POWERPLANT CONTROL SYSTEM TUNING ACTIVITIES

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Abstract

T-625 helicopter is a light utility multi role helicopter that is designed by Turkish Aerospace Helicopter Group. It is equipped with twin CTS800-4AT turboshaft engines developed by the Light Helicopter Turbine Engine Company (LHTEC). Engines are controlled by an advanced, redundant dual-channel full authority digital engine control (FADEC) system. This paper presents aspects of the load anticipation and dynamic response characterization of engine control system in powerplant integration process of T-625 helicopter, together with the results of engine control tuning flight test campaign which are performed to fine-tune FADEC controller parameters during flight.

1. INTRODUCTION

The T-625 Gökbey Helicopter Program was initiated in 2013 and it is being designed and developed by Turkish Aerospace. T-625 is a dual-engine 6 tons class multi-role helicopter, which can easily be adapted to perform various types of different mission profiles for civilian and military operators. It is designed for passenger transport operations and parapublic/governmental needs such as VIP, Air Ambulance, Search & Rescue, Cargo, and Off-Shore. First prototype of T-625 helicopter has performed its maiden flight in September 2018 and starting from June 2019, certification and qualification flight tests are being performed [1].

T625 Helicopter powerplant system consists of:

- Two-spool turboshaft LHTEC CTS800-4AT engines,
- Dual-channel FADEC
- Radial plenum type air inlet and screen,
- Engine cowling,
- Firewalls,
- Mounts,
- Engine drains and vents,

The engines are independently removable, and the replacement does not require any alignment procedure. Powerplant system components are installed in power plant section, pylon section and aft avionics bay of the helicopter. Engines are installed in parallel configuration on the upper deck and drive the main gearbox with shafts.

Engines are controlled via Full Authority Digital Electronic Control (FADEC) units. Each FADEC system consists of:

- Two Electronic Control Units (ECU) for each engine,
- Hydromechanical Unit (HMU), for fuel pumping and metering
- Aircraft command controls
- Aircraft and Engine condition sensors
- Engine actuators

- Wiring harnesses

N_P/N_R setting, torque override and OEI high/low selection are governed by engine controller. A collective pitch sensor provides inputs to ECUs. Figure 1 shows a drawing of CTS800 engine found in T-625.

Figure 1. CTS800 Turboshaft Engine [1]

Gas turbine engine control, when power turbine output shaft is mechanically coupled to the drivetrain delivering power to a helicopter rotor system, can present a challenging control problem when demanding controller performance is required [2].
Besides of the nature of the turboshaft engines fluidic coupling between gas generator and power generator turbines, helicopter installation also brings complex drivetrain adaptation and requirement of precise controlling of the set speed for power turbine, which in turns main rotor speed.

To satisfy those needs and to perform critical transient operations through the flight envelope, engine controls needed to be finely tuned according to both the needs and behavior of the helicopter.

As specified in [3], the engine control system is an integral part of the design of the whole helicopter and should therefore be related to its overall aerodynamic characteristics and its role. The behavior of engines while accelerating necessitates the implementation of engine control to ensure protection against surge and to maintain rotor RPM at a sensibly constant level, while avoiding excessive pilot workload. Moreover, in scenarios that involve multi engine installations (like twin-engine T-625), it is crucial to harmonize and match the engine characteristics.

This paper does not focus on development of the control system itself but rather on implementing the control unit and fine-tuning of the controller parameters. However, it is essential to point out some major functions of the engine/control system for a successful installation.

- Steady state function: The system needs to enable closed-loop control of rotor speed by modifying the engine's fuel flow. This adjustment should ensure that the rotor speed remains steady or stays within the acceptable NR limits.

- Transient Functions: When required, the system should provide safeguards/ protection and set limits on free turbine speed, gas generator speed, temperature, temperature change rate, and torque. Additionally, the system should manage the engine's acceleration during start-up and transient operations.

- Control loop opening: The system should provide for the control loop to be opened under certain conditions.

To achieve these functions, different kinds of limiters are being used as a part of the control system requirements. Four common limiters that are being used for this purpose are power turbine speed (N_p), gas-generator speed (N_G), temperature and torque limiters.

In this paper, the stages of preparation for FADEC controller parameters’ fine-tuning are presented. This preparation consists of engineering simulator, ground, and flight tests, which are described in the following sections.

