HARDWARE-IN-THE-LOOP-SIMULATION OF A FEEDFORWARD MULTIVARIABLE CONTROLLER FOR THE ALTITUDE TEST FACILITY AT THE UNIVERSITY OF STUTTGART

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Abstract

The altitude test facility (ATF) of the University of Stuttgart at the Institute for Aircraft Propulsion Systems (ILA) is a complex test facility which is used to test aero-engines and their components under altitude conditions. The ATF provides the total pressure and temperature at the inlet as well as the altitude pressure at the nozzle exit of the test object according to the conditions occurring during flight operations.

At present, a model-based controller is available to adjust the altitude conditions during test facility operation. The ATF control system is a complex and safety-critical system, and thus faults may cause damage to the test object or the test facility. Therefore, thorough testing of the ATF control system including hardware and software is essential to ensure system integrity and reliability after changes of source code or modifications of the control hardware.

A modular numerical performance model is available to simulate the steady-state and the dynamic operational behaviour of the altitude test facility. The modular approach permits the integration of test objects into the simulation. In addition the model-based controller must be included in the simulation in order to understand the dynamic interaction between test object, ATF control and test facility [1]. The existing model-based controller was extended by a feedforward controller. The Software-in-the-loop (SIL) simulation of controller and test facility offered a simple and cost-efficient way to verify the closed loop system requirements.

For validation purposes a Hardware-in-the-loop (HIL) simulation was set up. A real-time capable performance model of the altitude test facility has been developed. The real-time simulation provided both synthetically generated sensor data and disturbance data for the ATF control system. The HIL simulation was used to perform functional tests of the I/O devices and the graphical user interface. The limits of controlled operation could be tested without endangering the test facility or the test object. Tests using a passive test object were conducted in order to validate the simulation and to demonstrate the functionality of the ATF control system. Furthermore, the improved performance of the feedforward controller could be shown during the test campaign.

NOMENCLATURE

A	Cross-sectional area
c_p	Specific heat capacity
d	Disturbance variable
h	Specific enthalpy
M	Mach number
p	Static pressure
p_t	Total pressure
R	Specific gas constant
T	Static temperature
T_t	Total temperature
u	Valve position
$\mathbf{u}$	Vector of actuating variables
$\mathbf{w}$	Vector of set points
W	Mass flow
$\mathbf{x}$	Vector of state variables
κ	Heat capacity ratio
μ	Valve coefficient
Π	Pressure Ratio

INDICES

C	Cold stream
H	Hot stream
I	Inlet
O	Test object
SP	Set point

1. INTRODUCTION

The certification process of aircraft propulsion systems requires an experimental verification and validation of the steady-state and transient performance of the propulsion system. During ATF testing the per-

