Fault Analysis and Diagnosis of Aeroengine Fuel Metering Device

Kai Yin, Guo-long Jiang, Guo-jian Liu and Ying-qing Guo

ABSTRACT

Based on the failure analysis of the Hydro-Mechanical Unit (HMU) of aeroengine fuel control system, both of data-based and model-based methods are proposed to diagnose the typical faults of the Fuel Metering Device (FMD). Firstly, the AMESim model of FMD was established. Then its fault tree was set up and simulation analysis for two typical faults was conducted. Finally, two approaches were applied to these faults diagnosis and simulation results show their effectiveness.

KEYWORDS

Aeroengine control system; Hydro-Mechanical Unit; Failure analysis; Fault diagnosis.

INTRODUCTION

Full authority digital electronic control (FADEC) are widely used in the modern aeroengine [1-3]. As its actuating device, the behavior of Hydro-Mechanical Unit (HMU) affects aeroengine’s reliability, security and performance directly [4-6]. Therefore, the research of HMU’s condition monitoring and fault diagnosis has important significance.

The HMU fault diagnosis is based on the data collected by sensors installed in fuel control system, using the fault diagnosis method, realizes the fault detection and prediction of impending failure for its main parts [7].

As the key part of HMU, the Fuel Metering Device (FMD) regulates fuel supply to the combustion chamber, according to the command of the electronic controller, through anchging flow area under the condition of constant difference pressure. In this

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paper, with a high bypass ratio turbofan engine as the object, typical faults of its FMD were diagnosed for example. The FMD’s AMESim model, as well as the fault tree, were build and analyzed.

Two methods of data-based and model-based were applied to the FMD’s fault diagnosis.

MODELING, FAULT ANALYSIS AND SIMULATIONS

Modeling and Fault Analysis

FMD comprises a Differential-Pressure-Controller (DPC), a Fuel-Metering-Valve (FMV), and a Bypass-Valve. The FMD’s simulation model based on AMESim is shown as Fig.1. In order to research fault impacts on fuel control performance, the electronic PI controller was included so that a closed loop for the fuel control was established.

![Figure 1. FMD simulation model based on AMESim.](image)

According to some failure data in reality, valves’ clamping stagnation and nozzle’s clogging are two typical kinds of faults in FMD. The fault tree of the fuel flow control abnormity is shown as Fig.2.

![Figure 2. The fault tree of fuel flow control abnormity.](image)

Fault Simulation

The valve stagnation is simulated by adding friction. The analysis of valve stagnation by simulation can be generally divided into four steps. Firstly the minimum required force that could make the valve stagnation is found and the influence of the stagnation on the fuel system is analyzed. Secondly the conditions, causes and the influence of the crawling phenomenon on the fuel system are analyzed. Then the system oscillations caused by the valve stagnation if possible is analyzed. Finally the influence of general dynamic friction (no stagnation, crawling, oscillation) on the performance of the fuel system is analyzed.
When given the signal of displacement (step from 10.2mm to 11.2mm), the fault conditions of valve stagnation and valve crawling is shown in Table 1 and Table 2. "Stagnation force" refers to the minimum required force that will make the stagnation; "Possibility" refers to the relative possibility of the faults; "Impaction" refers to the change of steady-state error percentage in the fuel flow control. "Critical Force" refers to the minimum difference between static friction and dynamic friction that will make the crawling phenomenon. There is no strict boundaries between crawling phenomenon and general dynamic friction, so the "Critical Force" in Table 2 is for reference only.

Table 1. The fault conditions of valve stagnation.

| Parts                      | Stagnation force [N] | Possibility | Impaction [%] |
|----------------------------|----------------------|-------------|---------------|
| Head sensor                | 3.4                  | Larger      | 4.2           |
| Bypass valve               | 265.3                | Smaller     | 54.3          |
| Fuel metering valve        | 118.8                | Middle      | 100           |
| The main valve of servovalve| 18.3                 | Larger      | 100           |

Table 2. The fault conditions of valve crawling phenomenon.

| Parts                      | Critical Force [N] | Possibility |
|----------------------------|--------------------|-------------|
| Head sensor                | 0.5                | Large       |
| Bypass valve               | 15                 | Middle      |
| FMV                        | No                 | Smaller     |
| The main valve of servovalve| 0.1                | Larger      |

Fault simulation data shows: there is a greater impact on the system when the valve is staged; the crawling phenomenon causes not only the steady-state error, but also poor dynamic performance; multi-stage amplification mechanism may occur self-oscillation because of stagnation; general dynamic friction (no stagnation, no crawling and no self-oscillation) affects the response speed of the fuel system.

The simulation method of nozzle clogging is similar to the approach mentioned above.

**DIAGNOSTIC STRATEGIES**

**Diagnostic Strategies Design**

Data-based and model-based are both mature and classical diagnostic methods in the study of fault diagnosis. To diagnose fault of the fuel metering device, the paper combine the data-based and model-based.

