WHEN TRUST MATTERS

BLADED: ROTARY PITCH ACTUATOR HSS FLEXIBILITY VERIFICATION REPORT

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Verification Report

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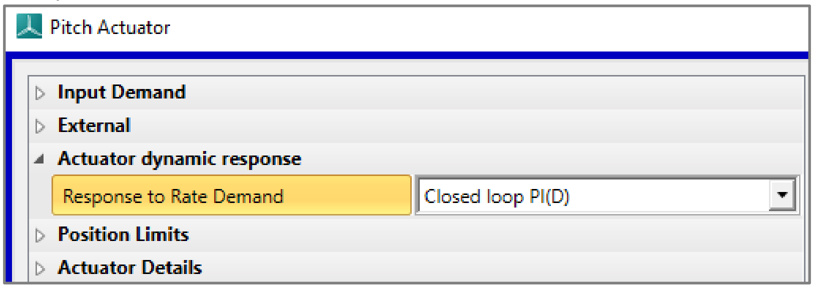
1 OVERVIEW

This document presents a verification study that demonstrates the calculated flexible pitch high speed shaft (HSS) kinematics agree with the theory against which they have been implemented. The implementation is verified by running four separate tests and comparing the obtained results with analytical approaches based on vibration theory. In the first test case a constant torque is applied to the shaft throughout the simulation making the shaft deflect. The second test case consists of applying an initial force, but with no damping such that the shaft experiences free vibrations. A third test case includes the damping, and qualitative observations are made based on various scenarios for the damping factor. Pitch bearing friction is set to a very large number to effectively lock the bearing and restrict the bearing motion. An external loads dynamic link library has been used to apply the torque on the shaft in all the three first test cases, and they are run as parked simulations. The fourth and final test case is a power production simulation of a fixed speed wind turbine, where a simulation with a flexible HSS is compared to a rigid HSS. A relatively low bearing friction is applied along with an external controller that is used to set step function for the demanded pitch rate.

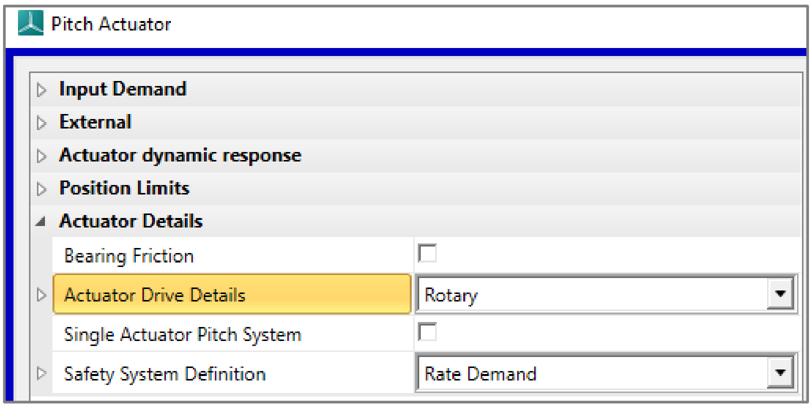
2 IMPLEMENTATION

The implementation of the flexibility in the high speed shaft of the pitch actuator is performed by including a hinge component. This allows displacements for the torsional degree of freedom in the shaft when the pitch actuator flexibility option is activated. The implementation is activated in the UI in the Control module where the Pitch Actuator settings are available under Supervisory Control.

The implementation is only supported for the torque output option *"Closed loop PI(D)"* under "*Actuator dynamic response*":



Moreover, flexibility is only available for the *"Rotary"* actuator drive under "*Actuator Details*":



The flexibility is activated in the "Linear Spring & Damper" option in "Flexibility" under "Actuator Details". This allows the user to specify torsional stiffness and damping coefficients.

3 VERIFICATION

The verification of the implemented flexible HSS in the pitch actuator is demonstrated with four tests. In Test 1, a constant torque is applied on the shaft throughout the simulation. Since the flexibility is implemented as a linear spring and damper system, the shaft should deflect according to Hooke's law. In Test 2 the torque is only applied initially and then the shaft freely vibrates with no damping. It is then possible to compare the natural frequencies obtained in the simulation with natural frequencies according to vibration theory. Test 3 is a qualitative observation of changing the damping coefficient in the simulation runs based on the analytically calculated damping factor. This allows for a demonstration of the different vibration cases that the shaft can experience based on what is expected analytically. In all the tests the pitch bearing is locked (done by setting bearing friction to a very large number), and the torque is applied using an external loads dll. Test 4 is a comparison in power production simulation results between rigid and flexible pitch HSS.

