FUEL METERING PUMP DEVELOPMENT AND MODELING

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Keywords: Aircraft electronics, BLDC motor, Control system, Fuel pump, Identification, Motor drive, Simulation.

Abstract: This article would like to inform reader about the research and development steps and practices which were used during the development of a control system for a fuel metering pump. The aims of the development were to design a control system for a brushless DC (BLDC) motor in accordance with rigid aviation standards and to verify new development practices and tools allowing faster and much simpler final certification. The paper comprised definition of first requirements, preliminary hardware (HW) and software (SW) design, system modeling and simulation, system optimization, detailed design, verification and testing. In addition, the first results measured on an evaluation sample are presented.

1 INTRODUCTION

The designed control system shall ensure safe and reliable control of the BLDC motor that drives the fuel metering pump (FMP) (Bose, 2009). FMP operation shall be ensured under various external conditions, including harsh environments and unknown initial states such as pressure in the system, position of the rotor or necessary starting torque of the BLDC motor.

1.1 Architecture

1.1.1 System Architecture

The fuel system will be composed of electrical, mechanical and hydraulic equipment necessary to measure, to provide and to control the required fuel flow (Cochoy et al., 2007).

The metered flow will be distributed to a fuel manifold.

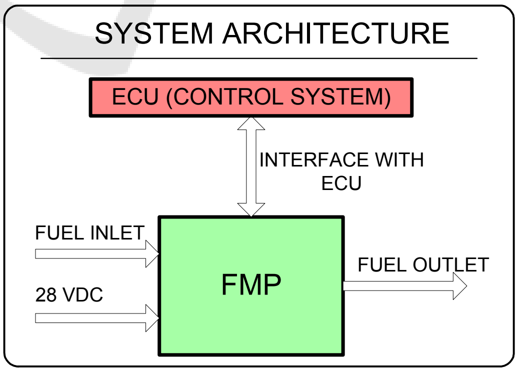

Figure 1: Block diagram of the system architecture.

1.1.2 FMP Architecture

The FMP is composed of three main components:

- Fuel pump with a by-pass relief valve,
- 28 Vdc brushless DC motor – BLDC,
- Control system (CS) of the FMP with power electronics.

A by-pass relief valve shall be part of the FMP in order to protect the equipment from overpressure. The FMP architecture is shown in Figure 2.

Toman J., Hubík V. and Singule V..
FUEL METERING PUMP DEVELOPMENT AND MODELING.
DOI: 10.5220/0003530804190426
In *Proceedings of the 8th International Conference on Informatics in Control, Automation and Robotics* (ICINCO-2011), pages 419-426
ISBN: 978-989-8425-74-4

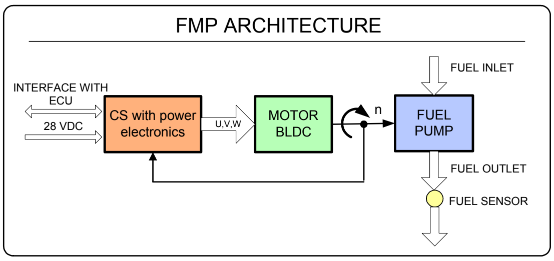

Figure 2: Block diagram of the FMP.

1.2 Control System Requirements

Requirements for the control system were defined during the early stage of the project in consultation with external aviation specialists. These requirements include electrical characteristics, reaction of the control system to defined incidents, start-up characteristics, control commands etc.

The FMP's variable flow rate will be controlled by the Electronic Control Unit (ECU) to maintain constant speed of the Auxiliary Power Unit (APU). In parallel with the pump, a by-pass relief valve will protect it against overpressure. The FMP shall provide the fuel inlet temperature to the APU ECU. The FMP shall control the fuel flow by varying the pump speed for the following APU operations:

- Start the APU (open loop: no closed loop control on APU speed for the ECU),
- Maintain the APU speed at a constant value (closed loop on APU speed for ECU) and transfer to the FMP via the digital data bus and/or the analog setting input.

The most important requirements of the control system are listed below.