The method of data-based or model-based is shown as Fig. 3.

The paper assumes that the sensors are working properly and the fault occurs alone. The AMESim simulation model is used in place of the real system for fault diagnosis.

The fuel metering device contains the following sensors: a pressure sensor in front of the FMV, a pressure sensor after FMV, the FMV’s displacement sensor. According to the sensor data, it is easy to get the fuel flow of the FMV. The next section will use these sensors’ data to diagnose.
Data-based Fault Diagnosis Strategy

Firstly, some specific data is obtained as diagnostic data by simulation; secondly, the fuel system can be programmed to a specific action in order to determine the fault component and furthermore assess component health indicators and system health indicators according comparing the diagnostic data and the date in the specific action.

The method was used in the diagnosis of static friction for the FMV as an example. There is a short time for valve to remain stationary when existing static friction. We can design an appropriate controller for the FMV in order to make the pressure of drive oil change as Fig. 4. According to the start-up time of the FMV driven by the oil, we can calculate the static friction.

Diagnosis of dynamic friction for the FMV and diagnosis of nozzle clogging for the FMV servovalve are both similar to the diagnosis of static friction.

Model-based Fault Diagnosis Strategy

Firstly, the simplified transfer function of the FMV loop is obtained. Secondly, the same signal is used to control the real fuel metering device and the transfer function, according comparing the data from sensors and the date from the transfer function, it is possible to assess component health indicators and system health indicators.

In order to compare the data from sensors and the date from the transfer function, the mean square of flow rate difference, the mean square function of pressure deviation, the average value of flow rate difference are defined as follows:

\[
\overline{\Delta q^2}(t) = \frac{1}{t} \int_{t_0}^{t_0+\Delta t} [q_r(t) - q_e(t)]^2 dt
\]  

(1)

\[
\overline{\Delta p^2}(t) = \frac{1}{t} \int_{t_0}^{t_0+\Delta t} [p_r(t) - p_e(t)]^2 dt
\]  

(2)

\[
\overline{\Delta q}(t) = \frac{1}{t} \int_{t_0}^{t_0+\Delta t} [q_r(t) - q_e(t)] dt
\]  

(3)
\( q(t) \) represents the fuel flow of fuel metering device (actual fuel flow), \( \Delta p(t) \) represents the DPC’s output pressure (actual differential pressure), \( \Delta q(t) \) represents the fuel flow in the transfer function model (estimated fuel flow), \( \Delta p(t) \) represents the DPC’s output pressure (estimated differential pressure). When \( t \) tends to infinity, these functions show the statistical significance. \( \Delta q(t) \) reflects the fault degree of the fuel metering device, \( \Delta p(t) \) reflects the fault degree of the DPC, the higher these parameters are, the more serious the faults are. \( \Delta p(t) \) is used to distinguish the difference between the fault caused by the servovalve’s clogging and the fault caused by the friction of the FMV.

It is possible to distinguish four typical faults according to the above fault parameters. According to a large number of simulation results, these typical faults diagnosis data are summarized as Table 3.

| State                      | \( \Delta p^2(t) \) [bar²] | \( \Delta q^2(t) \) [(L/min)²] | \( \Delta q(t) \) [L/min] |
|----------------------------|----------------------------|-------------------------------|--------------------------|
| Normal state               | (0, 0.05)                  | (0, 2)                        | (-1, 1)                  |
| Head sensor stagnation     | (0.05, +∞)                 | (2, +∞)                       | Un                       |
| The FMV stagnation         | (0, 0.05)                  | (2, +∞)                       | (-1, 1)                  |
| Left nozzle clogging of the servovalve | (0, 0.05)      | (2, +∞)                       | (1, +∞)                  |
| Right nozzle clogging of the servovalve | (0, 0.05)    | (2, +∞)                       | (+∞, -1)                 |

The value areas of these parameters in Table 3 shows the value of corresponding function when \( t \) tends to limit infinity, the "Un" in table is on behalf of uncertainty. Normal state: the limit of \( \Delta p^2(t) \) is about 0.02, less than 0.05; the limit of \( \Delta q^2(t) \) is about 1.35, less than 2; the limit of \( \Delta q(t) \) is about 0, the absolute valve is less than 1. The diagnostic function’s limits in Table 3 are not strictly determined.

CONCLUSIONS

Two fault diagnosis methods are introduced in this paper and applied to the fuel metering device, which can be popularized and extended to other parts in HMU. The AMESim model of the fuel metering device was established at the beginning of the paper; then the fault tree was proposed to analyze these faults that may happen and two kinds of typical faults in the fault tree were simulated; finally, two methods were applied to diagnosis these typical faults. The AMESim model is physics-based so that it is suitable to analysis the static and dynamic characteristics of each component part for fault simulation. The "data-based" method can be used to analysis the faults quantitatively and the "model-based" method can be used to analysis the faults quantitatively. Simulation results show that both these two fault diagnosis approaches are effective.

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