THE USE OF ONBOARD REAL-TIME MODELS FOR JET ENGINE CONTROL

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2 Introduction to Jet Engine Control

2.1 Jet Engines from a System Theory Point of View

This section shall give an overview of jet engines from a system theory point of view. In section 2.1.1, details of the different input variables (controlled inputs and disturbances) and the (measured) output variables of typical jet engines will be given. This is followed by a brief overview of the dynamic behavior of jet engines in section 2.1.5.

2.1.1 Controlled Variables

The most important variable to be controlled is the engine's thrust. If the pilot moves the pilot's lever, he wants the engines to give higher or lower thrust as soon as possible. Ideally, there would be no time delay between the commanded thrust and the thrust delivered by the engines. This is, however, not possible due to different operating limits of the engines. First of all, the temperature at the combustion chamber exit may not exceed a certain limiting value to prevent damage to the high pressure turbine. Another variable that is highly important for a safe operation of the engine is the so-called surge margin of the compressors. The surge margin describes the distance of the compressors' operating points from the limit line representing the beginning of instability. Reaching this line may lead to permanent mechanical damage of the engine's components. Furthermore, the engine spool speeds may not exceed certain limiting values to ensure the mechanical integrity of the engine.

For a classification of the different operating limits, see also section 2.2.

2.1.2 Disturbances

As described above, the engines should follow the pilot's thrust demand as quickly and accurately as possible. There are, however, external disturbances, which influence thrust and whose influences have to be compensated. One of the most important disturbances is the changing environmental condition, e.g. the ambient pressure, temperature and humidity that change significantly during flight.

Another important disturbance is the power, which is extracted from the engine to be provided to the aircraft. Furthermore, the amount of bleed air extracted from the engine's compressors to provide air for the aircraft environmental control system, wing anti-ice or tank pressurization systems, disturbs the system behavior.

There are also engine internal disturbances. First of all, there is some amount of power offtake necessary to power the engine accessories (e.g. fuel pumps, oil pumps). Another internal disturbance is the changing health parameters (efficiencies, flows) of the turbo components.

2.1.3 Manipulated Variables

The expression "manipulated variables" shall denote the variables which can be set by the engine control system. The most important manipulated variable is the fuel flow provided to the combustion chamber. In some engines, it is possible to change the angle of one or more stages of compressor blades. These are called "variable (inlet) guide vanes" or "variable compressor vanes". Furthermore, valves can be mounted on the compressor casing to bleed air to the bypass. Both variable guide vanes and handling bleed valves can be used to control the compressor operating point.

Military or high speed engines often feature a reheat system, where additional fuel can be injected into the hot exhaust gases. To minimize backlash of the reheat operation on the main engine, the geometry of the exhaust nozzles is variable.

2.1.4 Measured Variables

The variables measured by sensors and fed into the engine control system can be categorized as follows:

Speed signals:

Electromagnetic sensors measure the rotational speed of the engine spools. These sensors are very fast, accurate and reliable.

Temperature signals:

Relatively slow thermo-elements or thermo-resistors are used to measure temperatures at different locations within the engine. These can, however, not be used to measure the high temperatures at the combustion chamber exit. Some military engines (e.g. RB199, EJ200) feature optical sensors for high pressure turbine blade temperature.

Pressure signals:

Different pressures are measured mostly by pipes and pressure transducer modules. The pressure sensor signals are faster than the temperature signals, but still there is noticeable time delay between the pressure itself and the measured value.

Other signals:

In addition to the sensors mentioned above, which are used more or less directly for engine control purposes, there are various other sensors mainly needed for monitoring purposes. These include, for instance, vibration sensors or chip detectors in the engine oil system.

2.1.5 Dynamic System Behavior / Open Loop Poles

Looking at the transfer function poles of a system reveals details about the dynamics of the system. Figure 1 shows some basic relationships between dynamic system response and pole locations. Poles in the right half of the s-plane show unstable system modes. The further left from the imaginary axis the pole is located, the faster is the corresponding mode. Conjugate complex pole pairs reveal oscillatory modes.

For non-linear systems, the location of poles changes with the specific operating point. Jet engines are such non-linear systems. The location of the poles varies with the power setting (idle to maximum thrust) and with the flight conditions (ambient pressure and temperature). At all operating points, however, the poles remain to the left of the imaginary axis, i.e. in the stable range. Figure 1 shows the typical areas, where the poles are located. Just left of the imaginary axis, there are slow poles associated mainly with heat transfer effects. Typical time constants of these effects range from a few seconds to minutes. Left of these are located the poles that can be associated with the inertia of the engine's rotating shafts. These poles can also form conjugate complex pairs, albeit with high damping. Typical time constants would be from less than a second to a few seconds. Far left in the s-plane one can find poles associated with gas dynamic effects. These effects are very fast (in the range of kHz) and are often neglected in jet engine modeling. Oscillatory effects with high and low damping can be observed in this region.

The plot of the pole locations shows that the dynamics of jet engines are not very critical from a system theory point of view. The poles always remain in the stable range and the most important poles (spool speed dynamics and heat transfer) do not tend to be highly oscillatory. Thus, the problem of jet engine control is not forcing the jet engine into the desired dynamic behavior but to get a fast response of the engine without extending the limits described in section 2.1.1.

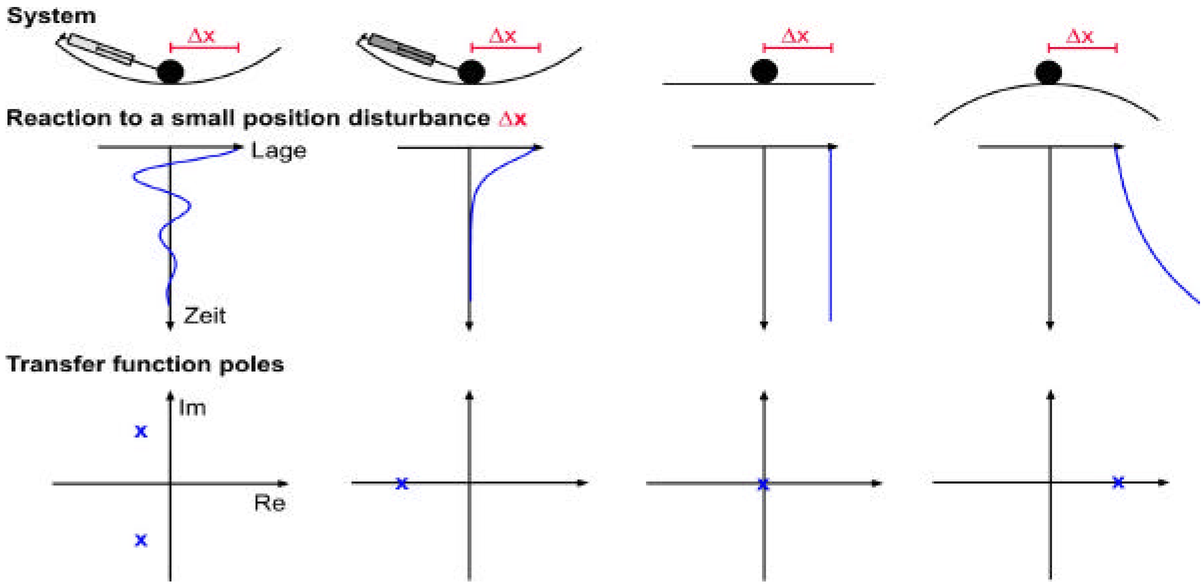

Figure 1: Dynamic System Behavior and Transfer Function Poles

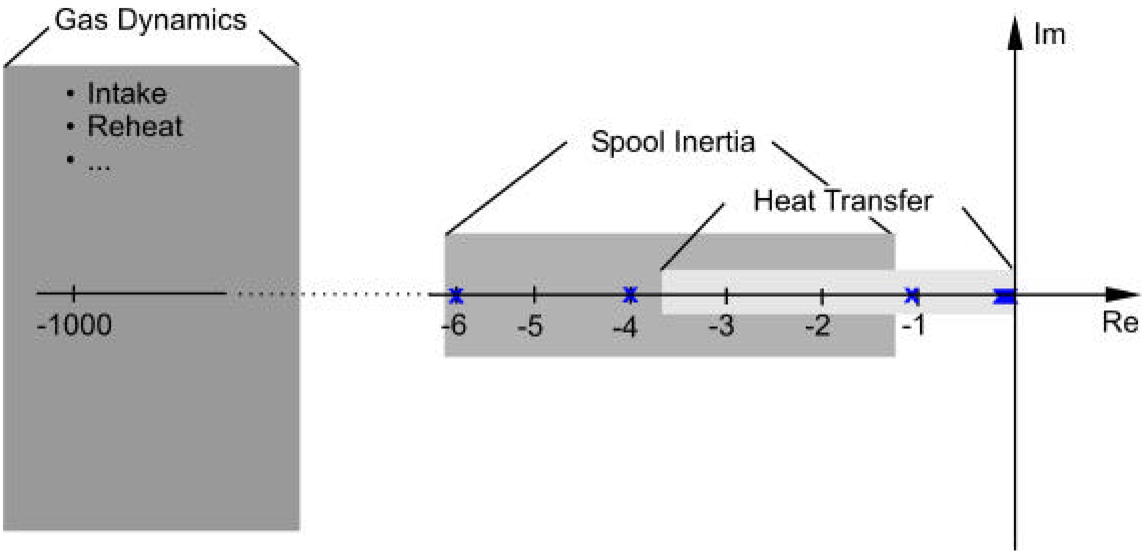

Figure 2: Typical locations of Jet Engine Transfer Function Poles; The 'x' denote actual values of a typical commercial jet engine (derived from a physical engine model)

2.2 General Requirements on Engine Control Systems

Different requirements have to be fulfilled by modern engine control systems. These can be categorized as follows [1]:

Unburden the pilot of any engine specific control and limiting tasks

The engine control system has to provide the thrust demanded by the pilot regardless of environmental disturbances and of changed engine health parameters. At the same time, the control system must keep all engine variables (pressures, temperatures, spool speeds, …) within predefined limits.