2. ENGINEERING SIMULATOR

During early stages of the T-625 helicopter program, the simulator environment was first constructed as a system integration laboratory (SIL), for performing hardware in the loop tests, especially for development and testing of the automatic flight control system (AFCS). However, with increased flight dynamics model-fidelity, and integration of real avionics, SIL transformed into a pilot in the loop preparation facility, which utilized like a training simulator for the flight test crew.

Figure 2. T-625 Engineering Simulator

T-625 has a fixed based simulator as shown in Figure 2 for pilot in the loop and hardware in the loop simulations. The simulator is equipped with the same glass cockpit as the prototypes, which consists of two touch screen integrated modular displays (IMDs) and two touchscreen cockpit control units (TCCUs). The outside view from the cockpit is illuminated by 12 projectors that reflect their images to a projection dome. The resulting field of view is 80 degrees vertical and 210 degrees in lateral plane which is enough to support any given helicopter maneuver. This wide field of view also enables pilots to visualize the ground and orientation of the helicopter through the chin windows.

The engineering simulator is equipped with conventional type flight control system including cyclic, collective and pedals. Flight controls are connected to the trim actuators by mechanical linkages just as in the real prototypes.

Other than glass cockpit and flight controls, the simulator is also equipped with other avionics. These avionics equipment includes real flight control computers (FCCs), AFCS Control panel and other mission critical panels like engine control panel (ECP), fuel system control panel etc.

During development flight test stages of T-625 helicopter program, simulator tests proved themselves to be invaluable tools not only for preparing the flight crew for the upcoming flight tests, but also for providing a means to the engineering team in the telemetry station what to expect during the real flight test. Additionally, simulator flight data reduction reveals any shortcomings in the flight test technique or the data reduction method itself, allowing the flight test team to modify and improve the test technique or data reduction method before the real test flights took place. In this regard, simulator tests increase the flight test safety and ensure overall cost reduction. With all these advantages presenting themselves early in the program, simulator test flights quickly became a prerequisite for any real test flight.

The helicopter model that is being used in the engineering simulator is constructed by TOROS, which is an in-house tool developed by TA in MATLAB-Simulink® environment. The principal structure of TOROS can be found in Refs. [4], [5]. Each rotorcraft component is modeled individually in a modular structure. Contributions of each component to the equations of motion are calculated based on detailed rotorcraft characteristics. The model of T-625 helicopter also includes the dynamic engine model that is composed of three subsystems, which are electronic control unit (ECU), hydro-mechanical unit (HMU) and aero-thermodynamics model. Both helicopter and powerplant models are being validated and updated according to the flight test results.

With the help of this comprehensive model, pilot-in-the loop simulations were performed at the engineering simulator to foresee both helicopter and powerplant characteristics before the actual flight-tests. These training tests enabled flight crew to practice the procedures and optimize the number of engine control tuning test points that will be performed during flight tests.

Maneuvers that were tested in the simulator include spot turns at hover, collective fixed turns, engine acceleration/deceleration tests and power-on autorotation tests at different target rotor speeds. Since the simulator test campaign is performed to assess the initial performance of engine controller, N_R/N_P droop, NP overshoot, NP de-clutch and clutch values; torque values, as well as collective input rates were examined and recorded.

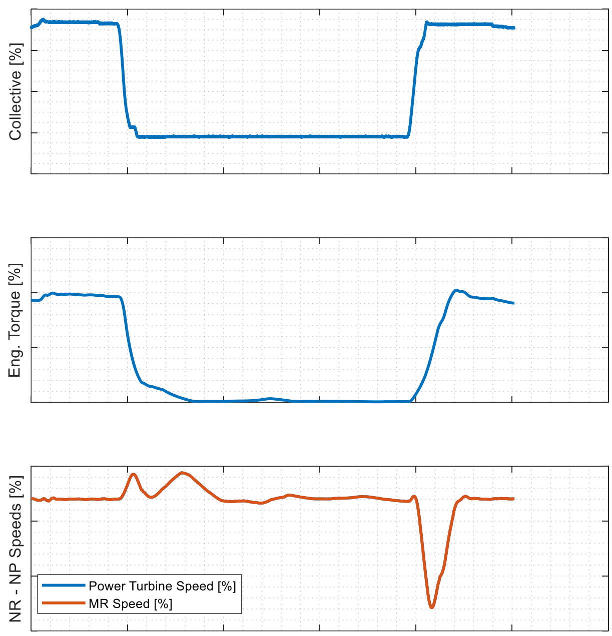

Figure 3. T-625 Engineering Simulator, Sample Transient Response Outputs

Sample results from an autorotation test, that was performed in the simulator, are provided in Figure 3. Starting from a steady climbing flight at maximum continuous power (MCP), rapid collective dump input is given until needle split autorotation state is reached. After reaching steady autorotation, collective is rapidly pulled again until MCP is reached. The behavior of engine governor to rapid collective inputs as well as changes in power turbine and main rotor speed during entry and recovery states can be observed in Figure 3.