3.1 Constant applied torque (Test 1)

In Test 1 a constant torque is applied to the shaft around the z-axis (longitudinal direction). According to Hooke's law the angular deflection of the shaft (θ) should be equal to the ratio between the applied pitch actuator torque (T) and the specified torsional stiffness (k_t):

$$\theta = \frac{T}{k_t}$$

In the simulation setup the stiffness and damping coefficients are set to 100 Nm/rad and 20 Nms/rad respectively, and the pitch motor inertia is set to 1 kgm^2. Note that the damping is set so that the shaft is critically damped. Two simulations have been run where the applied torque has been set to 1 and 3.2 Nm. The obtained results from the simulation for the angular deflection are then compared to the analytical angular deflection in **Table 1**. Time series of the angular deflection of the flexible pitch HSS for the two runs can be seen in **Figure 3-1**.

Table 1: Parameters and results for Test 1

	Applied torque, T $[Nm]$	Analytical deflection, θ $[rad]$	Simulated deflection, θ_{sim} $[rad]$
Run 1	1	0.01	0.0998
Run 2	3.2	0.032	0.0319

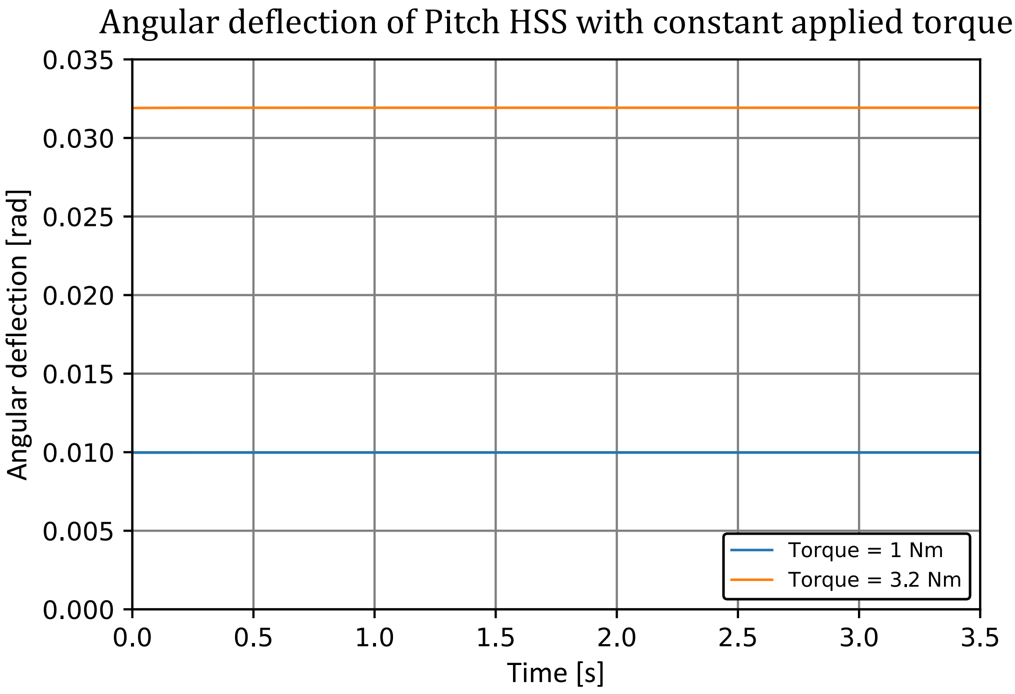


Figure 3-1 – Time series result of angular deflection of flexible pitch HSS for Test 1

3.2 Planar Initial applied torque with no damping (Test 2)

Test 2 applies an initial torque of 1 Nm the first 0.5 seconds and then removes it. This allows the shaft to freely vibrate. The free vibrations of the shaft should depend on the stiffness, damping and inertia properties. For this case the damping has been set to zero such that the shaft undergoes undamped free vibrations. Based on vibration theory the natural frequency of the oscillations (ω) can be calculated as the square root of the ratio between the stiffness coefficient (k) and the pitch motor inertia (J):

$$\omega = \sqrt{\frac{k}{J}}$$

In the simulation results the natural frequency can be determined by using the period of the oscillations (τ) in the vibrational response:

$$\omega_{sim} = \frac{2\pi}{\tau}$$

Four runs are setup with varying stiffness (k) and pitch motor inertia (J) parameters. The parameters, as well as the obtained analytical (ω) and simulated (ω_{sim}) natural frequencies can be seen in **Table 2**. Time series of the angular deflection of the shaft in the four different runs is shown in **Figure 3-2**.

