Simulation Modelling Practice and Theory 19 (2011) 996–1006

Contents lists available at ScienceDirect

Simulation Modelling Practice and Theory

journal homepage: www.elsevier.com/locate/simpat

Real-time multi-rate HIL simulation platform for evaluation of a jet engine fuel controller

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ARTICLE INFO

Article history:
Received 2 September 2010
Received in revised form 12 December 2010
Accepted 28 December 2010
Available online 4 January 2011

Keywords:
Hardware-in-the-loop
Multi-rate
Turbojet engine
Fuel controller
Electronic control unit

ABSTRACT

A new Hardware-In-the-Loop (HIL) platform is developed for testing of a turbojet engine fuel control system using a multi-rate simulation platform. The HIL equipment consists of an industrial PC and a commercial I/O board for jet engine simulation as the controlled process and an Electronic Control Unit (ECU) as the fuel controller. The controlled process consisting of actuator, physical process and sensors is fully simulated in HIL simulation. However, the high resolution signals of some components in the HIL simulation cause the real-time simulation to become difficult due to the need of small time-steps. As a result, the disparity between the jet engine model sampling rate and these high resolution signals requires a multi-rate simulation. In this study, a multi step size simulation is developed using multiple processors. These processors are designed to synchronize the status of the engine model with the control system as well as to convert the raw data of the I/O boards to actual input and output signals in real-time. These features make the HIL equipment more effective and flexible. The HIL environment is proved to be an efficient tool to develop various control functions and to validate the software and hardware of the engine fuel control system.

1. Introduction

Generally, the construction of aircraft is costly and time consuming. Safety is also a primary issue that one is facing in conducting actual flight tests. Consequently, Hardware-In-the-Loop (HIL) simulation can effectively evaluate the reliability of the overall aircraft system. HIL simulation is characterized by the operation of real components in connection with real-time simulated components. The simulated components are often the processes being controlled and/or sensors and actuators. In particular, the framework can be used to examine the performance of aircraft subsystems and equipments such as flight control system [1], camera hardware [2], fuel cell power [3], electro hydraulic actuators [4] and engine fuel control system [5].

Several studies have been reported for HIL simulation of jet engine control system. Iserman et al. [6] provided an overview of the various kinds of simulation considering of real-time simulators, architectures and the historical development of hardware-in-the-loop simulation. Cheng [7] discussed HIL testing system for the mini-type turbojet engine to study the transient and steady state performance of a conventional digital control regulator for ground start, air start, stopping, automatic acceleration and deceleration, and steady state regulation. The adjusting characteristics of air start and flying along the ballistic trajectory are also evaluated. In [8], HIL simulation system using MATLAB/xPC-target was developed for an electronic throttle idle speed control strategy based on ANFIS. Wang et al. [9] introduced and applied a method of non-fully

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doi:10.1016/j.simpat.2010.12.011

recovering LQG/LTR to design the aero-engine control system. In order to validate the performance of the designed control system, the HIL simulation system was then designed. Watanabe et al. [10] designed a fuzzy logic controller and tested on a turbojet engine in a simulated environment. The controller was tested in HIL simulation before being used with the real engine.

According to Fathy [11], a common problem in HIL simulation is virtual model stiffness, defined as a large disparity between the characteristic speeds of different components of a virtual model. When the disparity between the fast and slow dynamics in a virtual model cannot be eliminated, it is common to simulate these dynamics separately at different sampling rates. Such multi-rate simulation may take place on one processor via multithreading, but is more often achieved using multiple processors. The HIL literature describes the challenge to the simulation platform due to the high time resolution required for emulating high sampling rates signals of actuators and sensors [12,13]. The disparity between the jet engine control system components have not been considered for HIL simulation development.

In this paper, a new HIL simulation platform is developed for the evaluation of jet engine ECU performance. In this application, electrical signals including rotor speed encoder and servo valve drive signals are at high sampling rates rather than the engine model sampling rate of simulation. So this system is characterized by a combination of subsystems working at different time scales and with different needs of time resolution. In order to address this issue, the separation of the high resolution signals for the real-time operation from the software requirements has been proposed. This separation can be achieved by introducing a suitable hardware interface to catch and to generate these high resolution switching signals with a high accuracy without the need of reducing the integration time steps of jet engine simulation.

The outline of this paper is organized as follows. In Section 2, a thermodynamic model and the integration method which is proposed for the real-time simulation of single spool turbojet engine is presented. The structure of the min–max algorithm employed in the ECU is illustrated in Section 3. In Section 4, the software and hardware framework for HIL simulation is presented. The interface between the simulation model and hardware consists of some convertors described in Section 5. Finally the results of the simulation with the simulated ECU and actual ECU are compared in Section 6. Some concluding remarks are presented in Section 7.

2. Turbojet engine real-time model

The process considered is a single spool turbojet engine with a convergent nozzle, without bypass and bleed flow. The assumptions in the model presented here are that, there does not exist any heat transfer between the control volume and in each control volume, the gas is perfectly mixed. These assumptions imply that only two gas states per control volume are necessary to determine the condition there. Jet engine model has been composed of two parts. The first one refers to a system of static nonlinear equations that describe the thermodynamic relations in compressor, turbine and nozzle as follows [14,15].

Compressor:

$$\dot{m}_c = \frac{\delta_2}{\sqrt{\theta_2}} f_1\left(\frac{P_3}{P_2}, \frac{N}{\sqrt{\theta_2}}\right), \quad \delta_2 = \frac{P_2}{P_0}, \quad \theta_2 = \sqrt{\frac{T_2}{T_0}} \tag{1}$$

$$\eta_c = f_2\left(\frac{P_3}{P_2}, \frac{N}{\sqrt{\theta_2}}\right) \tag{2}$$

$$T_{3s} = T_2\left\{1 + \frac{1}{\eta_c}\left[\left(\frac{P_3}{P_2}\right)^{\frac{\gamma-1}{\gamma}-1}\right]\right\} \tag{3}$$

Turbine:

$$\dot{m}_t = \frac{\delta_4}{\sqrt{\theta_4}} f_3\left(\frac{P_4}{P_5}, \frac{N}{\sqrt{\theta_4}}\right), \quad \delta_4 = \frac{P_4}{P_0}, \quad \theta_4 = \sqrt{\frac{T_4}{T_0}} \tag{4}$$

$$\eta_t = f_4\left(\frac{P_4}{P_5}, \frac{N}{\sqrt{\theta_4}}\right) \tag{5}$$

$$T_{5s} = T_4\left\{1 + \eta_t\left[\left(\frac{P_4}{P_5}\right)^{-\frac{\gamma-1}{\gamma}-1}\right]\right\} \tag{6}$$

Nozzle:

$$\dot{m}_n = \begin{cases} C_d A_n \frac{P_5}{\sqrt{RT}} \sqrt{\frac{2\gamma}{\gamma-1}} \left(\frac{P_e}{P_5}\right)^{\frac{1}{\gamma}} \sqrt{1 - \left(\frac{P_e}{P_5}\right)^{\frac{\gamma-1}{\gamma}}} & \pi_n \le \pi_n^* \\ 0.2588 C_d A_n \frac{P_5}{\sqrt{RT}} \sqrt{\frac{2\gamma}{\gamma-1}} & \pi_n > \pi_n^* \end{cases} \tag{7}$$