Minimise engine fuel consumption and maximise thrust and engine life

These goals can be contradictory and depend on the aircraft mission. For commercial engines, the life of the engine components and the fuel consumption of the engine are most important. Nevertheless, the engine has to provide the demanded thrust. A trade-off in steady state regimes is usually only possible if the engine has controllable variables apart from the fuel flow, like a variable nozzle area, for example. During transient regimes, however, it is possible to find a trade-off between fuel consumption, thrust (acceleration time) and engine life.

Follow the pilot's commands as fast as possible

The controlled engine should follow a demanded thrust change as fast as possible. This is extremely important in case of emergencies like touch-and-go maneuvers, for instance. Flight authorities like the FAA pose certain demands on engine acceleration times. The corresponding section of the FAA regulations [2] reads:

"The design and construction of the engine must enable an increase--
(a) From minimum to rated takeoff power or thrust with the maximum bleed air and power extraction to be permitted in an aircraft, without overtemperature, surge, stall, or other detrimental factors occurring to the engine whenever the power control lever is moved from the minimum to the maximum position in not more than 1 second, except that the Administrator may allow additional time increments for different regimes of control operation requiring control scheduling; and
(b) From the fixed minimum flight idle power lever position when provided, or if not provided, from not more than 15 percent of the rated takeoff power or thrust available to 95 percent rated takeoff power or thrust in not over 5 seconds. The 5-second power or thrust response must occur from a stabilised static condition using only the bleed air and accessories loads necessary to run the engine. This takeoff rating is specified by the applicant and need not include thrust augmentation."

The FAA regulations as cited above only contain information about the required acceleration times of the engine. The aircraft manufacturer usually defines further important control requirements, like the maximum allowable thrust overshoot or the maximum allowable steady state thrust inaccuracy. Typical values are a maximum thrust overshoot of 2% and a maximum steady state deviation of 1%.

Safe and reliable operation in all operating conditions

The engine control system has to ensure safe and reliable engine operation regardless of current operating condition and ambient conditions. This includes the automatic observance of all relevant engine operating limits. These limits can be categorised as follows:

- Mechanical / structural limits (spool speeds, pressures)
- Thermal limits (temperatures)
- Aerodynamic limits (compressor surge margins)

Other requirements for the engine control system include the communication with diagnosis / monitoring systems and with aircraft systems (e.g. flight control system, auxiliary systems).

2.3 A Brief Overview of Jet Engine Control History

Jet Engines are, with the exception of malfunctions, stable dynamic systems. Therefore, it would be theoretically possible to control a simple jet engine manually, without the aid of a dedicated control system. The pilot or co-pilot would have to directly set the fuel flow by moving the power lever. The corresponding work load, however, increases with an increasing number of engines on one aircraft, with engines featuring more manipulated variables and last not least with changing flight conditions. The fuel flow necessary to drive the engines at the spool speed limits in high altitudes, for example, is only a small fraction of the fuel flow needed for the same spool speed at ground level. Without the aid of a control system, the pilots would have to manually check all engine operating limits and set the manipulated variables (e.g. fuel flows, variable geometry) accordingly. To reduce pilot's workload, some of the early jet engines built around 1940 already featured control systems. The most important advantages of controlled jet engines are:

- Reduced pilot workload
- Constant thrust despite of external disturbances
- Shorter response times to changed thrust demands
- More accurate adherence to operating limits, therefore increased engine life and safety
- Increased operating efficiency due to reduced fuel consumption

The first jet engine control systems were purely (hydro-)mechanic. The desired spool speed was commanded by the pilot via the pilot's lever. Centrifugal force controllers controlled the spool speed by changing the fuel flow accordingly. Beginning with 1950, more and more functionality was introduced into the control systems. The functionality was implemented by introducing complex hydromechanic systems. These hydromechanic systems sometimes included a main thrust control loop controlling the Engine Pressure Ratio (EPR) instead of the low pressure spool speed. The control systems typically featured loops to prevent engine overspeeds and prevent compressor surge, either by scheduling the fuel flow during accelerations and decelerations or by controlling the acceleration and deceleration rates of the engine spools. Due to the multitude of different mechanical and hydraulic components, like spring valve assemblies, the hydromechanic control systems often require relatively high maintenance efforts. The development of small digital computers, starting around 1970, enabled the implementation of complex functionality using digital circuitry. By means of digital hardware and the corresponding software, complex functions can be implemented that could not be implemented using hydromechanic systems. Another advantage of digital engine controls is the reduced maintenance effort. At the beginning of digital engine control, only very specific functions were implemented digitally, the main control loops were still hydromechanic. By and by more functions were transferred into the digital part of the control system, until the Full Authority Digital Engine Controls (FADECs) were introduced. Today, almost all new engines feature such a FADEC. However, some safety functions and subsidiary control parts like the Fuel Metering Unit (FMU) still feature hydromechanic controls. The digital engine control unit (DECU) of the Eurofighter/Typhoon engine EJ200 is shown in figure 3.

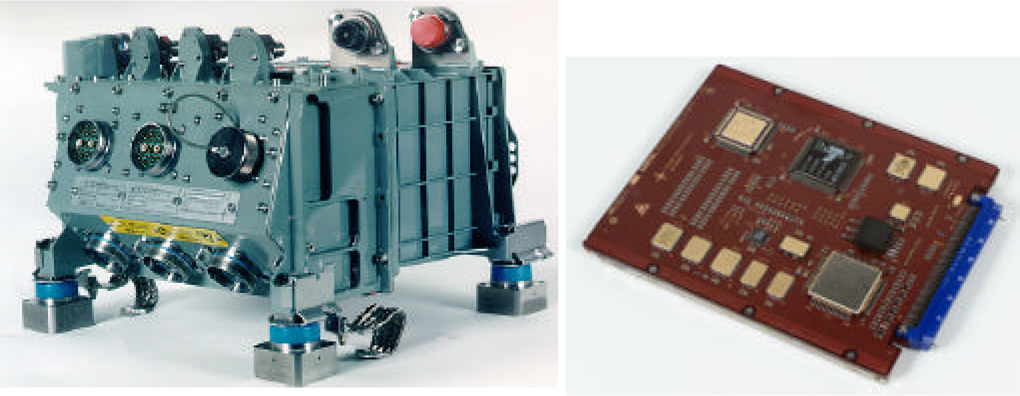

Figure 3: Digital Engine Control Unit (DECU) of the EJ200 engine

2.4 Current Trends

Despite the fact that almost all modern jet engines feature Full Authority Digital Engine Control (FADEC) systems, the underlying control laws are still relatively simple from a control theory point of view. With increasing engine complexity, however, it becomes more important to take interactions between the different engine systems and sub-systems (core engine, reheat, air intake) into account.

One important research program in the field of jet engine control was conducted in the 90s in the USA. The program was called "Performance Seeking Control" [4] and its goal was to integrate a simplified state space model into the engine control system of a F-15 aircraft to optimize the matching between supersonic air intake and engine operation. The advantages were demonstrated in flight tests [5]. Another major research program, the so-called HISTEC (High Stability Engine Control) dealt with minimizing the impact of inlet disturbances (distortion) on the compressor operating performance.

Different projects world-wide deal with the opportunities of applying newer control theories to jet engines. This includes the application of LQG (Linear Quadratic Gaussian Regulator) theory combined with LTR (Loop Transfer Recovery) [6], the application of robust control (H infinity) theory [7][8][9], fuzzy logic [10], adaptive one-step-ahead control [11] or model reference control [12]. Another main research area lies in the higher integration of the flight control system and the engine control systems, especially for enhanced emergency operations [13].

3 The use of Onboard Models for Jet Engine Control

3.1 Overview

Simulation models play a very important role in the design process of jet engine control systems. This application is, however, beyond the scope of this report. Here, we focus on the use of jet engine models within the actual control system algorithms (onboard models).

Onboard models can be applied in different ways. For example, relatively simple sensor models can be used to partly compensate for offsets and time delays of measured signals. If the physical effects leading to these offsets and delays are known, it is in some cases possible to calculate the actual value of the measured variable out of the measured signal.

Another application of onboard models is the so-called "model-reference" or model-predictive control [12]. Here, a model of the complete engine is used to determine the control signals (e.g. fuel flow) necessary to drive the engine to the desired operating point. In the "performance seeking control" [4] experiments, an onboard jet engine model was used to optimize the matching between engine intake, engine and nozzle.

The "model based control" approach, described in the remaining parts of this report, describes a way to use an onboard model to generate estimates of non-measured engine variables.

3.2 Model Based Control - Introduction and Application Examples

Many important engine variables cannot be measured directly or can only be measured with a complex, and hence unreliable, instrumentation system. This includes variables that are of imminent importance for the safety and the performance of jet engines, like the compressor surge margins, the turbine inlet temperature or the engine's net thrust. The engine control systems used today circumvent this deficiency by using substitute variables for the generation of demand and limiting values. Thus only measurable variables are used as controlled variables. This approach, however, leads to higher safety margins and thus not all of the engine's performance potential can be used.

A possible solution for this problem is to integrate a simulation model of the engine into the control system (onboard model). This model can provide real-time information about the variables that cannot be measured by the engine's sensors. Figure 4 shows the basic configuration of such a model based control system. The comparison between demanded and actual values can now include so-called "virtual" measurements supplied by the engine simulation model.

The integration of an onboard model into the engine control system enables the use of virtual measurements in the control system. This can help to increase the engine performance, safety and life and to reduce specific fuel consumption. Apart from the possible use of virtual sensor signals for sensor validation and substitution, new or enhanced control functions will be made possible that shall be explained by the following examples.