Table 2: Parameters and results for Test 2

	Stiffness, k $[Nm/rad]$	Inertia, J $[kg\ m^2]$	Analytical nat. freq. ω $[rad/s]$	Period in simulation, τ $[s]$	Simulated nat. freq. ω_{sim} $[rad/s]$
Run 1	50	2	5	1.256	5.003
Run 2	98	2	7	0.898	6.997
Run 3	100	1	10	0.6287	9.994
Run 4	289	1	17	0.369	17.03

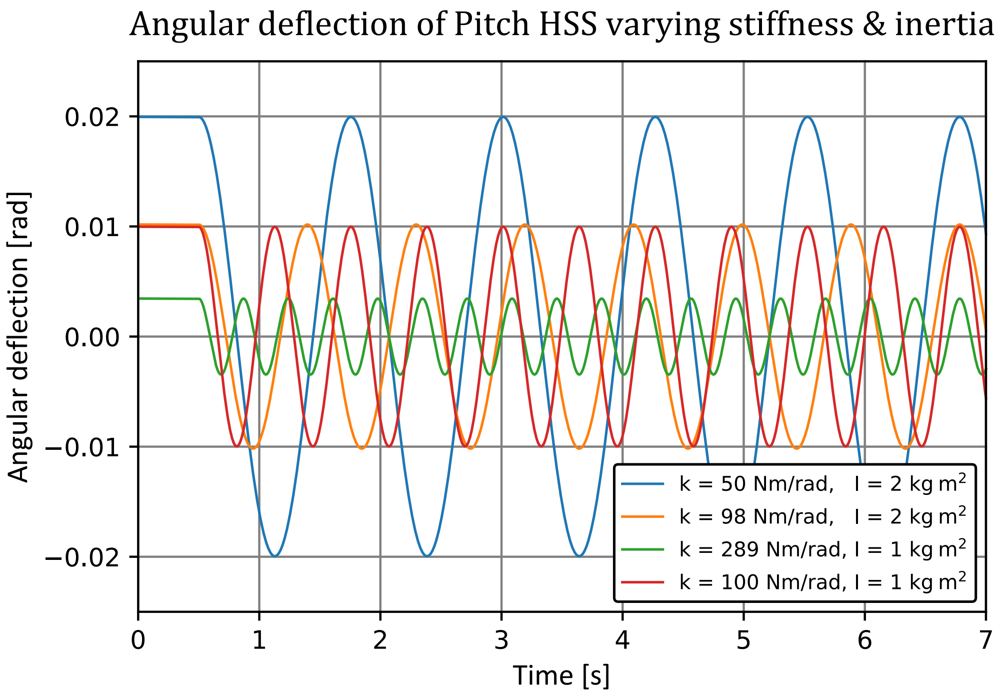


Figure 3-2 – Time series result of angular deflection of flexible pitch HSS for Test 2

3.3 Initial applied torque with damping (Test 3)

Test 3 is similar to Test 2, but now damping is introduced. This test is a qualitative test where the damping coefficient (c) is varied so that different damping scenarios should be observed. This is based on vibration theory that relates the damping factor (ξ) to the ratio between the damping coefficient (c) and the critical damping coefficient (C_c). The critical damping coefficient is dependent on the stiffness (k) and pitch motor inertia (J):

$$\xi = \frac{c}{C_c} = \frac{c}{2\sqrt{kJ}}$$

The system has been set up so that the stiffness (k) is 100 Nm/rad and the pitch motor inertia (J) is 0.5 kgm^2. Based on analytical calculations it is then possible to determine values for the damping coefficient so that different scenarios should be observed. The damping coefficient (c) has been determined such that the damping factor (C_c) fulfils the different criteria shown in **Table 3**. Simulated time series of the angular deflection can be seen in **Figure 3-3** where the four different scenarios exhibit the expected behaviour.