1.2.1 Interface Characteristics

- The control system of the FMP should be controlled via a digital data bus or a single analog signal,
- CS together with the BLDC motor should be supplied from an AC/DC bus with the option of supply from a battery,
- CS should receive only start/stop and flow throttle commands,
- CS should be able to indicate the flow level, power bridge current, status word, FMP mode, built-in-test results and start/stop command acknowledgement,
- The nominal power consumption should be less than 250W, the peak power consumption could be up to 500W for a defined period of time.

1.2.2 Functional Requirements and Performance Characteristics

- CS shall ensure safe and soft start of the BLDC motor under any conditions.
- During operation the CS shall maintain the fuel flow at required values.
- CS shall enable internal parameters setting in a dedicated maintenance mode.
- CS shall be able to precisely meter fuel flow during a defined interval.
- The maximum underflow should be less then 2% at $\Delta\omega > 40\%$ and the fuel flow should stabilize in 240 ms.
- In case of stop command the FMP shall stop in less than 100 ms.
- Minimum fuel flow is 3 l/h and maximum 117 l/h.

1.2.3 Physical Requirements

- CS should be designed for minimum dimensions and weight.
- CS cooling shall be designed with active fuel cooling to withstand ambient air temperature over +55°C.
- CS shall ensure normal non-degraded function under the defined circumstances and lifetime.
- Nominal operational temperatures shall be -55°C to +85°C, short-term operating conditions shall be -55°C to +125°C.
- During APU operation, the maximum steady state flow in worst temperature conditions (air: +85°C, fuel: +65°C) will be 76 l/h.
- The CS shall restart without problem after having been soaked 4 min at +125°C.

Beyond the above stated requirements, the control system and the FMP shall be designed in accordance with many other requirements regarding atmospheric pressure, temperature variations and humidity, shocks and vibrations, lightning and electrostatic discharges. For certification purposes the development, testing and verification must be performed in accordance with the aviation standards ”RTCA/DO-178B – Software Considerations in Airborne Systems and Equipment Certification” (RTCA, Inc., 1992), ”RTCA/DO- 254 – Design Assurance Guidance for Airborne Electronic Hardware” (FAA Advisory Circulars, 2005) and ”RTCA/DO-160F – Environmental Conditions and Test Procedures for Airborne Equipment” (RTCA, Inc., 2007). Failure mode analysis (FMEA) of the designed hardware and testing of the SW code by means of dedicated tools are mandatory parts of the development and both of these tasks were successfully performed at the final stage of the development. Compliance with the above mentioned aviation standards during the development was needed for demonstration of ability to design, develop and certify complex electronic control system for the aviation industry, using new approaches based on utilization of COTS components and integrated simulation tools.

2 CONTROL SYSTEM MODELING AND SIMULATIONS

Based on previous experience, every development of a control system starts with definition of requirements and system modeling. A mathematical model describes all parts of the control system together with the system under control. This gives the developers an exact idea about system behavior, reactions and the ability to verify different control strategy and algorithms in the early stage of the development. In addition, the control system can be tested by means of hardware in the loop simulation, e.g. using a tool such as dSPACE, without any previous hardware design. This is a considerable advantage since the team could predict many mistakes, dead ends and even damage to the first evaluation samples. Unquestionably, these are benefits that considerably decrease the development time and costs.

This part summarizes development of the mathematical model of the dynamic system, i.e. the fuel metering pump, using the mathematical modeling approach and methods of experimental identification. Next the development of the optimal control is discussed, according to the specific behavior demands. The system for identification is an experimental evaluation sample of FMP that is intended for aircraft engine fuel delivery. Increased demands are put on control electronics, because application reliability and safety according to actual aerospace standards are crucial. Identification and optimization of the controller constants have been performed in the MATLAB/Simulink environment.

2.1 Identification

It is necessary to set up a mathematical model to control the whole system according to the response demands. Because the dynamic system consists of electrical, mechanical and hydraulic parts, and is therefore non linear, a mathematical description based on the physical principles would be very complicated. For this reason a "Black box" method is used. This method is based on analysis of the single step response. The block schematic of the identification principles is shown in Figure 3.