3. SIMPLIFIED ENGINE CONTROL LOOP

In simplified control schematics, which is shown in Figure 4, there are three separate control loops that add on and creates main input for engine fuel controller:

- Main controller on the loop is core engine controller which has been designed and validated by engine manufacturer itself, with engine test cell and controller bench tests. It is mainly about the physical capabilities of the engine and helicopter drivetrain mechanical characteristics.
- NR anticipator controller is one of the two controllers that helps the main control loop to minimize deviations from set rotor speed. Its major feature is to improve power-on autorotation recoupling characteristics of the engine. CTS800 engine has a novel feature of increasing its power turbine speed during power-on autorotation NR decays.
- Collective pitch anticipator controller is another controller that has been helping the main control loop to minimize deviations from set rotor speed. It is working both in pilot collective up and down inputs. Moreover, this loop checks for both the rate and position of the collective pitch to anticipate loading and unloading of the rotor, also on power turbine, before it physically affects the system.

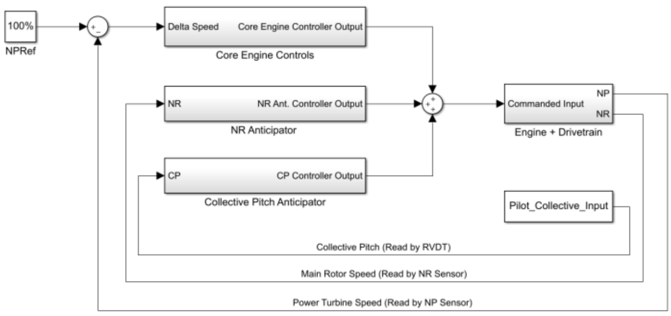

Figure 4. Simplified Engine – Power Turbine Speed Control Schematic

4. GROUND TESTS

Performing ground tests on the prototypes was another critical stage prior to performing engine control tuning tests during flight. These ground tests include procedures that are performed on ground for testing mechanical coupling between power turbine output shaft with drivetrain delivering power to helicopter rotor system.

4.1. Torsional Stability Tests

Engine-Drivetrain stability characteristics are evaluated by airframe tethered runs, applying collective pulses at various rates until apparent natural frequency of the drivetrain determined (natural frequency for platform and driveline must be analyzed before performing these tests). The controls are then pulsed at this rate for several seconds to determine if any divergent oscillation characteristics on fuel flow, power turbine speed, torque are present. The collective is then returned to initial setting (mean of the pulsating input) and the damping characteristics are evaluated. Sample torsional stability test results are given in Figure 5.

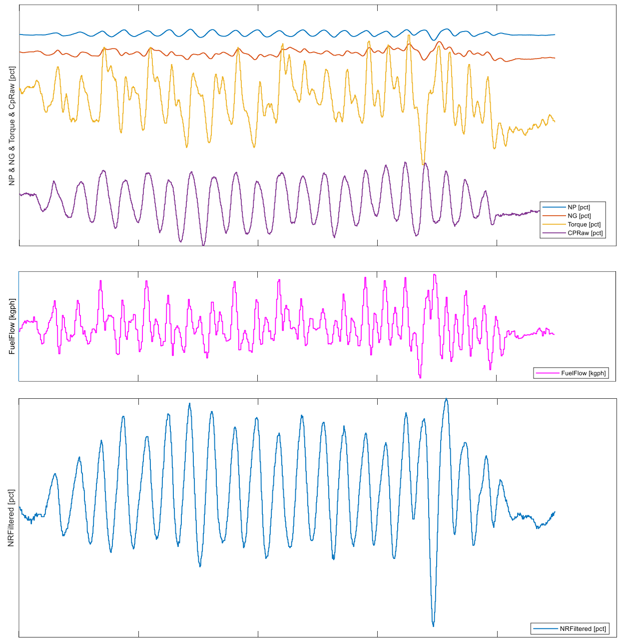

Figure 5. Sample Torsional Stability Test Data

Tests were successfully completed, and no divergent or sustained oscillations were observed. All the parameters described show that the rotor is heavily damped.