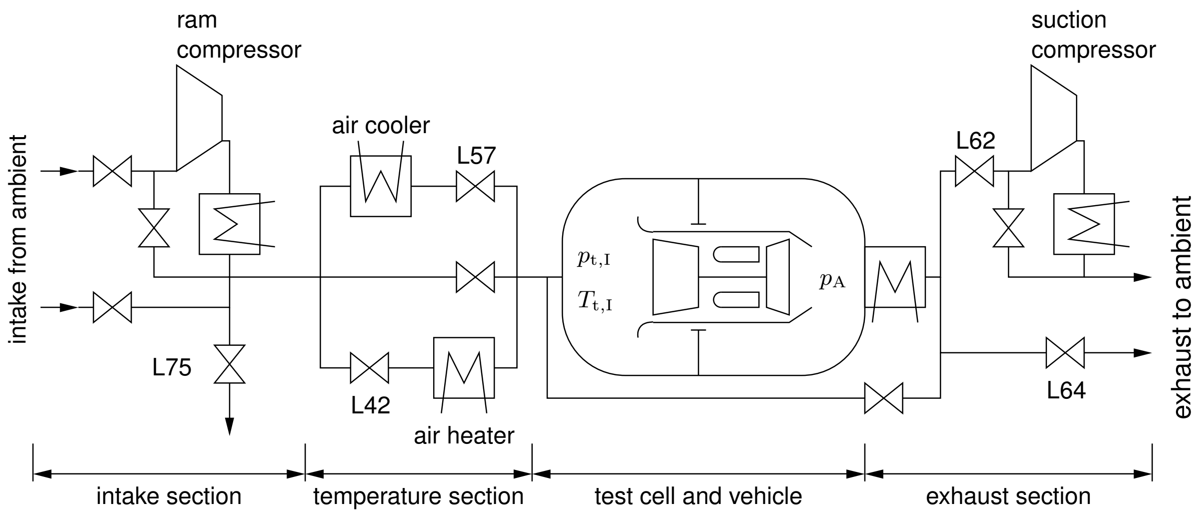

Fig. 1: Facility operation diagram of the ATF at the University of Stuttgart

formance of the propulsion system can be tested at different points of the flight envelope in a reproducible manner. The ATF has to provide ambient conditions for the test object as they occur during flight operation. The total inlet temperature $T_{\mathrm{t,I}}$ and total inlet pressure $p_{\mathrm{t,I}}$ in the intake plenum and the altitude pressure at the nozzle exit of the test object are adjusted according to the simulated altitude and Mach number M [2].

(1) $$T_{\mathrm{t,I}} = T_{\mathrm{A}}\left(1 + \frac{\kappa - 1}{\kappa} M^2\right)$$

(2) $$p_{\mathrm{t,I}} = p_{\mathrm{A}}\left(1 + \frac{\kappa - 1}{\kappa} M^2\right)^{\frac{\kappa}{\kappa - 1}}$$

For this purpose, the ATF features various compressors, control valves, and heating and cooling systems. A facility operation diagram including the main facility components is depicted in Fig. 1.

Depending on the total inlet pressure $p_{\mathrm{t,I}}$ the air taken from ambient is ducted directly or via ram compressors towards the temperature section. There, the air flow is divided into two parts that are lead through different heat exchangers. One part is ducted through an air cooler to allow low temperatures $T_{\mathrm{t,C}}$ whereas the other part passes through an air heater to reach high temperatures $T_{\mathrm{t,H}}$. The inlet valves L42 and L57 are used to adjust the total inlet temperature $T_{\mathrm{t,I}}$ through a variation of the ratio between the hot and the cold stream. Similarly, the total inlet pressure $p_{\mathrm{t,I}}$ in the intake plenum can be adjusted by a variation of the total mass flow through the inlet valves.

The exhaust gases of the test object are exhausted to ambience either directly via valve L64 or via suction compressors and valve L62. Similar to the adjustment of the inlet pressure, the static altitude pressure p_{H} can be modified by a variation of the total mass flow using valves L62 and L64.