Table 3: Parameters and results for Test 3

Scenario	Damping factor criteria	Damping coefficient, c $[Nms/rad]$	Damping factor, ξ
Run 1: Undamped	$\xi = 0$	0	0
Run 2: Underdamped	$\xi < 1$	1	0.0707
Run 3: Critically damped	$\xi = 1$	≈ 14.14	1
Run 4: Overdamped	$\xi > 1$	30	2.12

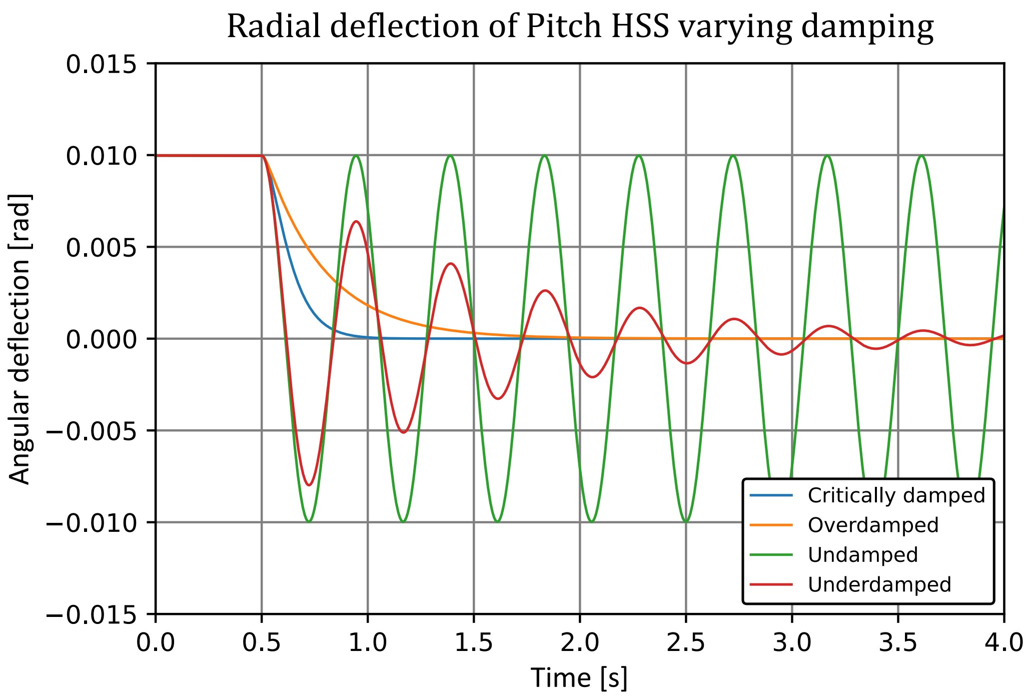


Figure 3-3 – Time series result of angular deflection of flexible pitch HSS for Test 3

3.4 Comparison in power production simulation (Test 4)

In Test 4 a power production simulation of a fixed speed rotor is run with bearing friction in order to compare results when using a rigid and flexible pitch HSS. This allows for a qualitative test where the stiffness is set relatively high to get comparable results between the two configurations. The wind speed is constant at 6 m/s and the tower and blade are set as rigid. The simulation lasts for 20 seconds, and the logging of the results starts after one second. An external controller dll is used to signal a pitch rate demand of 2 deg/s between 10 and 15 seconds. The comparison between the blade pitch rate in the rigid and flexible configuration can be seen in **Figure 3-4** and the comparison between blade pitch angle in **Figure 3-5**.