4.2. Dynamic Response Tests

The aim of these tests was mainly to collect data that will provide evidence to evaluate torsional stability of the system before flight tests.

Additionally, control system transient response (i.e., acceleration / deceleration schedules, etc.) were examined prior to flight tests.

5. FLIGHT TESTS

After successful completion of the ground runs and having lessons learned from the simulator runs, flight tests are planned and performed.

To compensate for the uncertainties between the helicopter/engine model with the actual prototypes, flight tests were performed with a build-up approach. The need for these flight tests arises from variable transient behavior of both engines and aerodynamic surfaces of the helicopter at different altitudes and power settings.

Most of the tuning activities were performed at lower altitudes because engines have more margin to avoid surges. Therefore, different combinations of transient inputs have been tried thoroughly where the time between input and engine acceleration limits has provided some margin to tune. High altitude runs are mostly performed to check the results of tunings that were performed before at lower altitudes in terms of their stability and operation.

Planned test activities mainly focused on rapid collective applications and rapid NR acceleration/deceleration transients because of the engine controller anticipator logics. However, maneuvers without collective inputs like pedal turns, collective fixed turns are also introduced to the test matrix to check controller behavior without anticipators.

In the following section, detailed flight test categories will be given and discussed. Additionally, flight test results for each test category will be provided.

5.1. Entry to and Exit from Power-On Autorotation Tests

The aim of this test is to check and tune the control system power turbine governing capability when having transients from true no-load condition to maximum continuous power conditions with additional rotor inertial energy.

In addition, N_P/N_R engagement in transition form is to be evaluated. Power recoveries from autorotation on level flight and climb conditions will be investigated. Differences between power turbine speed and rotor speed (N_P/N_R split), up to maximum operating power-off N_R speed will be evaluated. Recovery would be accomplished by increasing the application rates of collective pitch inputs.

To reduce Np overshoot slightly, engine controller gain sensitive to collective decrease movement was changed. After modifying corresponding controller parameters, the flight test was repeated, to examine the difference.

In repeated test result, it has been observed that total NP overshoot decreased due to controller parameter update.

A sample result from an autorotation test in which ECU parameter tuning performed, is provided in Figure 6.

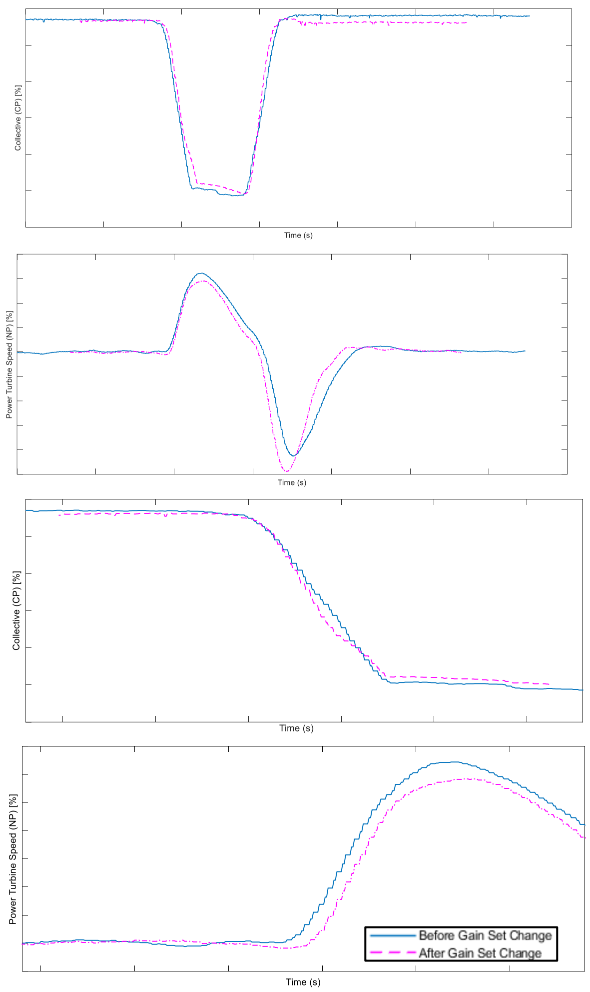

Figure 6. Effect of Gain Set Increment for Collective Decrease

Engine control tuning activities is a trade-off in perspective of overshoot and droop. While it can be decreased the Np droop, Np recoupling point can be increased due to gain set increment and quick engine response.