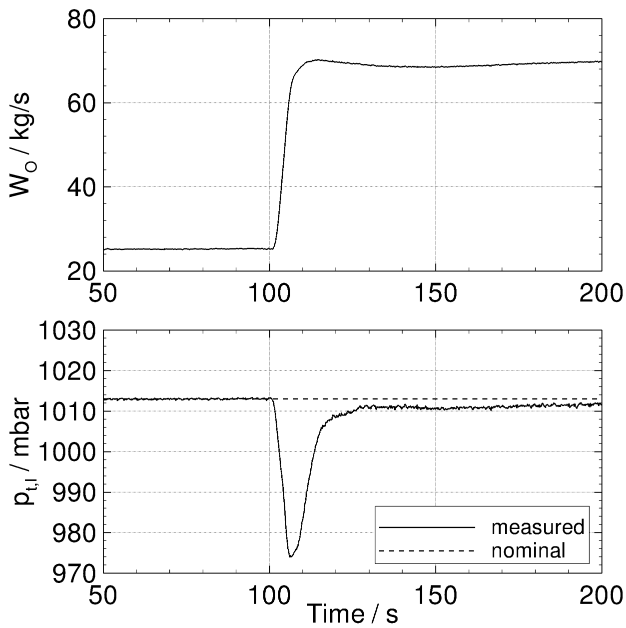

Fig. 2: Total inlet pressure during an increase of the engine mass flow

Previous studies showed that an automated facility control during steady-state and transient test object operation is possible [3, 4]. The valve positions of the inlet valves (u_{H}, u_{C}) were calculated dependent on actual engine mass flow and measured facility parameters such as pressure and temperature. Furthermore, the interactions between the automated facility control, ATF, and test object have been analysed [1]. Improvements regarding performance and stability of the control system were made through the introduction of a modular model-based controller [5]. This approach uses a model-based controller dependent on measured facility parameters to calculate the positions of the inlet valves and a separate PI controller to adjust the altitude pressure p_{H}.

During a slam acceleration test, the pressure within the intake plenum drops by 41 mbar, due to the increase of the test object's mass flow and the limited volume of the intake plenum. This effect can cause negative pressure differences between total inlet pressure and static altitude pressure especially during tests at low flight Mach numbers such as sea level static conditions (see Fig. 2). Negative pressure differences influence compressor stability and may cause compressor surge or damage of the test object. Therefore, negative pressure differences have to be avoided or at least minimised.

2. FEEDFORWARD FACILITY CONTROL

As shown in sec. 1 the system disturbance is mainly driven by the test object's mass flow. If the disturbance d is measurable, the performance and accuracy of the control system can be improved by introducing feedforward control [6,7]. Knowing the existence and size of a disturbance allows to react before the state vector **x** is affected. Therefore, the disturbance is measured and processed in a mathematical model in order to manipulate the vector of actuating variables **u** and to reduce the impact on the system state. The integral part of the model-based controller is used to eliminate control offsets that arise from model inaccuracies. A control block diagram of the feedforward control is shown in Fig. 3.

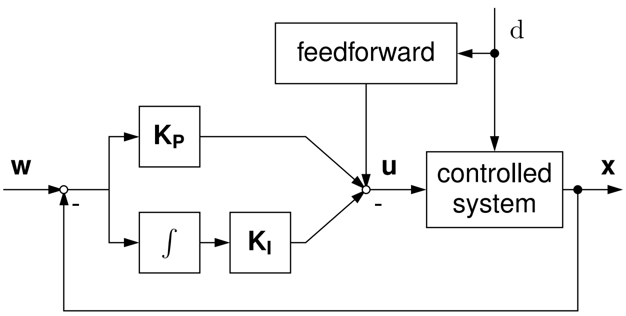

Fig. 3: Control block diagram of the feedforward control system

The mathematical model used for the feedforward control is based on the flow characteristics of the inlet valves. To avoid changes in inlet pressure during steady-state operation the mass flows of the hot and cold stream have to be equal to the total mass flow of the test object W_{O}

$$(3) \quad W_{\mathrm{H}} + W_{\mathrm{C}} = W_{\mathrm{O}}\,.$$

The temperature in the intake plenum is obtained as the mixing temperature of the hot and cold stream. Thus, the conservation of energy can be written as:

$$(4) \quad W_{\mathrm{H}} h_{\mathrm{H}} + W_{\mathrm{C}} h_{\mathrm{C}} = W_{\mathrm{O}} h\,.$$

With Eq. (3) and the assumption of a constant specific heat capacity the mass flows of the hot and cold stream can be calculated as:

$$(5) \quad W_{\mathrm{H}} = \frac{(T_{\mathrm{t,I,SP}} - T_{\mathrm{t,C}})}{(T_{\mathrm{t,H}} - T_{\mathrm{t,C}})}\, W_{\mathrm{O}}$$

and

$$(6) \quad W_{\mathrm{C}} = \frac{(T_{\mathrm{t,H}} - T_{\mathrm{t,I,SP}})}{(T_{\mathrm{t,H}} - T_{\mathrm{t,C}})}\, W_{\mathrm{O}}\,,$$

where $T_{\mathrm{t,I,SP}}$ is the target temperature in the intake plenum.

