Health Management System Based on Airworthiness of the Aircraft Fuel System

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Abstract

Since high demand for the safety of civil aircraft, airworthiness regulations and health management play an important role. Airworthiness and Health management are described and summarized about fuel system in this paper. Finally health management system for fuel system based on airworthiness is built to testifying it's ability of ensuring flight safety and increasing aircraft economy.

Keywords: Airworthiness; Fuel system; Health management; Simulation platform

Nomenclature

| Symbol | Description             |
|--------|-------------------------|
| $\rho$  | fuel density            |
| $P$    | pressure                |
| $m$    | mess                    |
| $L$    | fuel level              |
| $K$    | Coefficient of flow rate|
| $A$    | area of cross section of reservoir. |
| $a$    | depth of cavitation groove |
| $S$    | area of groove          |
| $d$    | height of impeller      |

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1. Introduction

Civil aircraft development has been more than half a century. The performance of the aircraft was boosting, meanwhile, the emphasis on aviation safety was increasing. Airworthiness regulations was born for safety requirement[1-3]. It was minimum standard regulation for protection of civil aviation safety requirements. Airworthiness regulations are constantly being revised due to the advancement of technology and the crash occurred and leading to great improvement of aviation security.

With the signal processing technology and the rapid development of computer technology and civilian aircraft for the economy sensitive, Health Management[4] is used to protect the aircraft flight safety and save replacement parts combined with perfect logistical support.

Airworthiness regulations are the first element to consider when engineers design aircraft fuel system. They must also be the fundamental to build fuel system health management system so as to meet the requirements of Aviation Administration. Fuel system health management system based on airworthiness is built and verified validity. The results show that it can greatly increase the aircraft flight safety and improve the economic efficiency of the aircraft.

This paper is structured as follows: section 2 gives the airworthiness requirements of fuel system. Section 3 establishes the sensors network to monitor the faults of fuel system. Section 4 builds the health management of fuel system based on airworthiness. Section 5 gives the application and section 6 summarizes the conclusions.

2. Introduction Airworthiness requirements of fuel system

Airworthiness is defined as aircraft inherent safety as while as suitable for navigation under standard circumstances. The airworthiness regulations containing in the specific requirements of the quality of civil aircraft are certification to civil aircraft access to commercial market[5]. Airworthiness regulations in foreign countries known as the "aviation regulations promulgated by the State must be strictly complied with. At very beginning, airworthiness should be considered by aircraft designer.

Airworthiness regulations associated with fuel system are concentrated in Part25, 26, 27.Since they are wide range of segments and emphasize on qualitative analysis, they are divided into eight categories and analyzed as follows[1].

Since fuel system must be constructed to ensure a flow rate and pressure of fuel for proper engine. Fuel system has strong robust to avoid interruption power for more than 20 seconds. Each engine has an appropriate manual switch to maintain flow if pumps or valves faults.

Fuel measurement system must detect mess of fuel in tank accurately and decrease the unusable fuel.

Since fuel in tanks are so dangerous for aircraft. All the fuel tanks must be able to bear the vibration, inertia, fluid, and structural loads that it may occur in operation. Fuel tanks within the fuselage contour must be able to resist crack and to retain fuel, by the inertia forces. Fuel tank must bear 125% of the maximum air pressure. Fuel tanks must be not destructed by fluid pressure developed during the most disadvantage combination of aircraft roll and acceleration. All the design for tanks make sure that construction of fuel tanks would be integrity and certificated by airworthiness.

With shift of the altitude of aircraft, atmosphere pressure changed quickly. Therefore, difference pressure between outside and inside of tanks may cause damage of construction of tanks. Vent system is designed for venting from the top part of the expansion space so that venting is valid under any normal
flight circumstances. Vent system capacity and vent pressure levels must maintain acceptable under normal flight, take-off, landing condition. Airworthiness regulation specify every details for vent tanks.

Airworthiness also specify time of refuel and jettison fuel and redundancy for bypass if key component fault.

Since several serious aviation accidents, airworthiness regulations define the maximum oxygen concentration and position of wire. To meet the requirements, aircraft manufacture developed inerting system which produce NEA(Nitrogen Enhanced Air) to drive oxygen in the tank ullage to reduce the oxygen concentration.

All the airworthiness regulation requirements for fuel system are extracted in Appendix A.

3. Fuel system fault detection analysis

The requirement of modern aviation tasks could provide real-time health status of system and troubleshoot accurately and predict remaining life, which can provide decision support for maintenance personnel, dynamic scheduling maintenance resources. As a result, ground maintenance and repair downtime reduce, aircraft utilization and airlines economic efficiency improve. Prognostics and Health Management(PHM) came into being[4, 6]. PHM requires real-time monitoring of key components. The sensor type and disposed object are shown in Fig. 1 and Table 1.

| Sensor type | position      | quantity | signal processing methods                              | Detection object               |
|-------------|---------------|----------|--------------------------------------------------------|-------------------------------|
| vibration   | Pump casing radial | 9        | frequency spectrum, Cepstrum envelope                   | Bearing fault                 |
| pressure    | Pump outlet   | 9        | frequency spectrum                                     | Inlet pressure insufficient   |
| Flow rate   | Pump outlet   | 9        | time-domain analysis                                   | anomaly detection             |
| pressure    | Engine inlet  | 2        | time-domain analysis                                   | anomaly detection             |
| temperature | Engine inlet  | 2        | time-domain analysis                                   | anomaly detection             |
| Flow rate   | Engine inlet  | 2        | time-domain analysis                                   | anomaly detection             |
| Liquid level| Tank          | 2        | time-domain analysis                                   | anomaly detection             |
| density     | Tank          | 1        | time-domain analysis                                   | anomaly detection             |
| temperature | Tank          | 3        | time-domain analysis                                   | anomaly detection             |
Airworthiness regulations and health management system has played a significant role in the flight safety of the aircraft. It could be enhance the safety of aircraft to consider both health management and airworthiness. It is difficult to combine health management with airworthiness due to qualitative analysis of airworthiness.