Increasing gain set of cp anticipation can make engine to response quickly before load change. This will decrease Nr droop. However beside decreasing Nr droop, Np will catch Nr in higher value during power-on autorotation due to quick engine response. Figure 7 is provided to summarize the effect of gain set increment.

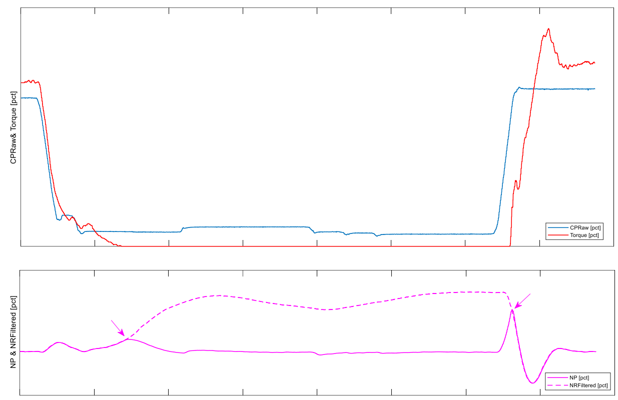

Figure 7. Np Separation and Recoupling Point

5.2. Engine Acceleration Tests (Collective Pulls & Dumps)

Engine acceleration characteristics to be evaluated using dual and single engine collective pulls to MCP from predetermined power ratings. These ratings vary incrementally from minimum pitch on ground (MPOG) collective levels to MCP. Rates of application of collective vary incrementally depending on helicopters flight characteristics. Test points are initiated when the helicopter is stabilized at the target test altitude and airspeed. Ramp input is given, and dynamic response is evaluated.

In order to decrease Np droop, gain set of ECU for collective up input is increased. After ECU tuning, same test step is reperformed, it was observed that Np droop is decreased perceptibly as shown in Figure 8.

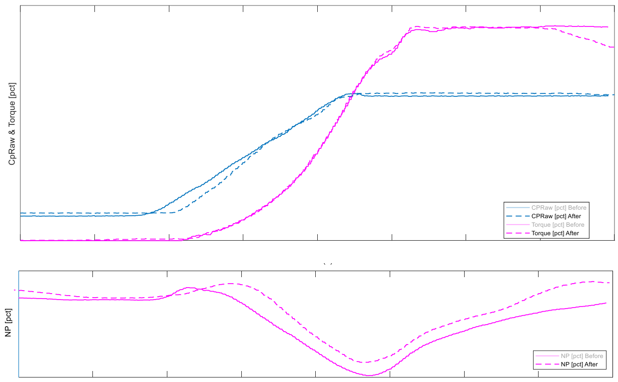

Figure 8. Np Droop Improvement by Increasing Gain Set of Cp Anticipation

Engine control system protects engine from surge during transient condition by limiting acceleration rate. Acceleration limit, which is defined according to engine surge map, overrides anticipation and control gain set. Even gain set is increased to maximum value, engine fuel flow will be limited to avoid surge if acceleration rate of compressor is higher than limit.

In order to decrease NR droop, gain set of ECU for collective up input is increased during power-on autorotation needle split test. After ECU tuning, same test step is reperformed, however it was observed that Nr droop do not change due to engine acceleration limit as shown in Figure 9.

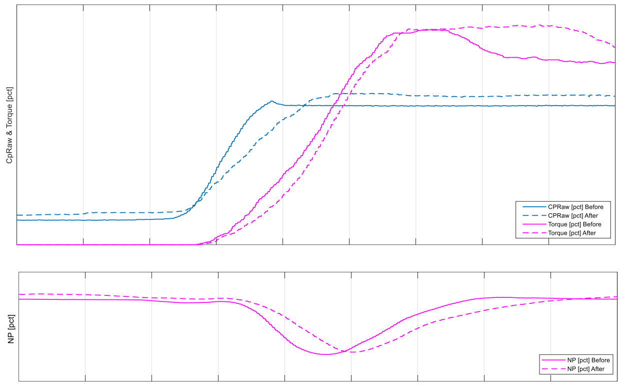

Figure 9. Rapid Collective Input

5.3. Engine Deceleration Tests (Collective Pulls & Dumps)

Engine deceleration characteristics to be evaluated using dual and single engine collective dumps to full down collective from predetermined power ratings. However, when decreasing collective pitch angle it should be observed that helicopter does not enter the autorotation. These ratings vary incrementally from MCP to MPOG collective level. Rates of application of collective vary incrementally depending on helicopters flight characteristics. Test points are initiated when the helicopter is stabilized at the target test altitude and airspeed. Ramp input is given, and dynamic response is evaluated.