The mass flow parameter through an inlet valve can be described as a function of the pressure ratio of the valve $\Pi = \frac{p_{\mathrm{t,out}}}{p_{\mathrm{t,in}}}$ and a valve coefficient μ [8]:

$$(7) \quad \frac{W_{\mathrm{O}}\sqrt{RT}}{pA} = \Pi \frac{\sqrt{2c_p\left[1 - \Pi^{\frac{R}{c_p}}\right]}}{\sqrt{R}\,\Pi^{\frac{R}{c_p}}}\,\mu(u)\,.$$

With the Eq. (5) and Eq. (6) a relationship between the required mass flows, the desired inlet temperature and the valve coefficients is obtained

$$(8) \quad \mu_{\mathrm{H}} = \frac{(T_{\mathrm{t,H}} - T_{\mathrm{t,I,SP}})}{(T_{\mathrm{t,H}} - T_{\mathrm{t,C}})} \frac{R\sqrt{T_{\mathrm{t,H}}}\,\Pi_{\mathrm{H}}^{\frac{R}{c_p}-1}}{p_{\mathrm{H}} A_{\mathrm{H}} \sqrt{2c_p\left[1 - \Pi_{\mathrm{H}}^{\frac{R}{c_p}}\right]}}\, W_{\mathrm{O}}$$

$$(9) \quad \mu_{\mathrm{C}} = \frac{(T_{\mathrm{t,I,SP}} - T_{\mathrm{t,C}})}{(T_{\mathrm{t,H}} - T_{\mathrm{t,C}})} \frac{R\sqrt{T_{\mathrm{t,C}}}\,\Pi_{\mathrm{C}}^{\frac{R}{c_p}-1}}{p_{\mathrm{C}} A_{\mathrm{C}} \sqrt{2c_p\left[1 - \Pi_{\mathrm{C}}^{\frac{R}{c_p}}\right]}}\, W_{\mathrm{O}}$$

This formulation has the advantage that the valve coefficients μ_{H} and μ_{C} are only dependent on the inlet valve positions (u_{H}, u_{C}). The valve parameters have been experimentally determined to account for model inaccuracies assuming isentropic choking [3]. Hence, the valve positions u_{H} and u_{C} can be obtained by interpolation from experimental data. In order to obtain a physically reasonable solution the valve positions are limited to values between 0 (closed) and 1 (open).

As already mentioned, control offsets may arise during operation due to the error in measurement and model inaccuracies. For instance the temperature loss between the mixing plane and the intake plenum are neglected in the model. A combination of the feed-forward with the existing model-based controller is an appropriate way to eliminate offsets.

3. ATF REAL-TIME PERFORMANCE MODEL

In order to develop a Hardware-in-the-loop simulation, a valid numerical model of the ATF that captures the steady-state as well as the transient operational regime is essential. Previous studies dealt with the development of a modular ATF model [8, 9]. The simulation model consists of first-order ordinary differential equations to describe the pressure and temperature gradients in the piping elements. In addition, supplementary algebraic equations are used to determine additional values such as the flow through valves (see Eq. (7)) and heat transfer. An explicit Runge-Kutta method is applied to the differential equations to perform the time integration in a discrete-time manner. At the end of each time-interval the state variables are updated.

The modular approach facilitates the integration of additional modules. To capture the interaction between the ATF and the different test object, several modules were introduced. Thus, the transient engine behaviour