Turbine Temperature

The temperature of the high pressure turbine blades is of extreme importance to engine life. This temperature, and also the gas temperature at the turbine inlet is usually not measured by engine sensors. This is especially the case for commercial jet engines. The simulated turbine temperature provided by an onboard engine model can be used by the control system to avoid or limit the temperature peaks that occur during accelerations at high power levels. Depending on the degree of detail of the used simulation model, either the metal temperature of the turbine blades, or the gas temperature at the turbine inlet can be used as virtual measurement.

Surge Margin

The surge margins of the compressors play a vital role for the safe operation of the engine. Especially during transient maneuvers, such as fast accelerations, a stall of the flow around the compressor blades leading to compressor surge must be avoided. The distance of the current operating point to the surge line (surge margin) usually cannot be measured by sensors. Current engine control systems circumvent this deficiency by using a limit on the spool accelerations or by using fuel schedules to prevent compressor surge. The onboard model can be used to determine the current margin between the operating point and the nominal surge line of the turbo compressors and provide the control system with this information. With the knowledge of the current shift of the operating line the surge margin stack-up could be reduced thus enabling improvements of engine performance, whilst guaranteeing safe operation even of degraded or worn engines. A further amendment to this could be made by onboard models that take into account effects on the surge line itself.

Net Thrust

Another quantity that is not measured in-flight is the engine's net thrust. Current control systems usually translate the thrust command given by the pilot (pilot's lever angle, PLA) into another demand value. This demand value is some measured variable, like the engine pressure ratio (EPR) or the speed of one of the engine's spools. However, this method can get quite complex, since the variations of the ambient conditions and flight envelope must be taken into account.

For the thrust vectoring of future combat aircraft, a detailed knowledge of the current engine thrust is of even higher importance. Here, the flight control system also commands side force components of the engine thrust. These have to be transformed by the engine control system into a corresponding deflection angle of the vectoring nozzle, under high demands on accuracy. For this application the onboard model must also include a model of the complex flow phenomena occurring in deflected nozzles. This model can be derived from CFD calculations and calibrated by test data. Extensive testing will be necessary to cover all non-linear effects occurring within the operating range of the engine and the multiple-degree-of-freedom vectoring nozzle.

Supersonic Inlet

In supersonic or hypersonic flight regimes, the matching between the air intake and the engine itself is of vital importance. If this matching is insufficient, the system of oblique and normal shocks outside and inside the inlet can collapse. This can lead to a detached bow shock outside the inlet, having severe consequences on the absolute value of the net thrust, but above all the direction of the net thrust vector angle. An onboard model integrated into the control system can be used here to gather accurate knowledge about the current positions of the different shock waves. Using this knowledge, the pressure recovery of the inlet can be optimized without compromising on the operational safety.

Section 4 deals with the different kinds of engine real-time models that could be used in a model based engine control system.

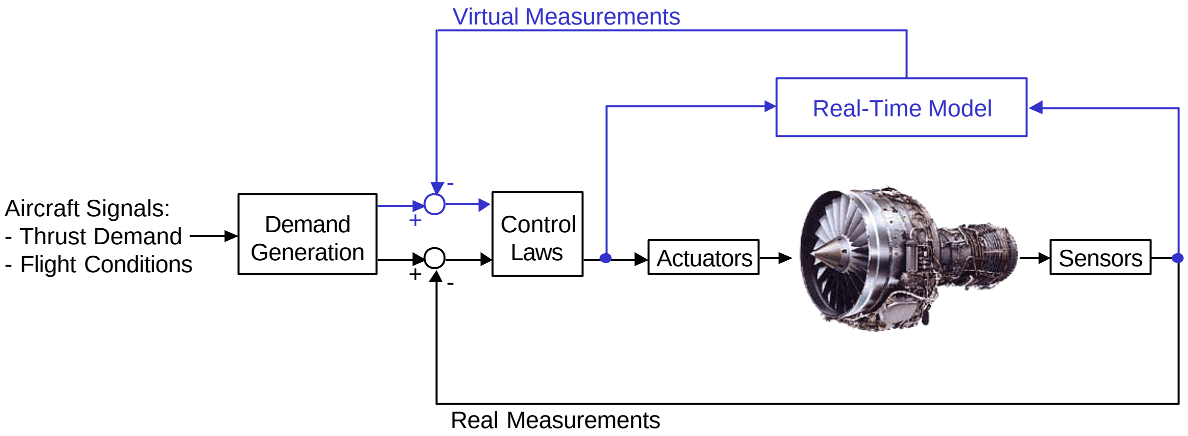

Figure 4: Implementation of onboard real-time model to generate "virtual" sensor signals

4 Jet Engine Real-Time Modeling

4.1 Definition of "Real-Time"

A common definition of "real-time" is that in a simulation environment, the simulated time equals the time needed to perform the simulation. This definition, however, does not imply any requirements on the time resolution or the accuracy of the simulation, both heavily influencing the computational demands of a simulation model.

As shown in section 2.1, the time constants of jet engine dynamics vary from less than one millisecond (gas dynamics) to a few minutes (heat transfer effects). Gas dynamic effects are often neglected in jet engine models since the impact on overall engine behavior is usually small, apart from malfunctions. The next-fastest effects in the jet engine are the spool dynamics, with time constants of several hundred milliseconds. Engine control systems, however, run with typical cycle times of 15 to 50 milliseconds. To be able to use a real-time model for engine control purposes, it is therefore desirable to run the simulation model with time steps of the same magnitude. The most common modeling methods are described below:

4.2 Full Thermodynamic Models

For the physical or performance analysis modeling of jet engines, the engine is first subdivided into its different components, like air inlet, compressors, turbines, combustion chamber, thrust nozzle, and so on. The operating behavior of the single components is either described through physical equations or by using characteristics and maps that can be obtained by rig tests or by CFD calculations. The component models can include energy conserving parts like spools (mechanical), blades, discs and casing (thermal) or gas volumes (thermodynamical). Thus also the transient behavior of the engine can be described.

The different components modeled as described above are coupled via laws of conservation of mass, momentum and energy. This usually leads to a non-linear set of equations, which can be solved by means of appropriate numerical methods. If the engine model includes energy conserving parts (transient model), the resulting set of equations is usually of a differential algebraic type (DAE). This DAE can be solved by special integration algorithms or by using the iterative solution mentioned before to explicitly solve for the vector of state derivatives and to use standard methods of integration to simulate.

4.3 Piecewise Linear State Space Models

State space systems originate from linear system theory. Generally speaking, a state space model is described by the two vector equations

$$\dot{\mathbf{x}} = \mathrm{f}(\mathbf{x}, \mathbf{u})$$
$$\mathbf{y} = \mathrm{g}(\mathbf{x}, \mathbf{u}),$$

where $\mathbf{x}$ denotes the state variables, $\mathbf{u}$ the input variables and $\mathbf{y}$ the output variables of the system. In the case of a jet engine, spool speeds and metal temperatures could be chosen as state variables. In system theory, often linear state space models are used. Linearization of the two non-linear equations stated above leads to:

$$?\,\dot{\mathbf{x}} = \mathbf{A}\Delta\mathbf{x} + \mathbf{B}\Delta\mathbf{u}$$
$$\Delta\mathbf{y} = \mathbf{C}\Delta\mathbf{x} + \mathbf{D}\Delta\mathbf{u}$$

A, **B**, **C**, and **D** are called "system matrices" and the equations describe the behavior of a dynamic system in the vicinity of an operating point. $\Delta\mathbf{x}$, $\Delta\mathbf{y}$ and $\Delta\mathbf{u}$ denote the deviations of the state, output and input variables from the corresponding values at this operating point. To be able to describe the behavior of a non-linear system, the matrices A, B, C and D have to be scheduled according to the operating point. This leads to a so-called "piecewise linear" state space model of the form

$$?\,\dot{\mathbf{x}} = \mathbf{A}(\mathbf{p})\Delta\mathbf{x} + \mathbf{B}(\mathbf{p})\Delta\mathbf{u}$$
$$\Delta\mathbf{y} = \mathbf{C}(\mathbf{p})\Delta\mathbf{x} + \mathbf{D}(\mathbf{p})\Delta\mathbf{u}$$

These systems are especially suited for real time applications due to the low computational power necessary for simulation. However, the complexity and hence the computational demand increases with the number of non-linear dependencies (the order of the parameter vector p) to be taken into account. To accurately describe the dynamic behavior of a jet engine, at least two parameters, one of the spool speeds and a parameter characterizing the flight envelope point, have to be considered.

The biggest advantage of piecewise linear state space models compared to physical models is the comparatively low computational demand. This, however, is no longer a significant issue due to the constantly increasing computing power available. The biggest disadvantage of piece-wise linear state space models is that the complexity of the model increases rapidly with the non-linear dependencies of the system. Another disadvantage is that state space models are less flexible as physical models, especially with respect to the incorporation of changed engine health parameters.

4.4 Comparison of Different Modeling Methods

In the following, a brief comparison between the different modeling methods shall be given. The abbreviation "state space models" will be used in this section to describe piece-wise linear state space models.

One of the most important criteria for comparing modeling methods is the achievable accuracy. Since state space models are often generated from physical models, their maximum accuracy equals these of physical models. Typical accuracy today is in the range of 1% full scale for pressures, temperatures and speeds.

When comparing the computing power needed to perform the calculations, the state space methods are clearly advantageous. Depending on the non-linearities to be considered, the computational demand of state space methods could be magnitudes lower than with physical models. This advantage fades with increasing available computing power. However, physical models usually use iterative methods, so they require additional means to achieve deterministic calculation times.

Another important criterion to judge the benefits and drawbacks of different simulation methods is the flexibility of the method under consideration. Flexibility, in this context, describes both the ability to simulate complex engines (for example variable cycle engines) and the possibility to quickly change simulation parameters like component efficiencies. In this discipline, physical models outperform their state space counterparts.