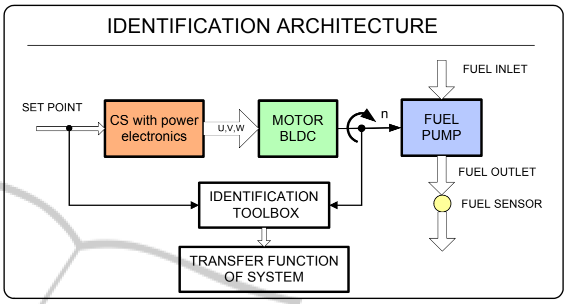

Figure 3: Block schematic of the identification process.

The monitored parameters are input voltage step change and rotational speed response of the BLDC motor. These characteristics are then imported into a MATLAB environment for further post-processing using the "Identification toolbox". The result of the identification process is the description of the system, which consists of two transmission first-order functions. The achieved transmission equations are 1 and 2.

$$F_1(s) = 415 \cdot \frac{1}{9 \cdot 10^{-3}s + 1} \quad (1)$$

$$F_2(s) = 9 \cdot \frac{s}{0.12s + 1} \quad (2)$$

2.2 FMP Model and Simulation

According to the obtained identification results a system model in MATLAB/Simulink environment is created. The model is made of basic Simulink blocks from common libraries and its structure is depicted in Figure 4.

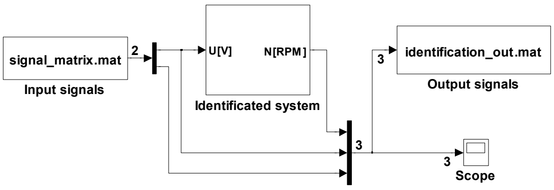

Figure 4: The basic diagram of the FMP simulation.

The measured voltage step change is the input value to the block and the output presents the transient response of the model. Both parameters are stored and displayed in the Scope block. The measured rotational speed transient characteristic of the FMP is also added to the structure and therefore makes it possible to compare response of the model with the real system.

Comparison of the model and the real FMP system response is shown in Figure 5. The blue colored line represents the transient characteristic of the model, the red colored line transient represents the transient characteristic of the real FMP. This result is sufficient for controller algorithm development to the target embedded platform.

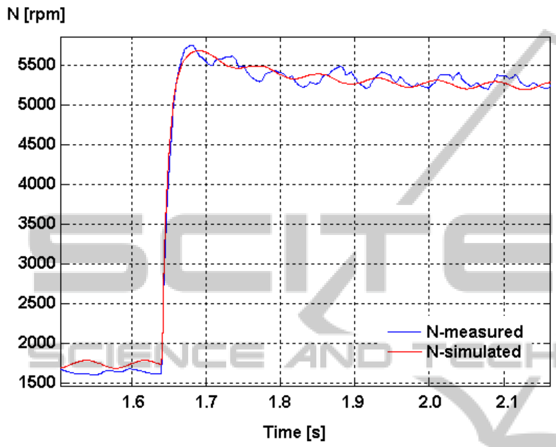

Figure 5: The simulation results of the controller respond.

2.3 FMP Model and Simulation

The “Controller” block has been added to the previous model. A cascade controller structure of discrete proportional – summation - differentiation (PSD) controller is implemented inside this block (Leonhart, 2001). The block schematic of the PSD controller is depicted in the Figure 6. The rotational speed controller has priority over the power controller.

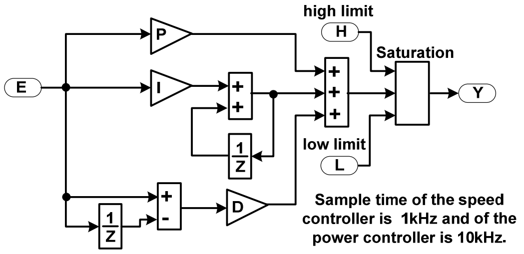

Figure 6: Inside structure of the PSD controller.

The difference between the required and actual values of rotational speed is one input parameter to the “Controller” block. Another input is the input voltage. The actual rotational speed is driven by feedback from the FMP model. The controller output is the actuating signal, which has voltage representation. The block schematic of the controller loop is depicted in the Figure 7.