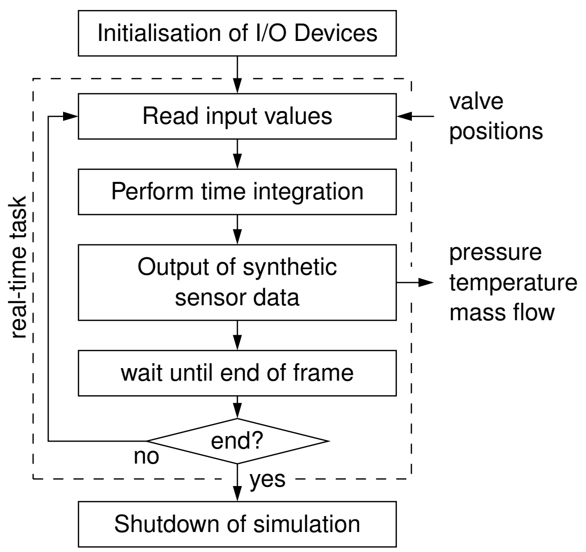

Fig. 4: Software flow diagram of the ATF real-time performance model

can be represented as a rotational speed to mass flow parameters map or as customerdeck using standard interface definitions [10, 11]. Another module was created for the model-based controller including the feedforward control in order to conduct software-in-the-loop (SIL) simulations.

For the HIL simulation a module for the communication with the I/O-Devices was developed. This allows the simulation to obtain control values and to provide synthetic sensor data for controller. In order to run a useful and valid HIL simulation a real-time capable simulation that executes I/O-Opperations in precise intervals is essential [12]. Therefore, the simulation was split into a task for the initialisation and shut-down and a cyclic real-time task. A basic software flow diagram is shown in Fig. 4. During each cycle the simulation reads the actual valve positions, performs a time-integrations and sends the updated temperatures and pressures in the piping as well as the actual mass flow via the I/O-Devices. After sending the synthetic sensor data the task waits until the end of the current cycle. Then, the cyclic task is repeated until the end of the simulated time is reached.

4. HARDWARE-IN-THE-LOOP SIMULATION

The HIL simulation used for the testing of the feed-forward controller consists of three subsystems: the ATF simulation, the test object control and the control system itself. A structure of the simulation hardware is shown in Fig. 5.

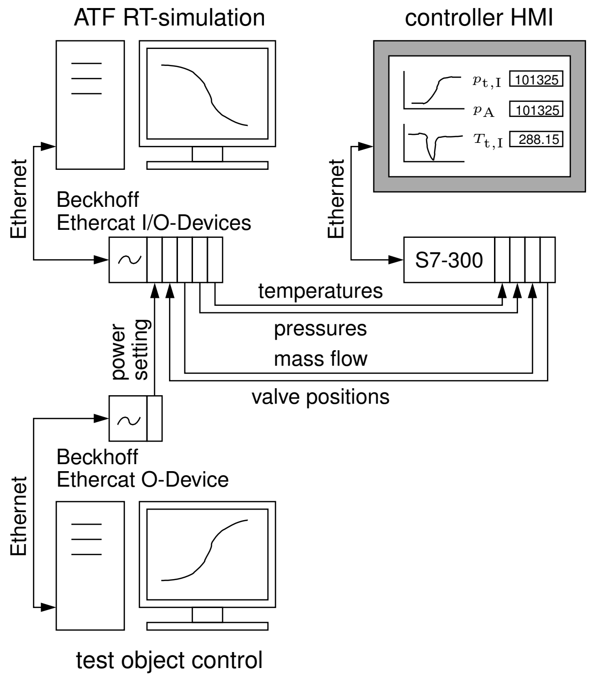

Fig. 5: Structure of the Hardware-in-the-loop simulation

The ATF simulation (see sec. 3) that provides synthetic sensor data for the control system is run on a desktop computer. A Linux Kernel using the Xenomai Real-

Time Framework [13] was used as operating system, in order to ensure a repeatable real-time simulation having a well-defined sample frequency of 100 Hz. The ATF simulation was connected to digital and analog Beckhoff Ethercat I/O-Devices [14] via Ethernet connection using the EtherLab project's open-source EtherCAT-master [15]. Similarly, the computer for test object control was set up using only one Ethercat O-Device to send the requested power setting to the simulation.

Since the control system is safety-critical, the system was set up using a failsafe SIMATIC S7-300 CPU [16] that was connected to failsafe I/O-modules. The CPU was connected via Ethernet to a large touch display that provides to the user an interface for the input of nomial values and for performance monitoring of the control system.