The most important reason for using physical jet engine models is their availability. Physical models are usually built in early engine pre-design stages. When using the same models for other purposes, the same database can be used for different modeling applications. This is extremely advantageous with rapidly changing engine build standards. State space models cannot be easily updated to new build standards and have to be completely re-generated every time the engine design changes.

	Physical Models	State Space Models
Accuracy	o	o
Low computational demands	-	+
Deterministic calculation time	-	+
Flexibility	+	-
Simulation of complex engines	+	-
Availability	+	-

5 Simulation Examples of Model Based Control

The following section shows simulation results of model based jet engine control. The results were obtained within the Brite/Euram project OBIDICOTE (On Board IDentification, DIagnosis and COntrol of gas Turbine Engines).

The simulations show comparisons between a reference control system and an enhanced control system featuring model based control loops.

The baseline engine for which the simulations were conducted is a typical commercial jet engine with a take-off thrust of about 130kN.

The simulation model is a complete physical jet engine model, which has been integrated to run under the control design / simulation tool MATLAB/Simulink.

5.1 Reference Control System

5.1.1 Introduction

A "reference" control system was designed to provide a basis for the implementation of model based extensions and to obtain a reference for judging the benefits of these extensions. This section shall describe the implemented reference control system. The basic control strategy closely resembles that of the systems used in commercial engines today.

5.1.2 Model Analysis

At the beginning of the control design process, a thorough analysis of the engine from a control point of view was performed. This included linearization of the non-linear model across the aircraft operating range and the engine power range.

5.1.3 Fuel Control

The most important controlling variable for the jet engine is the amount of fuel flow fed into the combustion chamber. The fuel mass flow is used to drive the engine according to the pilot's command input.

Thrust Modulation

The pilot is usually not interested in getting a specific net thrust value (in kN) from the aircraft engines. What the pilot usually wants to achieve when moving the thrust lever is to get the engines to deliver a certain percentage of the thrust that is available at the current flight conditions. Since thrust itself is not measurable in-flight, the relative thrust command given by the PLA (power lever angle) setting must be translated into a command change of a measured variable. Different possibilities exist, the following two being the most common:

- The relative thrust corresponds well with the low pressure spool speed. This especially holds for modern commercial high bypass engines. There is, however, a dependency on ambient temperature that has to be taken into account.
- The relative thrust corresponds very well with the engine pressure ratio, in this case defined as mixer exit total pressure divided by engine inlet pressure, i.e. EPR=P5/P2. A disadvantage of this thrust modulation method compared to the spool speed method is that the sensor pressure signals have a larger noise content and are usually slower than the spool speed signals. The biggest advantage is that no dependency on ambient conditions has to be taken into account.

For the reference control system, the EPR method is selected to modulate engine thrust. The corresponding control loop to be implemented has to comprise an integrator to drive the difference between commanded and actual EPR to zero. A Proportional-Integral (PI) control loop is chosen for thrust modulation. To reduce the effects of sensor noise, filters are applied to the P2 and the P5 sensor signals.

Fuel Pre-Steering Function

A huge amount of error integration and therefore also a large integral gain is needed for the EPR control loop. Large integral gains, however, decrease the system stability. To reduce the necessary amount of error integration, a feed-forward fuel pre-steering function is implemented. This function calculates the amount of fuel flow needed to hold the current LP spool speed. This pre-steering fuel flow is then added to the fuel flow calculated by the EPR control loop.

Limiting Control Loops

The engine control system is not only responsible for delivering the demanded thrust but also for keeping all engine variables within tolerable limits. The limits can be of an aerodynamic (surge margins), thermal (temperatures) and structural/mechanical (pressures, spool speeds) nature.

Maximum HP Spool Acceleration

One of the most safety critical engine limits is the compressor surge margins. During accelerations, the operating point in the high pressure compressor map moves in the direction of the surge line due to the spool inertia. Since the surge margin of the HPC can not be measured, the surge margin limit must be translated into limits of measurable variables. The two most common approaches are either to limit the allowable change in fuel flow or to limit the acceleration rate of the high pressure spool. The last method also helps to ensure that all engines of the same type behave in the same way with respect to acceleration times.

To limit the acceleration of the high pressure spool and thus ensure enough high pressure compressor surge margin, another PI control loop is integrated into the control system. This loop calculates the fuel flow necessary for achieving a given spool acceleration and is combined with the thrust modulation control loop as described above. Since the beginning of the acceleration phase at low spool speeds is especially critical for the HPC surge margin, the limit value for the spool acceleration can be scheduled with spool speed.

Maximum XNLP Limitation

To ensure the structural integrity of the low pressure spool, the absolute spool speed value must be held below a certain limit. To ensure the observance of this limit, another PI loop is integrated into the control system. This control loop computes the fuel flow that would be necessary to drive the engine exactly to the given low pressure spool speed limit. The LP spool speed loop is combined with the other control loops as shown below.

Maximum HP Spool Deceleration

To ensure constant deceleration times, the maximum spool deceleration of the HP spool has to be limited. This is performed by another PI type control loop, connected to the other loops as described below.

Control Loop Selection

Both the thrust modulation (EPR) control loop and the limiting control loops calculate a fuel flow value to drive the correspondent variable towards the demand or limiting value. The task of the control loop selection algorithm is to decide which of these fuel flow demand values (WFE) is passed on to the fuel actuation system. The selection logic uses the following lowest/highest wins algorithm:

$$WFE = min(min(max(WFE_{Dec}, WFE_{EPR}), WFE_{NL}), WFE_{Acc})$$

The overall setup of the reference control system's fuel flow control including the different control loops and the selection logic is depicted in figure 5. Different strategies are known to prevent the common problem of integrator windup. In this case, the idea is to use the same integrator by all fuel control loops. This is done by computing and selecting the integral part of the control loops before passing the selected value into the common integrator.

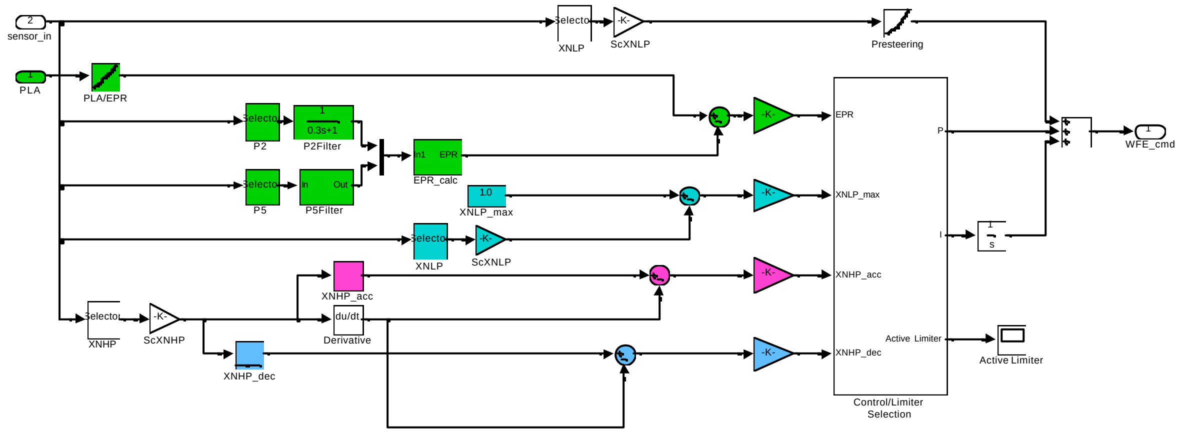

Figure 5: Simulink diagram of the fuel control block

Compressor Guide Vane Control

The spool speed dependent schedule for the inlet guide vanes of the HPC is included in the model's HP compressor map. Scheduling the IGV settings on corrected NH is commonly done in control system today, so this nominal schedule is used by the reference control system.

Handling Bleed Valve Control

The OBIDICOTE engine model features a compressor handling bleed valve that can be modulated. This helps to keep the compressors away from the surge margin during accelerations from low spool speeds. The percentage of air that is extracted at the bleed valve is usually scheduled on corrected low pressure spool speed. This approach is also used for the reference control system.

Overall Control Behaviour

Several simulations were carried out to test the overall behaviour of the reference control system. Step and slam accelerations and decelerations with and without sensor noise will be shown here as examples. All simulations are performed under sea level static (SLS) conditions.

Step Accelerations/Decelerations

First, the whole thrust range from idle to take-off power is passed in four PLA (Pilot's Lever Angle) steps. Then, the engine is decelerated again to ground idle setting also using four step inputs.

Figure 6 depicts the results of the simulation. The PLA command is transformed into an EPR (Engine Pressure Ratio) demand. The controlled engine follows this demand with some delay. The engine's net thrust (FGN) corresponds with the actual EPR value. The HP (High Pressure) spool acceleration is held within the given limits. When looking at the active control loop indication, it can be observed that the acceleration and deceleration control loops (indices 3 and 4) are active at the beginning of the acceleration and deceleration phases. The control authority is handed back to the EPR control loop (index 1) later in the transients.

Slam Accelerations/Decelerations

Slam accelerations/decelerations are performed from ground idle to take-off power and back to ground idle setting. Figure 7 shows the results of these simulations without taking sensor noise effects into account. The control system follows the EPR demand, keeping the spool acceleration within the relevant boundaries. During the major part of the acceleration and deceleration phases the spool acceleration/deceleration limiting loops (indices 3 and 4) are selected. The EPR control loop (index 1) is back in command when spool speeds are near their final values.

If the same simulation is carried out taking sensor noise into account, similar results are produced (see figure 8). When the engine operates at full take-off power, however, a constant switching between control loops 1 (EPR) and 2 (XNLPmax) can be observed. This is due to the fact that the engine is operating near the XNLP limiting value.