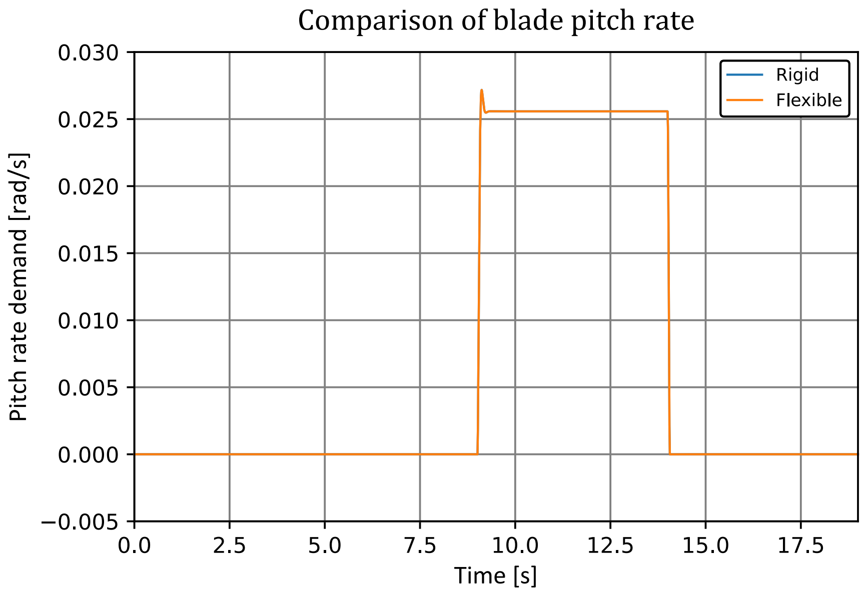


Figure 3-4 – Comparison of time series result of blade pitch rate for Test 4

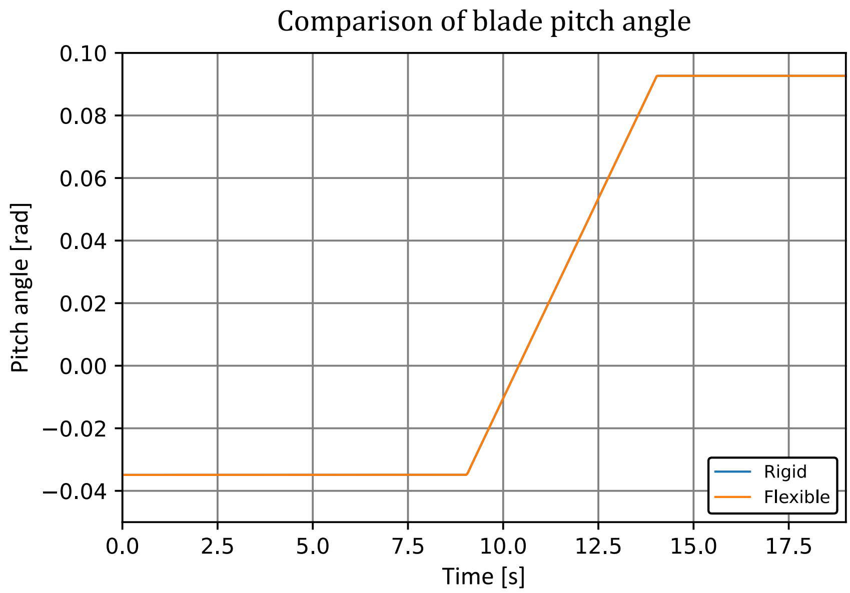


Figure 3-5 – Comparison of time series result of blade pitch angle for Test 3

The blade pitch rate in **Figure 3-5** increases to the demanded pitch rate of 2 deg/s at time equal to 10 seconds. An overshoot in the actual blade pitch rate signal is observed when increasing the pitch rate to 2 deg/s and when decreasing it to 0 deg/s again after 15 seconds. The PID controller can be adjusted in the actuator dynamic response in order to affect this behaviour. It is seen that the pitch rate only increases up to ~1.5 deg/s, and this deviation can be attributed to the pitch bearing friction present. There is no clear divergence in pitch rate demand between the flexible and rigid pitch HSS. This is also the case for the blade pitch angle, where a linear increase is observed in the blade pitch angle between 10 and 15 seconds in **Figure 3-6**. The difference in blade pitch angle between the flexible and the rigid configuration is illustrated in **Figure 3-7**. The rigid and flexible simulations varies most when the pitch demand is stepped up, but there is still only a minor difference.

