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HIL TEST BENCH FOR ENGINE'S FUEL CONTROL SYSTEMS INVESTIGATION

Salimzhan Gafurov[1,2], Leonid Rodionov[1], Aleksandr Kryuchkov[1], Heikki Handroos[2]
[1]Samara National Research University, [2]Lappeenranta University of Technology

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Abstract

This paper describes a number of hardware-in-loop (HIL) test benches for investigation of both gas turbine engine's (GTE) fuel and control systems. Developed HIL test bench with the virtual model of GTE for research of fuel supply and control systems characteristics is described. An aggregate composition of hydromechanical system and the methodology of the HIL testing technique are presented. Developed test bench is better than analogs by both using the mathematical model of the GTE and full-scale aggregates. Some aspects of controlled object mathematical simulation and the basic approaches for its implementation are described. Developed bench allows us to simulate and define performances of whole fuel system and particular its aggregates in steady-state and transient operating regimes in the closed and open loop circuits. Additionally, it allows us to perform the analysis of available control system stability margins, to carry out the interaction of separate circuits and aggregates, to study influence of perturbations and external factors on control system fail safety.

1 Introduction

Experimental research and theoretical simulations of GTE and their systems are one of the most significant and necessary stages in their design process, refinement, testing and certification. But high cost and poor ecological friendliness are severe disadvantages of the control systems (CS) full size refinement as a part of GTE. In case of full-scale tests an engine operates under the off-nominal regimes. It can lead to enormous error probability. Additionally pejorative factor is an increased fuel consumption in case of full-scale engine tests. As a result, the CS tests are usually reduced to inspection of its reliability and serviceability, characteristics verification of the aggregates and GTE systems before their installation on the full-scale engine.

The problems solved by HIL stands are thoroughly described in papers [1] and [2]. The necessity of HIL stands application originates if:

- the controlled object is at the stage of engineering while the control units are already exist;
- the object cannot be tested in the laboratory conditions;
- the control units have nonlinear characteristics, frictions, and noise which could not be considered in their equations;
- carrying out full-scale experiments to configure the control unit is expensive or not acceptable.

The method of the integrated studies of GTE aggregates and its systems on HIL stands is described in works [1] and [3]. It consists of carrying out the whole complex of tests in real time with help of integration of full-scale control and diagnostic systems with GTE mathematical models.

Nowadays there are information about a variety of stands and techniques providing the semi-natural test benches of GTE and its systems in publicly available sources. A variety of GTE HIL models and their systems processes development are described in papers [4], [5], [6], [7] and [8]. The conception of hardware, algorithmic and software support for HIL simulations of GTE systems in all their life cycle stages are considered in paper [9]. Paper

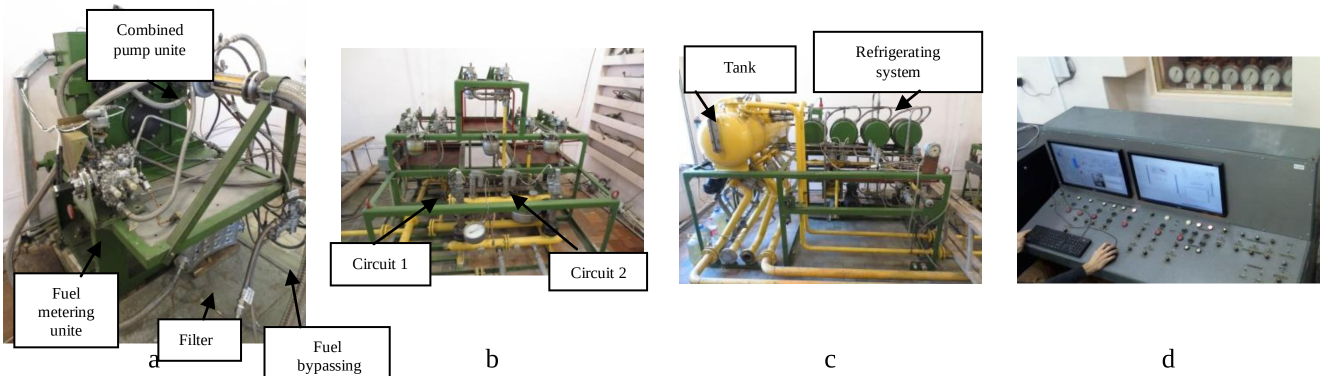
[8] describes bench for the control laws development for GTE elements mechanizing system. This bench consists of the GTE model, engine housing (with the dismantled compressor's and turbine's rotors), fuel metering equipment and air intake mechanization devices. The HIL test bench in work [10] has a possibility of a comparative assessment of embedded real-time systems architectures at early development cycles [11], [12]. This feature set this bench apart from other existing solutions [13]. In work [14] the HIL test bench with demonstrational CS and electric executive devices is developed. The HIL demonstrational GTE control and fuel supply systems with full-scale electric actuators is described in work [15]. The HIL approach was used for the airplane adaptive automatic control system development in work [16]. The HIL technology was used for the characteristics investigation of the GTE full-scale aggregates and its systems in works [17-21].
Thus, the possibility of applying the complex mathematical models or the combination of both full-scale aggregates and aggregates' mathematical models is common for all described stands. Application of each particular approach depends on a degree of aggregates completion and tests type.
However, HIL approach does not widespread in aviation engine industry in particular. In spite of a number of works, there is still a lack of papers devoted to the aviation fuel systems. There is no significant information how to design HIL test bench for the characteristics investigation of a turbofan engine fuel system. There is still a question about how to provide a good accuracy of these tests. As a result, the main objective of this paper is to describe the HIL test bench for development and investigation the aviation turbofan engine fuel and control systems. This test bench was developed in Samara National Research University (SNRU). Some features and parameters of the developed test bench were already described in [22].