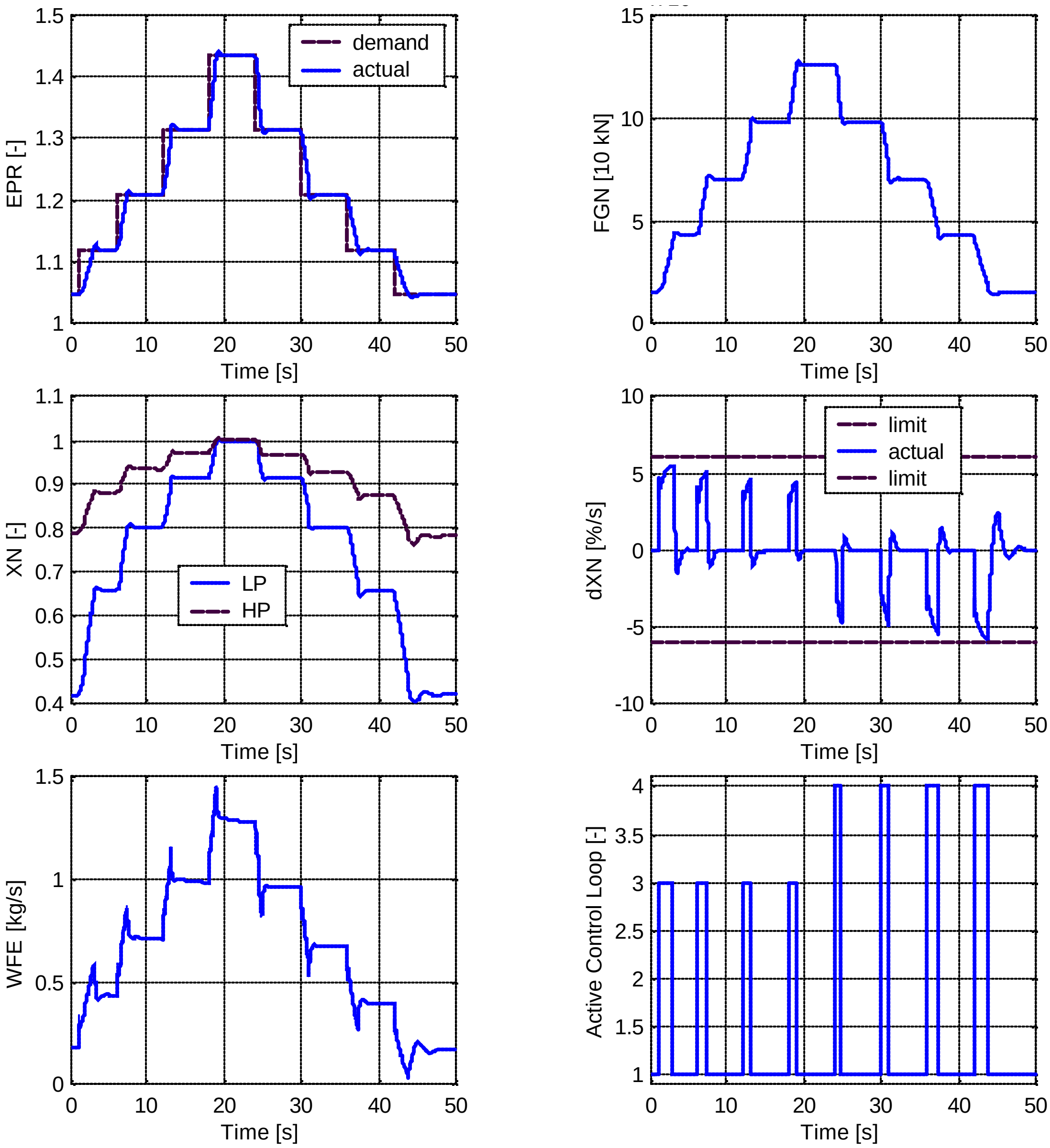

Figure 6: Step accelerations from ground idle to take-off power and subsequent decelerations (no sensor noise)

EPR = Engine Pressure Ratio
FGN = Net Thrust
XN = Spool Speeds
LP = Low Pressure
HP = High Pressure
WFE = Fuel Flow

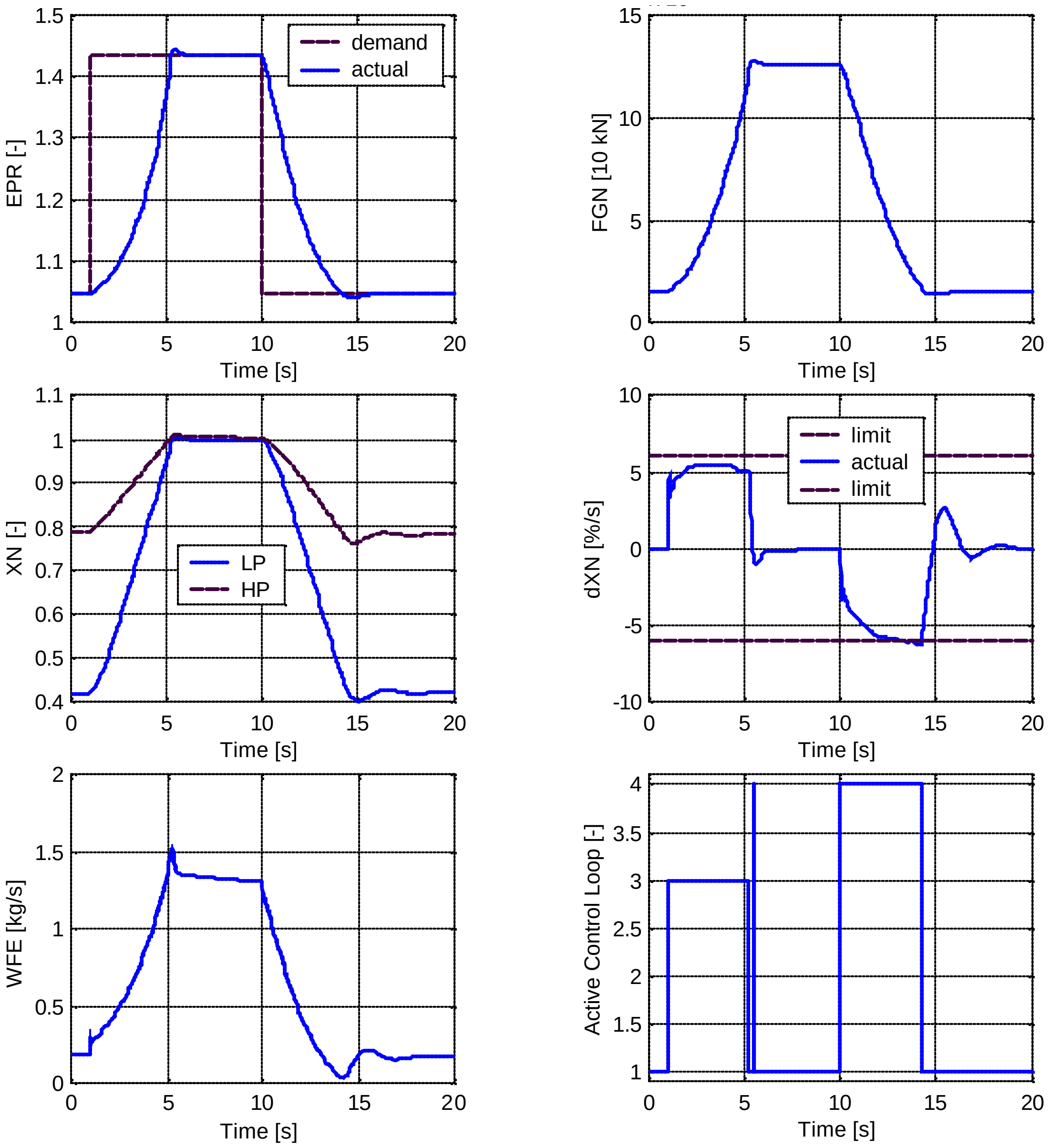

Figure 7: Slam acceleration from ground idle to take-off power and subsequent deceleration (no sensor noise)