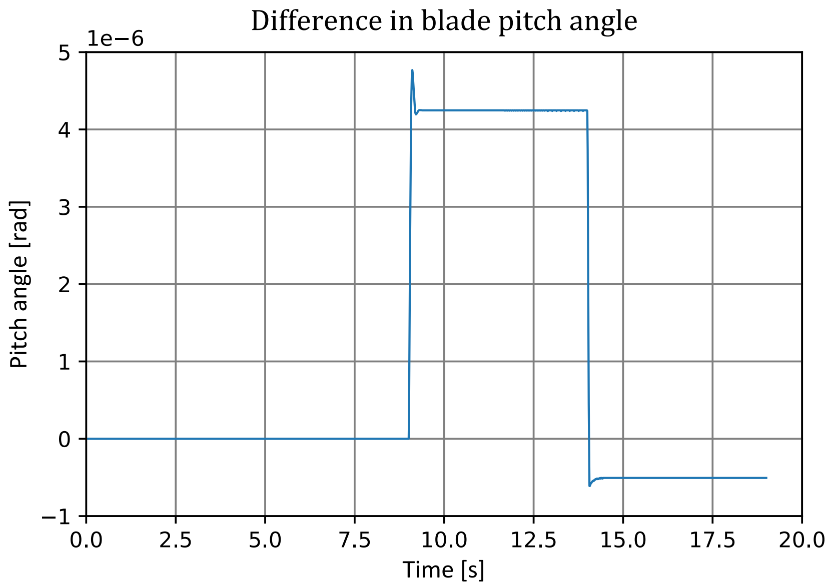


Figure 3-6 – Time series result of difference in blade pitch angle for Test 4

A pitch actuator torque of 3 kNm is observed in the time interval where the pitch rate demand is increased. This is due to the bearing friction being set to 3 kNm, so the pitch actuator must overcome this to meet the demanded pitch rate. At the same time the pitch actuator HSS deflects 0.003 rad, which is as expected since the torsional stiffness has been set to 10^6 Nm/rad.

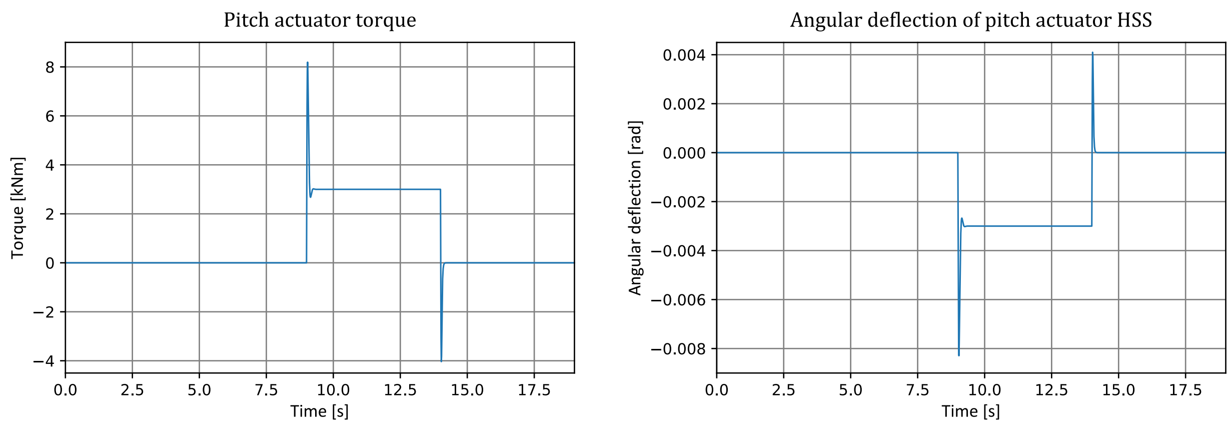


Figure 3-7 – Time series result of pitch actuator torque and angular deflection of pitch actuator HSS for Test 4

4 VERIFICATION MATERIALS

This document is accompanied by a collection of files that can be used to replicate results in the present study. These are summarised in the table below.

File	Description
parked.$PJ	A Bladed project file that is used to compute angular deflection of the flexible high speed shaft of the pitch actuator drive. Stiffness and damping coefficients as well as pitch motor inertia has been varied in the different test cases. This file relies on the ExternalLoads.dll to apply forces.
powprod.$PJ	A Bladed project file that is used to compare power production simulations for a rigid and flexible pitch HSS. This file relies on the ExternalController.dll to signal a pitch rate demand.
ExternalLoads.dll	Dynamic link library used to apply torque on the pitch actuator drive. There is both the possibility to apply a constant torque and an initial torque for a specified time period. This is specified in the main.cpp file.
ExternalLoadsMain.cpp	Main file used to generate ExternalLoads.dll
ExternalController.dll	Dynamic link library used to set a demanded pitch rate in Test 4.
ExternalControllerMain.cpp	Main file used to generate ExternalController.dll

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