1.1 SNRU HIL Bench

Developed HIL test bench (fig. 1) consists of:

- operator station with its own CS;
- data acquisition system;
- full-scale aggregates of the GTE fuel and control systems.

The general views of the developed test bench are presented in fig. 1.



a b c d

a – combined pump (gear stage and screw-centrifugal stage), hydromechanical fuel metering unite, fuel aggregates; b – a system for combustion chamber simulation; c – fuel supply system and refrigerating system; d – operator station
'Fig. 1. SNRU HIL test bench'

Top-of-the-range system is an operator station, which was organized on the basis of the industrial computer National Instrument PXIe and provides connection between computation system and operator. Operator station provides:

- real-time displaying of the controlled object conditions;
- archiving and registration the information from transducers;
- calculating;
- hardware and aggregates condition monitoring and real-time control.

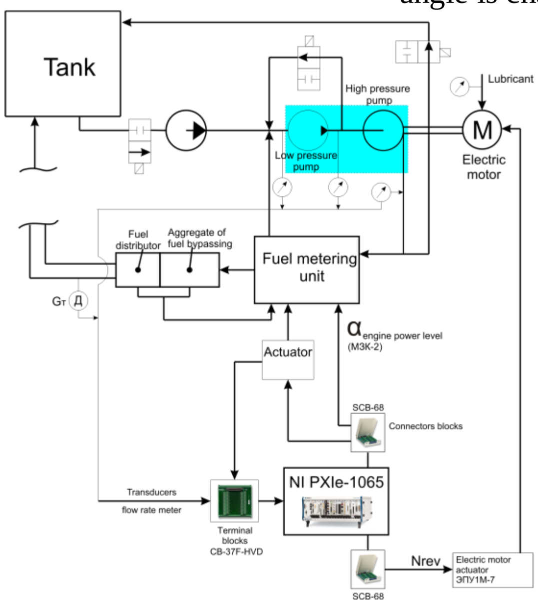
The lowest level of the HIL test bench is the data acquisition system. This is a computer system, which has a controller for direct connection with controlled object and transducers. The controller's functions are:

- collection and processing of the primary data from the transducers;
- direct automatic control of the controlled object;
- emergency situations debugging.

HIL test bench scheme is given in fig. 2.

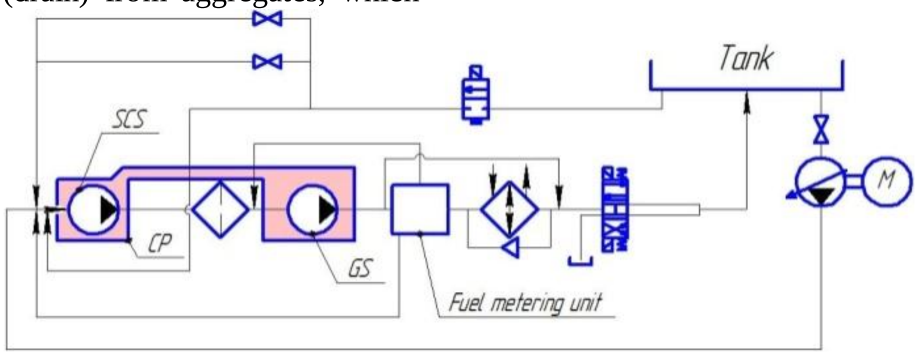
The primary target parameter is an engine rotor rotational speed and the control factor is the fuel consumption (it goes to the GTE combustion chamber simulator). The mathematical model provides control of fuel aggregates by three main control parameters:

- rotational speed of the pump unit electromotor. It aligned with the GTE rotor rotational speed at a software level. The three-phase drive unit with a digital control is used as a electromotor;
- rotational speed of the hydromechanical fuel metering unit electromotor. It simulates rotational speed of the GTE rotor;
- an angle of the engine power control located on the fuel metering unit. The angle is changed by the operator.



‘Fig 2. The Circuit Diagram of the SSAU HIL Bench’

The hydraulic circuit diagram of the developed HIL bench is given in fig. 3. Imitation of the fuel bypassing (drain) from aggregates, which have not been installed, was provided by means of installation of the corresponding nozzles.



SCS – screw centrifugal stage; CP – centrifugal pump; GS – gear stage

‘Fig. 3. The hydraulic diagram of the fuel system’

The mathematical model of the controlled object needs the values of system parameters in particular pressure in key points and mass flows in imitators of circuits of combustion chamber to accurate bench control during testing. Necessary values are taken with help of pressure or flow sensors as well as by feedbacks from actuators (for example an angle of engine power control). Signal converters are necessary for the hybrid bench control by means of GTE mathematical model. Consequently, the electric actuator of the engine power control mounted on the fuel-metering unit was installed in the system.

The hardware facilities of the bench (such as processors, memory, converters, distribution panels, etc.) were assembled from the standard industrial equipment focused on real-time operation. Mathematical models of the engine and its systems were created by means of visual simulation tools in LabView and MATLAB/Simulink.

Operating conditions of full-scale fuel aggregates have been made maximally close to real operation conditions during tests. Therefore, they were mounted into altitude-temperature chamber and on shaking tables.

The developed HIL bench operates as a part of the distributed remote access network. It allows using global network Internet to perform experiments on the remote engine bench.

3 GTE Mathematical Simulation

The GTE mathematical models as a part of HIL stand should be adequate and provide the real-time interacting with the full-scale fuel aggregates. GTE mathematical models embedded into the full-scale CS allow to execute not only adaptive control algorithms and controlling accuracy, but also to ensure reliable diagnostic of the engine and its systems.

The characteristics of the engine's fan, high and low-pressure compressors are simulated in their all frequency range of pressure and rotational speed to provide a possibility of engine testing in its all-range unsteady-state processes. It results in getting all numerical values of engine working parameters in its broadest working regimes apart from the engine start mode.

The mathematical simulation includes two reproducing techniques of the dynamic processes in engine gas-generator. The first uses the piecewise linear approximation of throttles characteristics taking from previous experiments. The second one is a full-sized part in terms of equations.

Our mathematical model has been developed and debugged in MATLAB Simulink software. Further development has been made in NI LabView software. The mathematical model was converted from Simulink into NI LABVIEW for this purpose. It resulted in providing HIL tests with full-scale hydromechanical aggregates by means of National Instruments equipment. The mathematical model has a subassembly structure, where output parameters of one block are input parameters for next one. The turbofan mathematical model consists of the following sections: inlet duct, fan, low and high-pressure compressors, combustion chamber, high and low-pressure turbines, mixing chamber and jet nozzle.

The working parameters such as pressure, p, temperature, T, turbine power, N, torque, M, and pressure ratio, π at the corresponding node are calculated in corresponding block at each calculation time step. As to the most important compressor parameter is a stall margin, it can be found in every compressor stage as well. The combustion chamber is simulated in simplified form and values $H_U, \eta_{comb}, c_p, c_v, \upsilon_{combchamb}$ are constant and are chosen depending on fuel type, air and air-gas mixture conditions. The rate of the fuel consumption, G_{fuel}, is received from the flow rate transducers.

The engine thrust, R_N, is the product of exhaust velocity and flow rate:

$$R_N = G_N \cdot V_N, \quad (1)$$

where

G_N- flow rate thought the nozzle,

V_N- velocity thought the nozzle.