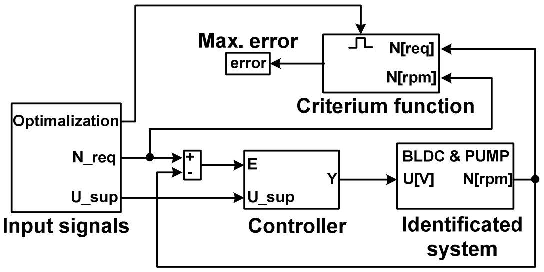

Figure 7: The block schematics of the control loop.

The PSD controller constants were iteratively changed to evaluate quality of control according to the given requirements. The FMP response was compared using the least squares method according to the limit characteristics and the lowest difference from the calculated required characteristic. The “Criterion” function (block) was then created to limit characteristic definition, which determines the controller requirements. The maximum overshoot (upper limit) and required dynamic response of the controlled system (lower limit) are also defined in the block. The upper limit is evaluated as a percentage of the required rotational speed. The lower limit is then determined by the time constant, which defines the maximum time for system stabilization for the required speed. The lower limit is realized in the model as a first-order transfer function with the required time constant.

The system response with optimal PSD constant settings is shown in Figure 8. There are also depicted the limit characteristics and required value of the rotational speed. From the results it can be seen that the developed controller fulfills the controller quality demands and it is possible to use it in a real system on the target platform. The whole methodology proves to be useful in development of the optimal control algorithms. Time and cost reduction of the whole development cycle is evident.

Values provided by the simulations of the control system were used in the hardware design which was the next step of the project.

3 HW DESIGN OF THE CONTROL SYSTEM

The control system is of a modular design and consists of three parts that can be interchanged according to customer needs. The three basic

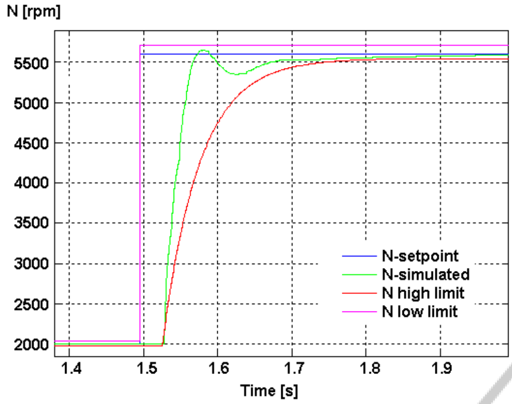

Figure 8: The system response with the optimal PSD settings.

modules are Control and Communication Unit (CCU), Power Electronics Unit (PEU) and I/O Unit (IOU).

3.1 Control and Communication Unit

The main microcontroller is mounted on the Control and Communication Unit (CCU). The CCU is replaceable according to application performance requirements and the architecture of the control system. The core of the CCU is a multipurpose microcontroller (MCU).

The CCU has a unified interface for all the analog and discrete signals that are used for control and communication with other control system modules. Using a unified interface enables replacement of the CCU in case of system enhancement or maintenance.

The electronic control system for the FMP can provide selected information about its internal states and measured values to the higher level control system via an internal communication network. The higher level control system can be a Flight Control Computer (FCC) or a multifunction avionic display placed in the pilot's cockpit.

3.2 Power Electronics Unit

The Power Electronics Unit (PEU) consists of a full H-bridge comprising six power switching transistors. Motion of the BLDC motor is controlled by a switching power supply to the particular coils of the BLDC motor.

An integral part of the PEU is the Protection module that measures temperature, current and voltage on the BLDC motor. If any parameter exceeds a limit value the protection module sends a fault signal to the MCU. Detection of the fault signal causes disconnection of the load from the power supply source.

3.3 I/O Unit

BLDC motor signals/sensors - depending on actual configuration, the electronic control system could operate either in sensor or sensor-less mode.

In sensor mode, signals from Hall sensors are used as feedback. These sensors are usually mounted inside the BLDC motor by its producer. These signals are triggered and used as inputs to the control MCU.