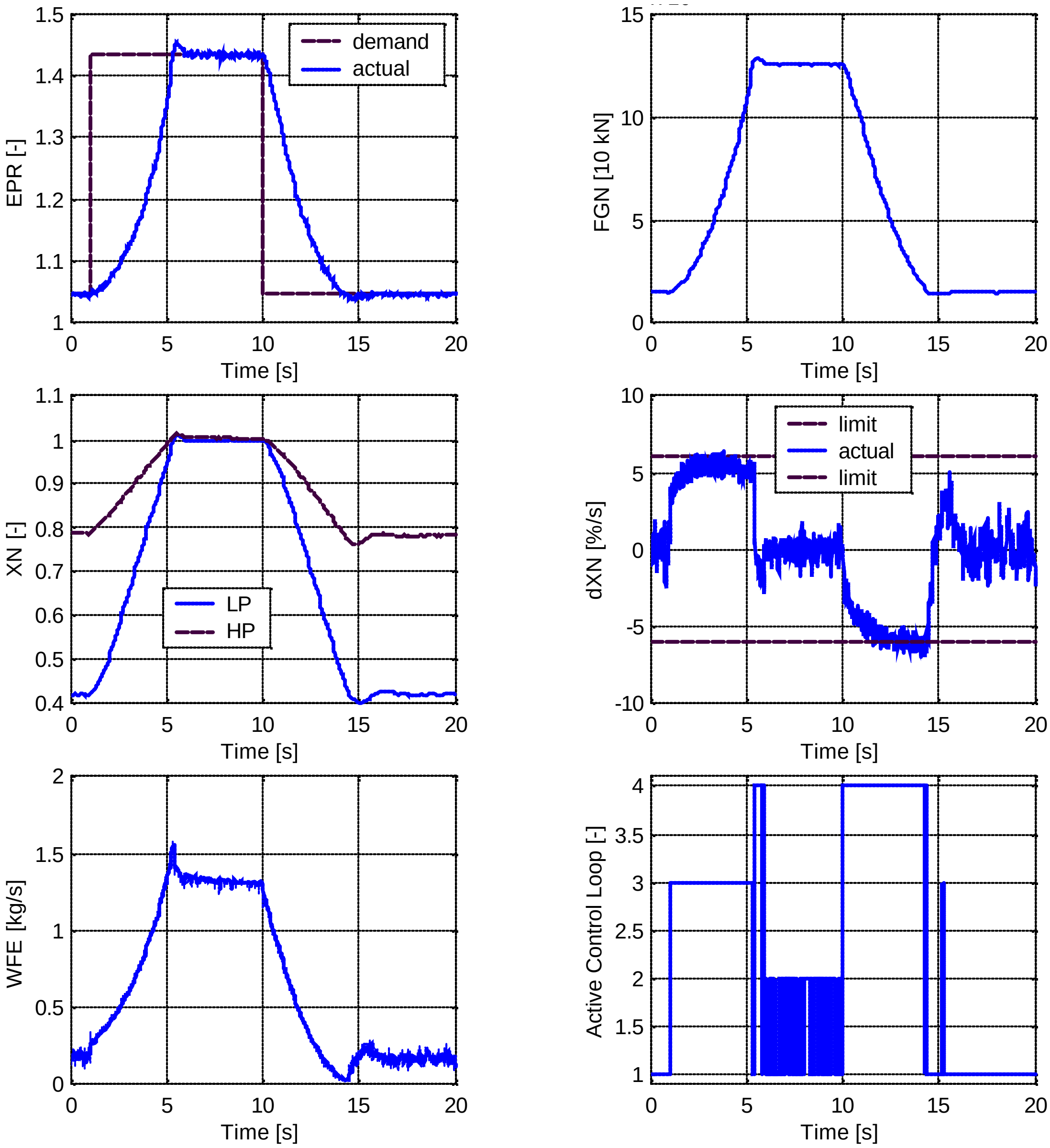

Figure 8: Slam acceleration from ground idle to take-off power and subsequent deceleration (with sensor noise)

5.2 Engine and Onboard Simulation Models

To simulate the behavior of a model based control system, two engine simulation models are needed. One represents the "real" physical engine; the other represents the onboard engine model. To avoid confusions, the term "engine" shall be used for the model of the real engine; the term "onboard model" will designate the simulation model integrated in the control/diagnosis system.

In the final application, there will always be deviations between the engine and its simulation model. There are different reasons for these deviations. Even if the simulation model is properly adjusted to the engine shortly after the engine's production, deterioration effects will lead to a growing discrepancy between the actual values of engine variables and the values predicted by the onboard model. These discrepancies can be minimized by an onboard detection of changed engine health parameters. Other causes for a mismatch between engine and onboard model may be inaccuracies of engine actuators as well as physical effects that are not included in the simulation model to reduce computation time. These can partly be compensated by using an observer configuration for the onboard model [14].

If, however, the same simulation model is used to represent both the engine and the onboard model, there is no inherent difference between the engine variables and the variables provided by the onboard model. To produce realistic simulation results, some mismatch between the "engine" and the onboard model can be created by changing the dynamics of the onboard model (offset in the state derivatives, switching off the heat transfer effects) or by including biases on the actuator signals. The simulations in this section use an onboard model that does not take heat transfer effects into account and thus deviates significantly from the simulated engine behaviour.

5.3 Model Based Control Loops

For the creation of the Simulink simulation model, a version of the complete thermodynamic engine without heat transfer is included in the control system. Subsequently, control loops are implemented that make use of the variables provided by this onboard model. Model based control loops are integrated for the high pressure turbine inlet temperature (section 5.3.1) and the high pressure compressor surge margin (section 5.3.2).

5.3.1 Turbine Inlet Temperature

The temperature of the high pressure turbine blades is of extreme importance to engine life. This temperature, and also the gas temperature at the turbine inlet is usually not measured by engine sensors. This is especially the case for commercial jet engines. The simulated turbine temperature provided by an onboard engine model can be used by the control system to avoid or limit the temperature peaks that occur during accelerations at high power levels. Depending on the degree of detail of the used simulation model, either the metal temperature of the turbine blades, or the gas temperature at the turbine inlet can be used as virtual measurement.

To test the behaviour of an adaptive control system featuring a model based turbine inlet temperature (T41) limitation, an additional PI loop is added to the reference control system. This PI loop receives a virtual measurement of T41 generated by the onboard model.

5.3.2 Compressor Surge Margin

The surge margins of the compressors play a vital role for the safe operation of the engine. Especially during transient maneuvers, such as fast accelerations, a stall of the flow around the compressor blades leading to compressor surge must be avoided. The distance of the current operating point to the surge line (surge margin) usually cannot be measured by sensors. Current engine control systems circumvent this deficiency by imposing a limit on the spool accelerations or by scheduling fuel flow to prevent compressor surge. The onboard model can be used to determine the current margin between the operating point and the nominal surge line of the turbo compressors and provide the control system with this information. With the knowledge of the current shift of the operating line the surge margin stack-up could be reduced thus enabling improvements of engine performance, whilst guaranteeing safe operation even of degraded or worn engines.

A further model based PI control loop is added to the reference control system for a limitation of the high pressure compressor surge margin (PRSHPC). This control loop is fed by the onboard model.

5.4 Simulation Results

For a demonstration of the model based control system's advantages, numerous simulations are carried out. The simulation results shown in the subsequent sections are generated at sea level static conditions. Being the most crucial operation both for high pressure compressor surge margin and for turbine temperature, slam accelerations from ground idle to takeoff thrust are performed. Both new production engines and deteriorated engines are considered.

5.4.1 New Engine

Slam accelerations for production new engines (=nominal values for health parameters) are performed at SLS conditions with and without the model based surge margin limitation loop. The results are depicted in figure 9. At the beginning of the acceleration (t=2s to t=4s) the model based PRSHPC loop reduces the allowed spool acceleration to keep the high pressure surge margin above the minimum limit of PRSHPC=10%. Because of the differences between the onboard model and the engine model, the 10% surge margin is not fully used but the actual value remains above 11%. Due to the slower acceleration from t=2s to t=4s the whole engine response to takeoff power is slower than without the model based limit. This effect could be compensated if the model based system was allowed to accelerate faster than 6%/s from t=4s to t=7s where the acceleration is not critical for PRSHPC anymore.

Next, the turbine temperature limitation is implemented. To isolate the effects of this new model based limitation mode, the surge margin control loop is switched off. Figure 10 shows the difference between using the model based T41 loop and the original reference control system. The model based T41 limit is set to 1550K. As shown by figure 10 this helps to reduce the temperature peak at t=6s significantly without compromising the engine acceleration time (95% response time). Eventually, figure 11 shows the behavior of a model based control system featuring model based T41 and surge margin limitation loops when compared to the reference control system.

5.4.2 Deteriorated Engine

The same simulations as described in section 5.4.1 above are carried out with a deteriorated engine (=changed health parameters). The simulations assume that there is an onboard diagnosis system available, which provides information about changing engine health parameters (e.g. [14]). With this information, the onboard model is "tracked" to represent the actual engine as accurately as possible.

In figure 12, the results of using the surge margin control loop are shown. The surge margin loop keeps PRSHPC above the desired limit of 10%. In contrast to the results achieved with new engines, the difference in overall acceleration time is almost not perceivable.

When the T41 loop is tested without surge margin control (figure 13), it can be seen that the turbine temperature is held below the limit of 1550K also for the deteriorated engine. This reduces the temperature peak significantly and thus improves engine life consumption. As the T41 limit is only effective at the end of the acceleration, the time to reach 95% of the final XNLP value is not compromised.

Figure 14 shows the behavior of both the T41 and the surge margin model based limitations applied to a deteriorated engine. The results show significant improvements for T41 and for PRSHPC without perceivable effects on the overall engine response time.

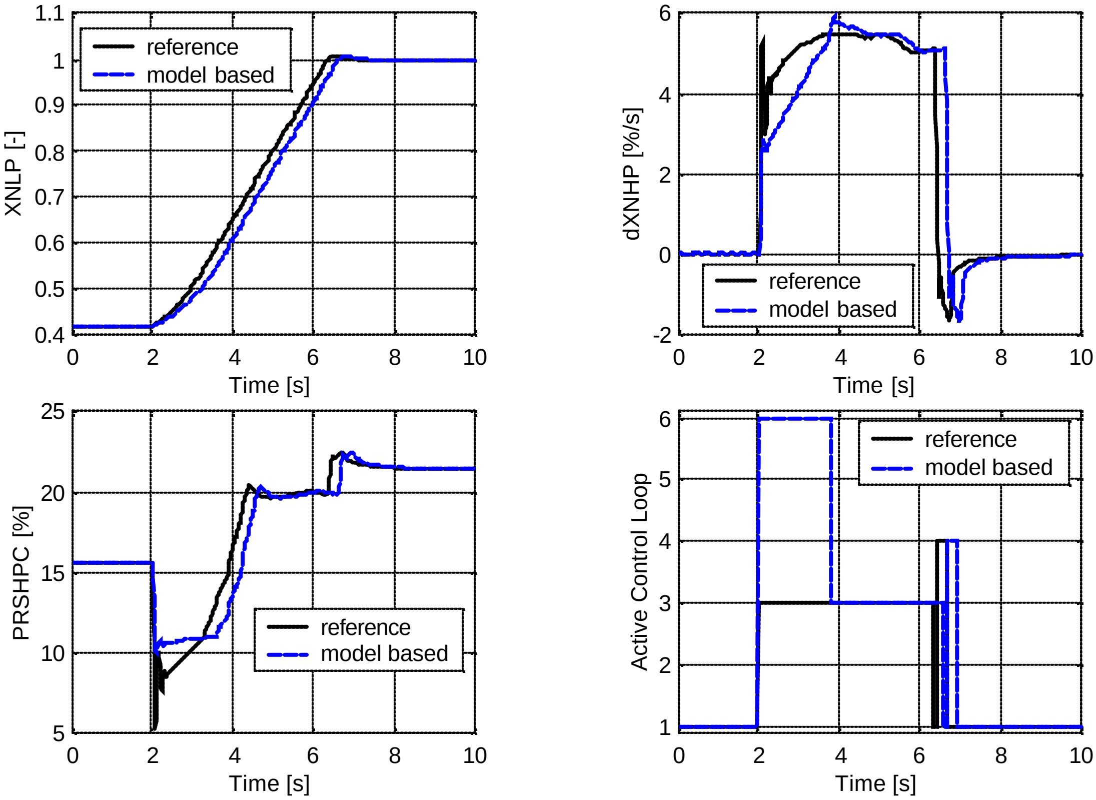

Figure 9: Slam acceleration at SLS conditions with model based surge margin limitation ("model based") and without ("reference"), new engine