The flow rate at predetermined parameters can be found by the following equation:

$$G_N = \frac{m_F \cdot q(\lambda) \cdot p_{mix} \cdot F_N}{\sqrt{T_{mix}}}, \quad (2)$$

where

m_F- fuel mass;

p_{mix}, T_{mix} - pressure and temperature in mixing chamber correspondingly;

F_N- nozzle area.

An outlet control parameter for test bench is the rotational speed of the engine’s shaft. The rotational speed of the engine’s shaft can be found like difference between turbine and compressor torques. The rotary accelerations are calculated in the block with derivatives with help of following equation:

$$\omega = \frac{M}{I} = \frac{M_{turbine} - M_{compressor}}{(2\pi/60) \cdot I}, \qquad (3)$$

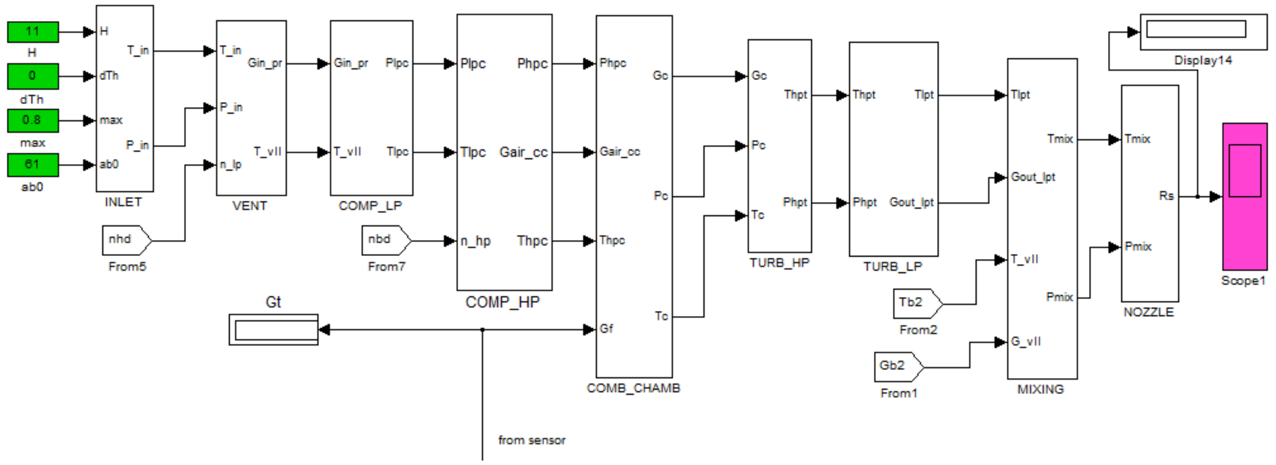
where

M - turbine and compressor torque,

I - rotor inertia.

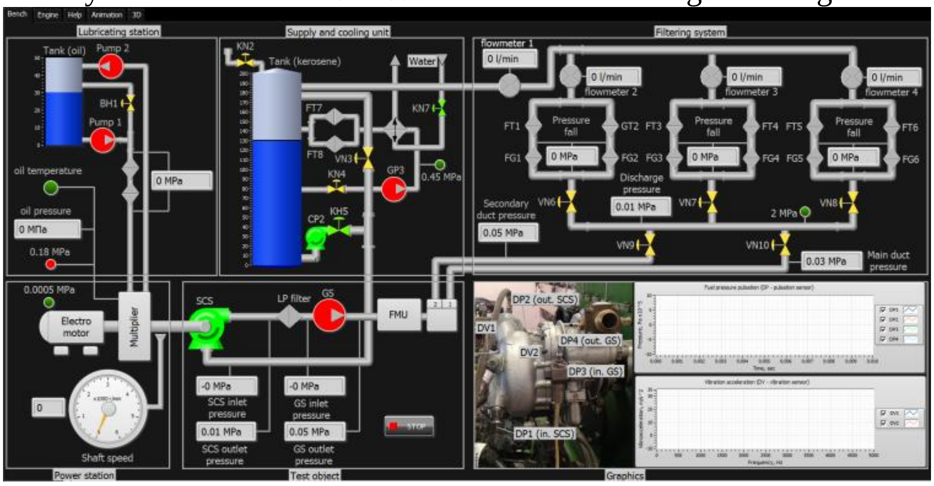
Integrating these values results in getting rotational speed in terms of “rpm”.

The flowchart of the subassembly model is shown in fig. 3.



‘Fig. 3. The Subassembly Mathematical Model of Turbofan Engine (MATLAB Simulink)’

The HIL test-and-measurement system was created by LabVIEW. The measurement system and control software are shown in fig. 4 and fig. 5 correspondingly.