5. RESULTS

After the implementation of the feedforward controller, tests using the HIL simulation were conducted in order to perform system test, to optimise the usability of the user interface and to train the operators. Furthermore, tests were run at the ATF of the University of Stuttgart for validation purposes. The slam acceleration of an

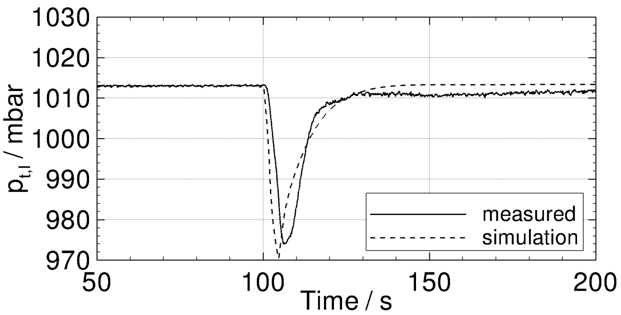

Fig. 6: Total inlet pressure without feedforward control

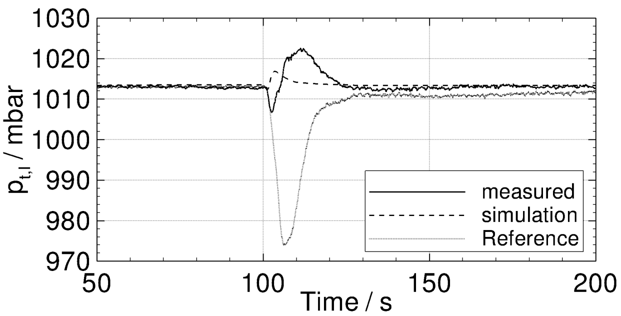

Fig. 7: Total inlet pressure with feedforward control

two spool high performance turbojet at sea level static conditions was chosen as manoeuvre for testing of the feedforward controller, since it is the most challenging manoeuvre at constant conditions. The change in mass flow is shown in Fig. 2.

The pressure drops during the increase in mass flow using the model-based and feedforward controller are depicted in Fig. 6 and Fig. 7. It could be demonstrated by both the HIL simulation and the experimental measurements that feedforward control is an appropriate method to reduce pressure drops of the total inlet pressure during dynamic manoeuvres. Experiments showed that the pressure drop during slam acceleration was reduced to 6.4 mbar, representing a reduction of 84.5 %, by using feedforward control.

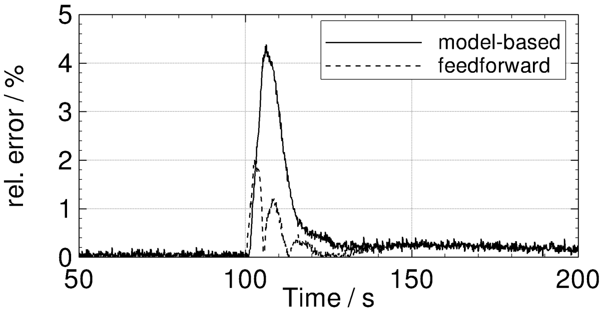

Fig. 8: Relative error of total inlet pressure

Furthermore, the HIL simulation is able to reproduce both the steady-state and the dynamic operation conditions sufficiently accurate. The relative error between the HIL simulation and the measurement is even during dynamic manoeuvres less than 5% (see Fig. 8).

6. CONCLUSION

The HIL simulation of the ATF control system using a real-time performance simulation of the ATF was an efficient and cost-effective technique for performing system tests and for operator training. The functionality of the control system could be tested on the real hardware.

For validation purposes tests were conducted at the ATF of the University of Stuttgart. It could be proven that the real-time simulation reproduces the steady-state and dynamic operational behaviour of the ATF sufficiently accurate. Experimental data showed a reduction of the pressure drop during slam acceleration at sea level static conditions of 84.5 % by using feedforward control.

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