Sensor-less control mode operates on the principle of sensing induced voltage caused by Back Electro Motive Force (BEMF) on one of three BLDC motor phases. Feedback is extracted by means of BEMF and zero-cross detection.

Functionality and safe operation of the actuator is ensured by monitoring of selected parameters and restricting the actuator's fault operation. If one or more signals exceed their limit value, the fault is detected and appropriate action is taken.

3.4 Evaluation Sample

The control system was designed to fit the requirement of mounting into the FMP to create a monolithic box with an explosion-proof design. The development runs in accordance with the aviation standards RTCA/DO-254 (FAA Advisory Circulars, 2005) and RTCA/DO-160F (RTCA, Inc., 2007).

The electronics of the control system are designed in a custom tailored shape with logical partitioning according to the functions performed. Logical partitioning of control, power electronics and sensing board provides the added advantage of custom configuration and much simpler service.

4 CONTROL SYSTEM SW DESIGN

The main aim taken into consideration was that the control system had to be portable and easy to implement on a common 16-bit MCU. The final control system is written in the C programming language and is implemented in a DSP MCU.

Algorithms are designed with regard to the high criticality of the application; therefore no artificial methods or fuzzy control algorithms could be used. The requirement for high reliability also limits the code complexity, thus simple but efficient software algorithms are used wherever possible.

Software design was preceded by detailed decomposition of system requirements, interface definitions, data flow and control flow. These requirements and definitions determined the final form of the source code. And so their thorough evaluation was extremely important for design of control algorithms. Proper definition and evaluation simplified the software development cycle and eliminated errors caused by further implementation of additional functions.

The algorithm consists of initialization part, motor start-up, closed loop control, interrupt service routines and communication routines.

4.1 Initialization

Initialization part serves for initial hardware set-up, parameter setting and power-on self test. During this stage all the parameters and values are checked against the standard values. In case of abnormal values or malfunction, the control system issues a warning and tries to re-initialize hardware.

4.2 Motor Start-up

In critical applications, it is necessary to ensure correct startup of the motor. Thus, many simulations were done before implementing the control algorithm into the controller. The motor start-up algorithm ensures reliable start-up of different types of BLDC motors. Sinusoidal and conventional trapezoidal methods of control are used.

4.3 Closed Loop Control

After initialization and motor start-up sequence, the control algorithm switches to closed loop control. Closed loop control algorithms consist of the two nested PSD controllers - the speed controller and the power controller (Leonhart, 2001).

The power regulator sets the desired value by means of PWM. It compares the desired value from the superior speed regulator and the measured current through the BLDC and sets the output value according to their variance.

The speed regulator sets the desired value for the current controller. Actual rpm speed could by measured by Hall sensors or using a Back Electro-Motive Force (BEMF) (Holtz, 2007).

4.4 Interrupt Service Routines

Interrupt service routines serve for performing repeated tasks that evaluate critical values such as power electronics temperature, current flowing into the BLDC motor, DC bus voltage, etc.

Separate interrupt service routines also serve for input/output processing and measurement.

5 FIRST EVALUATION SAMPLE TEST RESULTS

To evaluate the performance of the control system and the designed electronics, two types of evaluation test benches were used. Firstly, the in-house developed evaluation test bench. First measurements and simulated dynamic testing were performed on this evaluator and different control algorithms were tested and controller variables were set.

The control system electronics were then mounted on the FMP and performance tests were carried out on an evaluation mock-up platform that simulates a real fuel circuit. These tests were performed with the help of an external company with particular emphasis on start and stop sequences of the FMP.

The start sequence of the fuel pump, shown in Figure 9, was verified for a step change request from 50 percent of the fuel flow. This means that the starting flow level was 43 l/h (3250 rpm of the BLDC motor) at 2 MPa of back pressure. The required flow after step change should be 92 l/h (7300 rpm of the BLDC motor) at 3.9 MPa of back pressure.