In order to decrease Np overshoot, gain set of ECU for collective dump input is increased. After ECU tuning, same test step is reperformed, it was observed that Np overshoot is decreased perceptibly as shown in Figure 10.

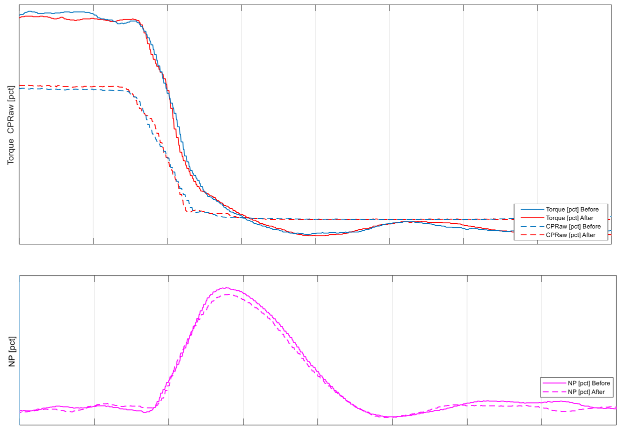

Figure 10. Np Overshoot Improvement by Increasing Gain Set of Cp Anticipation

Beside gain set adjustments, decreasing of minimum fuel flow is another method to reduce NP droop. If the control system has a margin to decrease minimum fuel flow without causing engine flameout, decreasing minimum fuel flow can be useful for Np overshoot during collective dumps.

A sample is given in Figure 11 to show improvement on Np separation point by decreasing minimum fuel flow schedule.

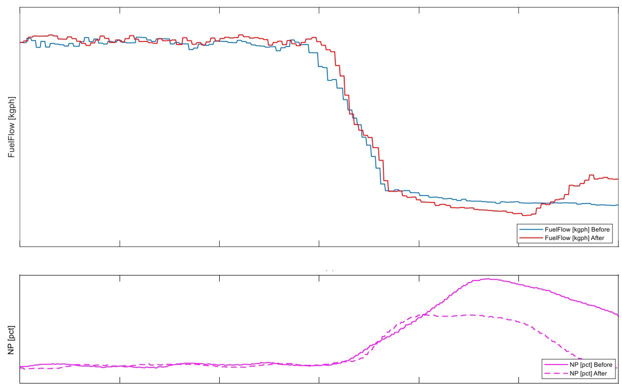

Figure 11. Np Separation Point and Minimum Fuel Flow Schedule

5.4. Collective Fixed and Pedal Turning Tests

The purpose of these tests is to evaluate dynamic response of the engines to off-axis inputs in which collective pitch anticipator loops do not create any control.

By fixing the collective pitch angle, N_P/N_R droops that might be caused by rapid inputs made with the cyclic or pedals are evaluated. These tests are made to determine the dynamic characteristics of the engine(s) and governing systems. Transient droop, transient torque response and over-swing testing involves assessing how the propulsion system reacts to sudden changes in required power.

6. RESULTS & CONCLUSION

Through the flight test campaign, gains from the main control loop and collective pitch anticipator have been improved. These improvements were basically:

- Collective Down Input Gain Set (increased gain sets)
- Collective Up Input Gain Set (increased gain sets)
- Fuel flow schedule and fuel/air ratio at minimum flow rate (decreased gain sets)

When approaching to gain set changes both test data and model-based simulation results have been evaluated systematically. In some change decisions, different increase/decrease rates are implemented to different channels to evaluate order of magnitudes of the given changes. Also, test points are repeated with decided improved gain sets to validate changes

NR anticipator gain set has been evaluated through testing and some model-based simulations have been performed with different variations in gain sets. However, as test/simulation results showed, not to lose performance from NR Droops and to avoid higher re-coupling speeds there has not been any change introduced to that controller.

In addition to these improvements, to check whether any instabilities have been introduced to system and bench calibrated core controller validation, some maneuvers like “Collective Fixed Turns”, “Pedal Turns” and “Step Collective Increase/Decrease” are performed. Results showed that no unusual behavior is observed, and transient performance is as expected in terms of power turbine speed.

After completion of the tuning and validation activities, some mission representative maneuvers like Jump Takeoff and Acceleration/Deceleration runs have been made to validate improvements in real usage environments. Results showed that no unusual behavior is observed, and transient performance is as expected in terms of power turbine speed.

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