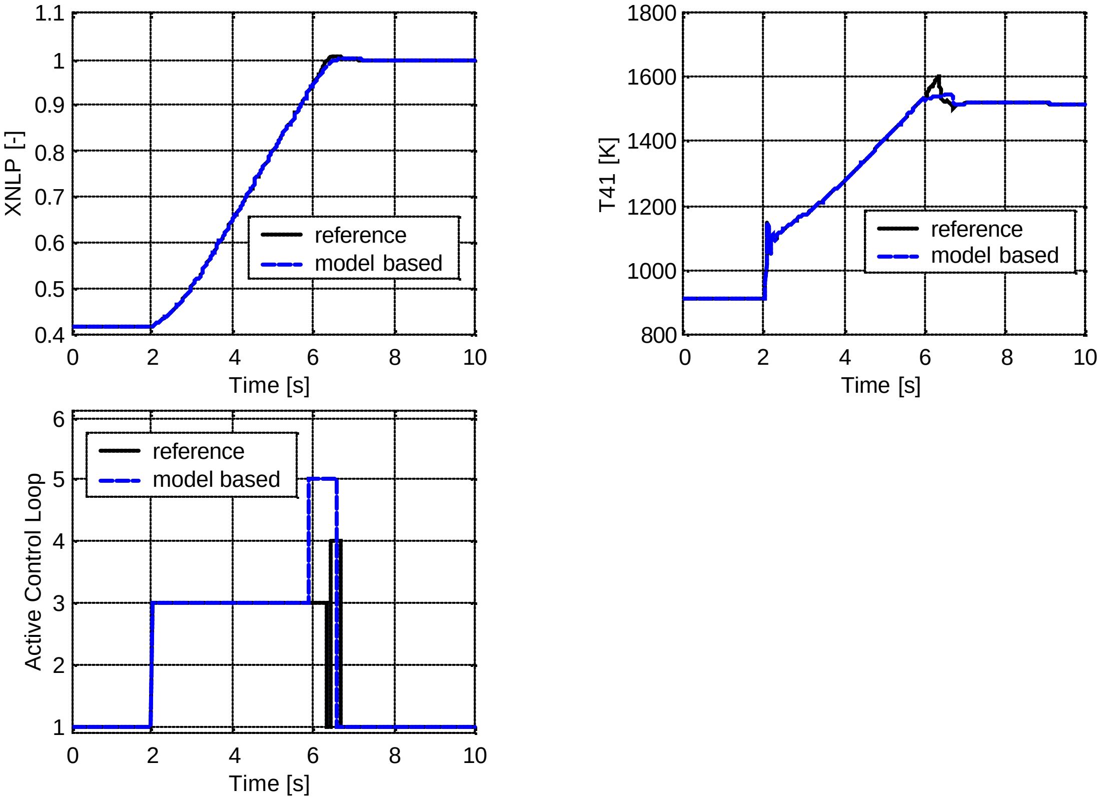

Figure 10: Slam acceleration at SLS conditions with model based T41 limitation ("model based") and without ("reference"), new engine

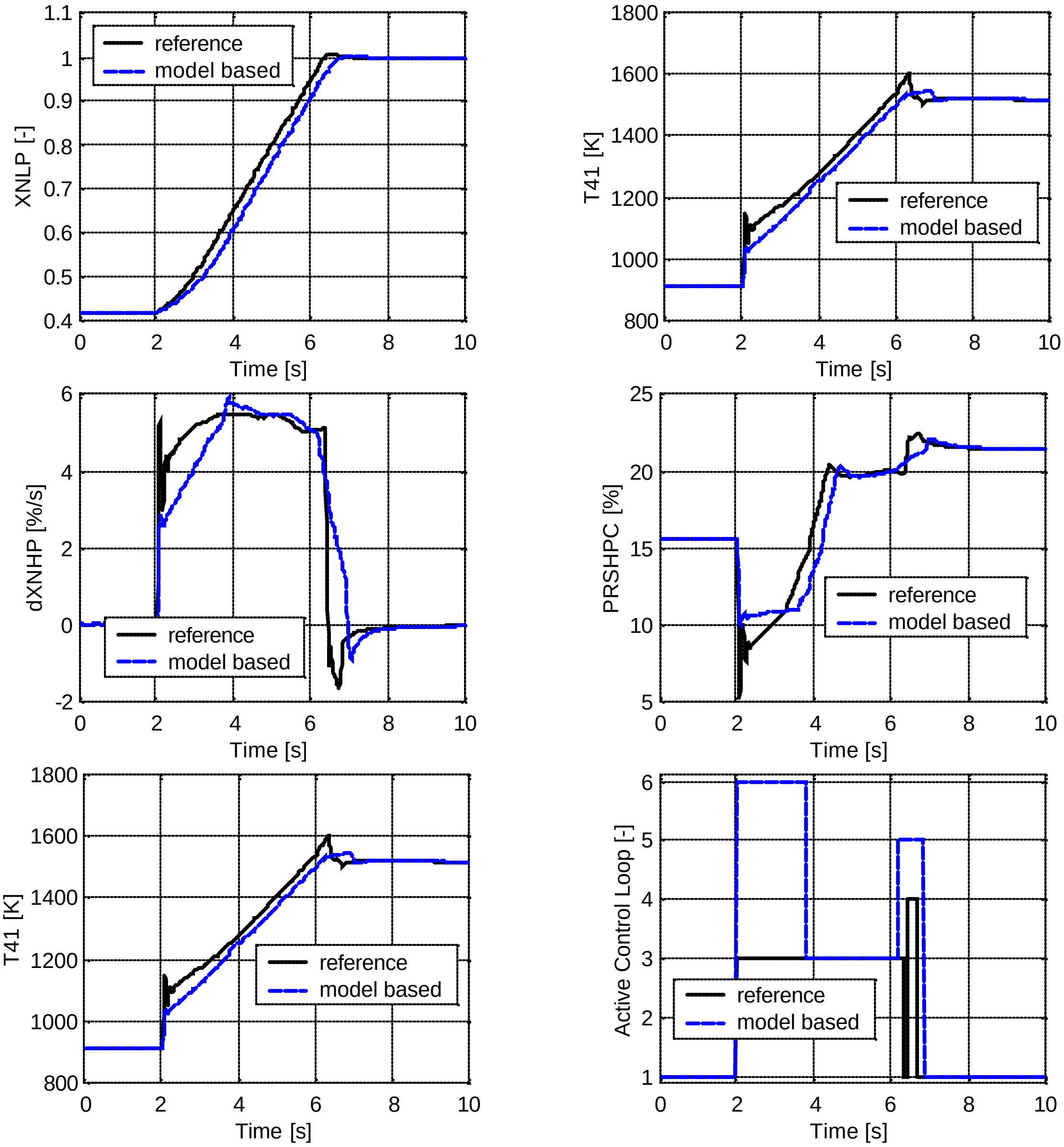

Figure 11: Slam acceleration at SLS conditions with model based T41 and surge margin limitation ("model based") and without ("reference"), new engine

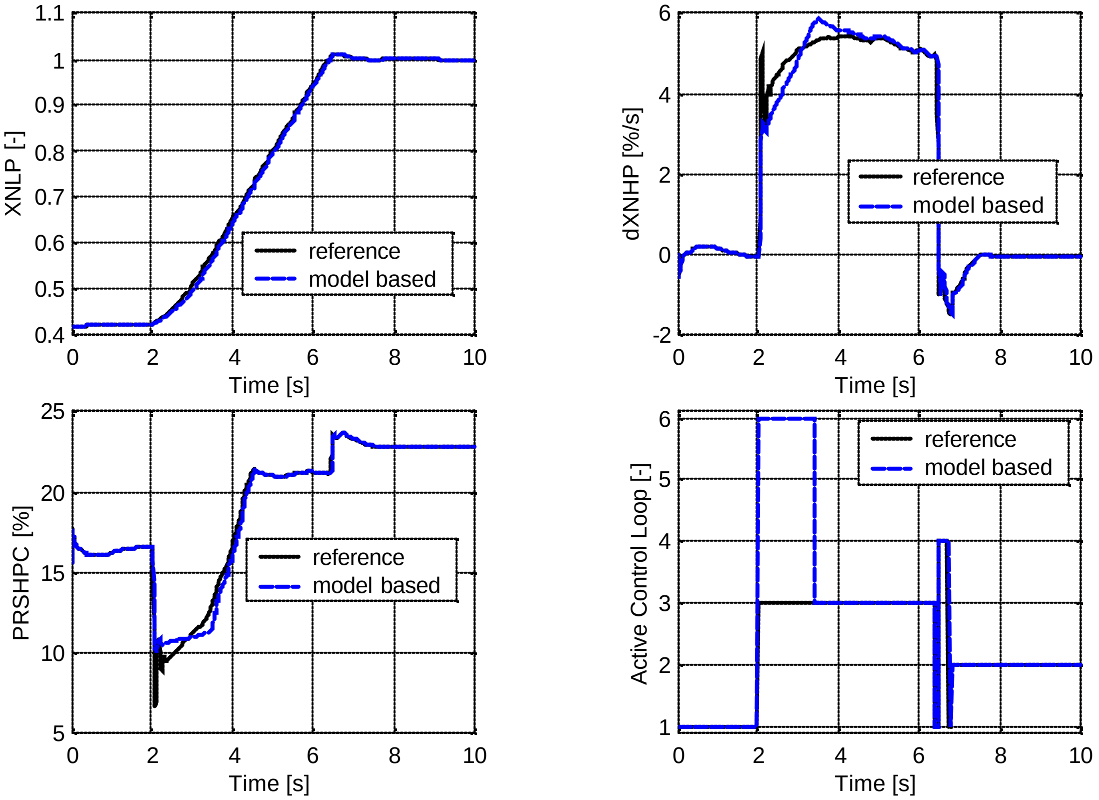

Figure 12: Slam acceleration at SLS conditions with model based surge margin limitation ("model based") and without ("reference"), deteriorated engine