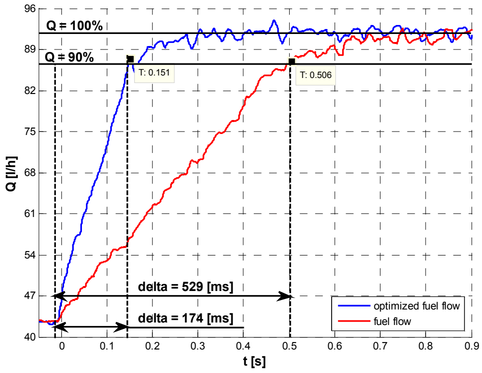

Figure 9: The FMP start sequence measurement.

Figure 9 compares the optimized pump characteristic with the original values. With a precisely tuned motor controller it is possible to achieve a start time of less than 200 ms and to fulfill the customer requirements.

The next important feature of the fuel pump is the stop time performance. This behavior is crucial for the turbine control system and dynamic of the whole hydraulic chain. According to the technical specification, the requirement is a stop time of no more than 100 ms after receiving the stop command.

The stop time characteristic was much more difficult to measure. The directly connected speed or flow sensor to the fuel pump influences the stop time characteristic. The only way was to measure the speed from the motor's internal Hall sensors. There are three graphs in Figure 10 and Figure 11 that represent the output signal from the position sensors. After a simple MATLAB post-process it is possible to evaluate the actual rotor speed.

Figure 10 shows the stop time characteristic when the system is not perfectly optimized. The fuel pump should stop in this case from the nominal fuel flow of 92 l/h (7300 rpm of the BLDC motor) at 3.9 MPa of back pressure. It is obvious that the technical specification requirement has not been fulfilled. The stop time is more than 200 ms.

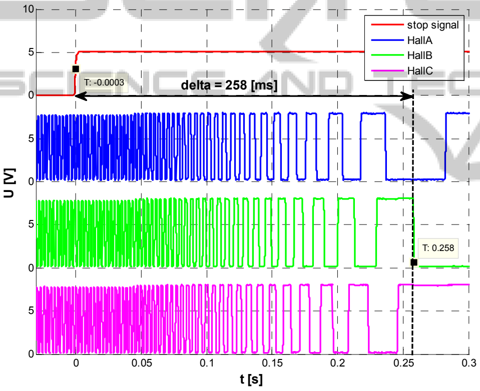

Figure 10: The stop time characteristic with not optimized controller.

Figure 11 shows the stop time characteristic of the optimized controller. The same measurement method has been used in this case. The stop time has reduced to 83 ms which is acceptable.

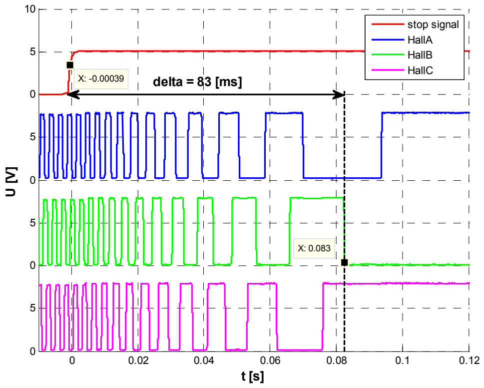

Figure 11: The stop time characteristic with optimized controller.

6 CONCLUSIONS

Development and certification of any device in the aerospace industry requires a thorough approach, including definition of requirements, design of electronics, software coding and testing. In addition, very complex documentation must be maintained for the whole development and lifetime cycle.

Use of COTS components and development tools enables a faster development cycle with the ability to carry out modeling and preliminary design in the early stage of project. Results from this stage can be used as the basis for hardware and software design which saves additional costs and greatly accelerates the process.

The development procedures described in this article indicate that they can bring about significant improvements in performance, safety and reliability of the control system along with reduction of development time and costs.

ACKNOWLEDGEMENTS

Published results were acquired using the support by MPOČR project No.FR-TI2/313. Hardware and software development and physical modules were realized and project was supported by UNIS, a.s.

This work was also supported by project No. MSM 0021630518 "Simulation modelling of mechatronics systems" solved on the Faculty of Mechanical Engineering, Institute of Production Machines, Systems and Robotics, Brno Technical University.

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