‘Fig. 4. Measurement system front panel’

'Fig. 5. Control system front panel'

The functions of the test's control system are:

- monitoring and processing parameters taken from flow, pressure, pump's rotor rotational speed and the incidence angle of flow metering unit actuator transducers;
- controlling a rotational speed of the pump rotor changing, both in a manual mode and in an automatic mode by means of engine power control;
- reproduction and monitoring of emergency conditions.

The front panel of developed software displays in real time the full 3D geometric model of all controlled objects, as an engine, its units and assemblies, as well as geometrical models of bench aggregates and components. In the same manner the location of installed transducers can be shown in developed software, allowing to visualize the working processes. As far as remote control concerned, developed software is able to bring about it by getting the tests data to remote user.

We used Control Design and Simulation modules to realize the main equations. As to entering the turbine and compressor characteristics, we implemented MathScript module of LabView software, which works with MATLAB.

HIL test bench is known to be provided a reliable accident-protection system on both hardware and software levels. The protection system on bench's analog operating console objected on accidental pressing, restriction of aggregates working without preliminary oil and fuel supply and other are implemented on developed stand. The program utilizes a protection against accidental rupture data with the bench, which in its turn duplicated in analogue form on operating console.

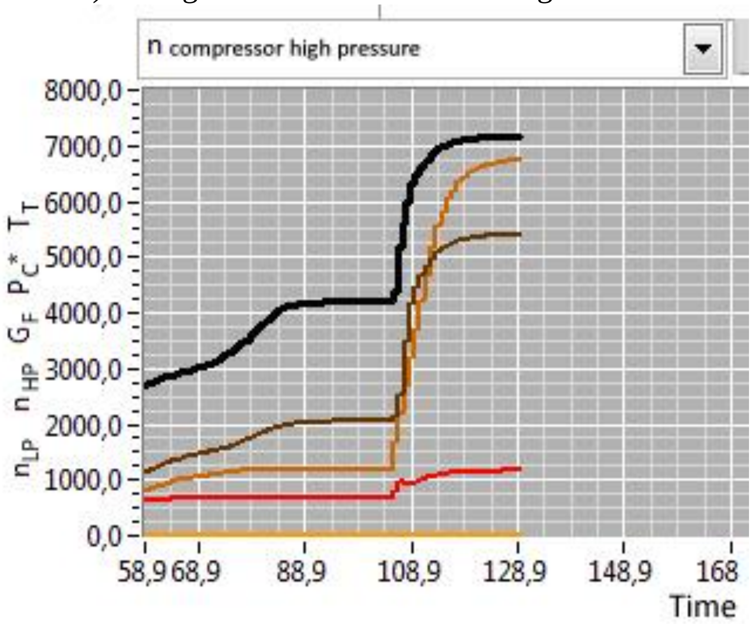
Application of LabVIEW software as a programming language allows the end user to make changes in the mathematical model quickly.

Various numerical methods for solving the differential equations, for example, some kinds of a Runge-Kutta method are accessible to the user. The model can be run with as quickly as the computer allows and taking into account the real-time that imitate the behavior of real engine, when this is realized the possibility of user interaction with the simulated process.

Conclusion

Developed HIL bench allows to model and to determine the main characteristics of engine's system and full-scale fuel aggregates on steady and transient operating modes in closed-loop and open-loop schemes, to analyze the available margin stability of the control systems, to perform the interaction of separate loop and aggregates, to investigate the effect of perturbations and external factors, the performance of the control system failure.

The diagram of engine main parameters changing (such as rotational speed of high-pressure and low-pressure shafts, fuel consumption, compressor delivery pressure and combustion outlet temperature) during tests are shown in fig. 6.



‘Fig. 6. The Diagram of Engine Parameters Changing’

Developed HIL test bench has allowed to:

- reduce the amount and timing of expensive aggregates and CS full-scale tests on the engine;
- obtain a certificate of the tested object capability to presented parameters immediately after the test, while the object is on the bench;
- simulate accident conditions that are not permitted in the full-scale engine testing.

Universality of the developed HIL bench is that it can be adapted for any control system investigation, depending on its type, components structure and their interconnection.

However, developed HIL bench also has several disadvantages. The first of them is the engine mathematical model, which does not account of all perturbations in the control system. The second one is the scope of mathematical model and full-scale aggregates work coordination.

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Contact Author Email Address

Mailto: gafurov@ssau.ru

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