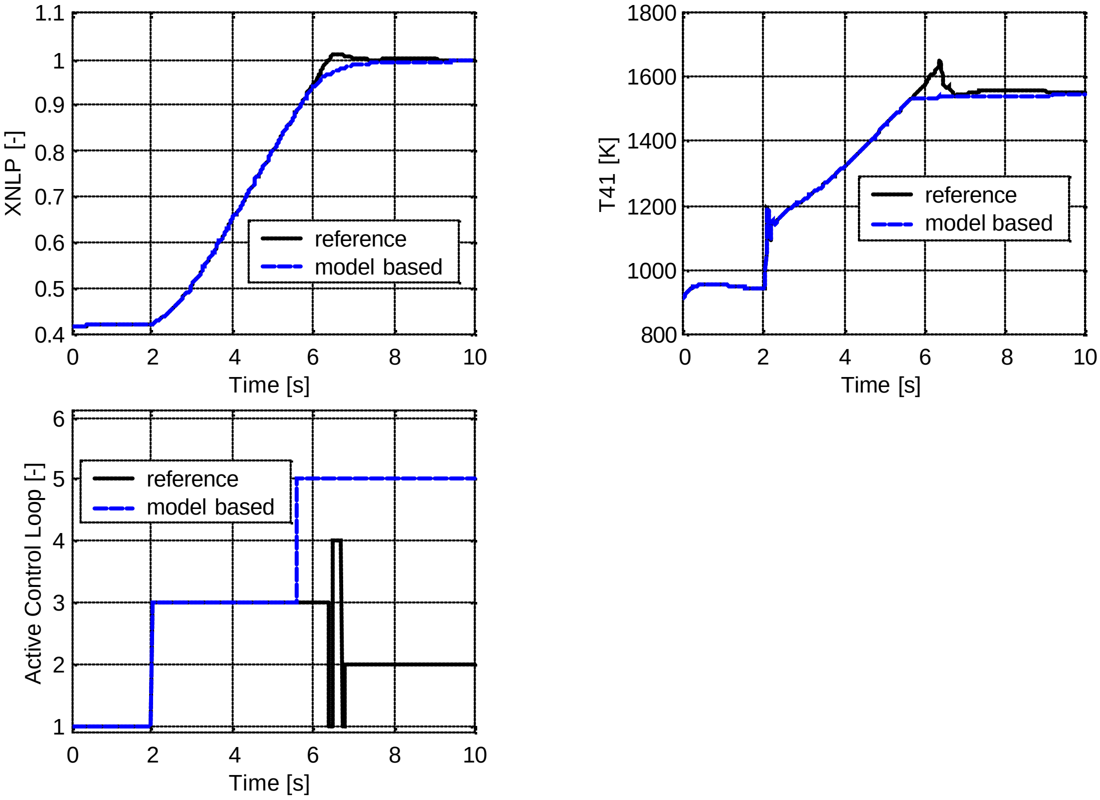

Figure 13: Slam acceleration at SLS conditions with model based T41 limitation ("model based") and without ("reference"), deteriorated engine

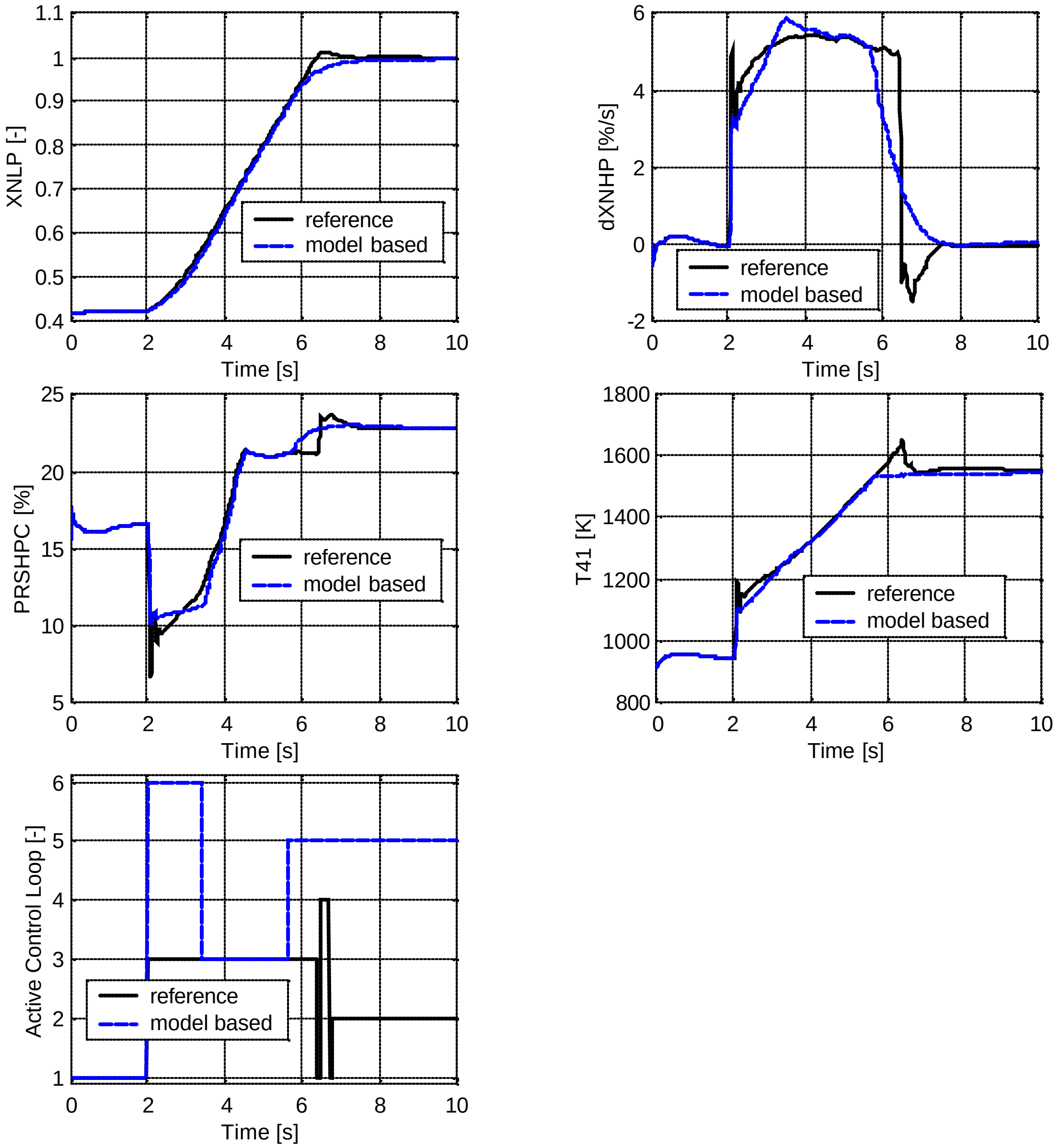

Figure 14: Slam acceleration at SLS conditions with model based T41 and surge margin limitation ("model based") and without ("reference"), deteriorated engine

5.5 Evaluation of Results

The model based control extensions for turbine temperature and compressor surge margin show significant improvements when compared to the original reference control scheme. This holds for new production but especially for deteriorated engines. As far as new engines are concerned it should be noted, however, that a similar behavior could be achieved by other means. These could include a variation of the spool acceleration limit with spool speed or an introduction of PID instead of PI loops to minimize the temperature peak near the end of the acceleration phase. These means, however, can not ensure the same behavior for different levels of engine deterioration. Thus the biggest advantage of model based T41 and surge margin limitations probably lies in the compensation of engine degradation.

6 Conclusion and Outlook

An onboard model integrated into a jet engine control system can provide different engine variables that are usually not measured by engine sensors, for instance:

- Turbine blade or turbine inlet temperature
- Surge margins of the turbo compressors
- Net thrust

The use of these virtual measurements could improve safety, engine life, specific fuel consumption and engine performance, especially in conjunction with a diagnostic system, which provides information about changed engine health parameters. With the information about the changed parameters, the onboard model can be "tracked" to represent the actual engine as accurately as possible.

Showing the simulation examples of model based turbine temperature and surge margin control, the structure and behavior of model based control systems with model tracking were demonstrated. The advantages of such a model based system were outlined.

To be able to determine the usability of such a system for real-world applications, it is necessary to test the different simulation and diagnostic methods with test rig engine data. These tests will show the accuracy achievable for the different modeled variables.

The integration of a complete physical model into the control system, as shown by the simulations in section 5, needs far more computing power than is available in typical engine control systems today. It can be assumed, however, that the available computational power will constantly increase, following the general trends of computer technology. Until sufficient power is available, it is also possible to integrate simplified, single-purpose, models into the control system.

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