when controlled by the PI control algorithm: All five directions show varying levels of difficulty tracking the reference signals

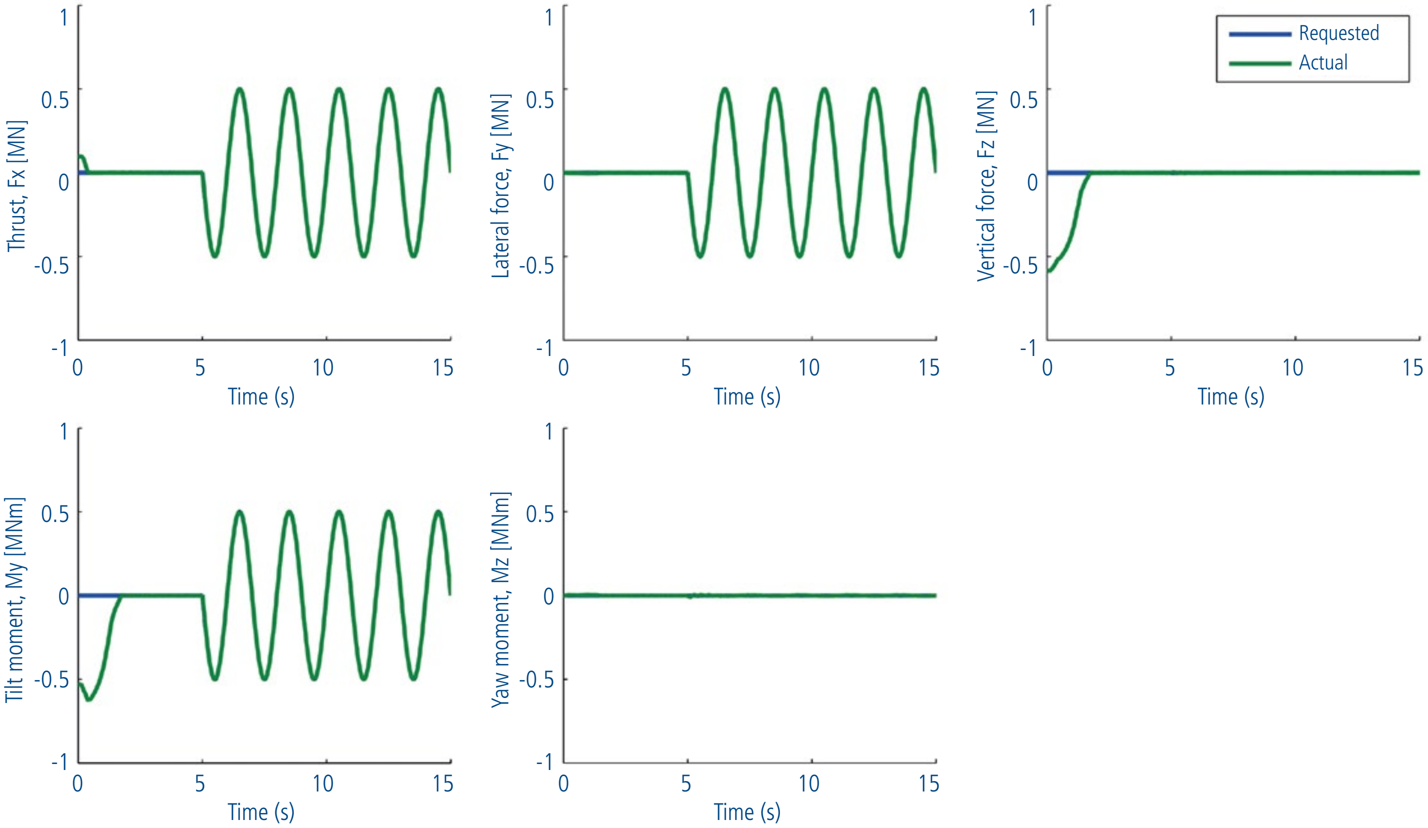

Fig. 9: Response of the LAU when controlled by the sliding mode control algorithm: Aside from some startup transients, the "Actual" (green) is almost indistinguishable from the "Requested" (blue)