A large number of sensors are distributed widely on key component to monitor the status of fuel system. When the failed component is detected, ground maintenance staff will be notified the information immediately and mobilize effective resources to replace corresponding parts. Health management of fuel system based on airworthiness in this paper is designed fully consideration to distribute sensors and acquire signal which is transmitted to pilot and ground maintenance crew as shown in Fig.1.
In order to verify the feasibility of the fuel system health management system based on the airworthiness, simulation plat is built in this paper. The simulation plat can simulate fuel system and monitor the key component both of health management and airworthiness demand.

4.1 Fault modeling

Both normal and fault model established in flowmaster can easily switch when fault occur. The key components of fuel system are established as follows[7].

i. Reservoir Model

Changeable height of reservoir is used to simulate variable pressure boundary condition, the user can define the curve of liquid level versus time and the loss of flow rate of inlet and outlet. The pressure is calculated as follow

\[ P_t = P_s + \rho g (L + Z) - k \frac{\rho v^2}{2} \tag{1} \]

Where \( P_s \) is surface pressure set as local atmosphere pressure, \( L \) is liquid level, \( Z \) is reservoir level which is associated with leakage.

The two outlets of reservoir are:

\[ P_t - P_i = \frac{K \dot{m}_i |\dot{m}_i|}{2 \rho A^2} \tag{2} \]

Where \( K \) is coefficient of flow rate, \( A \) is area of cross section of reservoir.

ii. Pipeline model

Considering Friction and inertia of the fluid in the pipeline rather than elastic of fluid and pipeline, the pipeline is modeled. Although pressure fluctuation is ignored in most consideration, it will bring disaster during period of the shut-off or start both of pump and valve. The pressure is calculated as follow.

\[ \Delta p = \rho a \Delta v \tag{3} \]

Where wave velocity is

\[ a = \sqrt{\frac{1}{\rho \left( \frac{1}{k} + \frac{d \Phi}{tE} \right)}} \tag{4} \]

iii. Valve Model

The opening degree of the valve can be set to 1 indicates that the valve is normally open position. If set to 0, the valve is normally closed position; if set to between 0-1 indicates that valve experiences severe wear of the valve core. The valve pressure loss is shown as follow.

\[ \Delta p = k_v C_{re} C_f \frac{\rho v^2}{2} \tag{5} \]

iv. Fuel Pump Model

Fuel pump also called booster pump is a centrifugal pump composed of impeller, volute with output tube, draft tube. The theoretical head of the fuel pump as shown as follow.

\[ H_T = \frac{\Delta p}{\rho g} \frac{1}{g} (u_2 v_{2u} - u_1 v_{1u}) \tag{6} \]

The general failure of the fuel pump is motor burned, bearing failure and cavitation. When the motor burned, fuel pump speed becomes zero and the fuel pump stops working. Bearing failure of the fuel pump can be detected through vibration signal mentioned later. When cavitation occurs, the head of the fuel pump come into below.
\[ H = H_f - H_L \]  \
\[ H_L = \frac{1}{2 \rho g^2} \sum_{i=1}^{n} S_i \frac{a_i}{a_i + d} \left[ \left( \frac{a_i}{a_i + d} \right)^2 + \frac{1}{2} \left( \frac{a_i}{a_i + d} \right)^{3/4} \right] \]  

Where \( a_i \) is maximum depth of cavitation groove, \( S_i \) is surface area of the groove, \( d \) is the height of the impeller blade slot, \( R_i \) is inlet circle radius, \( R_s \) is outlet circle radius.

v. Scavenger Pump Model

Scavenger pump is generally divided into four parts: high-pressure fluid nozzle, low pressure fluid nozzle, mixing chamber and diffuser chamber. High-pressure fluid is ejected from the ejector nozzle to form a jet. an area of low pressure formed in the inlet section of the mixing chamber. The jet is constantly ejected along with the working fluid into mixing chamber and outflow from diffuser chamber to the system. Scavenger pump meet the conservation of mass, conservation of momentum as shown as follow. When the scavenger pump stuck due to ice, both of flow rate and pressure is zero.

\[ q_{m,m} = q_{m,s} + q_{m,p} \]  

Where \( q_{m,p} \) is mass flow of jet, \( q_{m,s} \) is mass flow of working fluid, \( q_{m,m} \) is mass flow of fluid mixture.

\[ \sum F = q_{m,p} (1 + \mu)v_m - q_{m,p}v_p - q_{m,s}v_s \]  

Where \( F \) is combined force, \( v_m \) is the velocity of mixed fluid in the outlet section of the mixing chamber, \( v_p \) is the velocity of jet in the inlet section of the mixing chamber, \( v_s \) is the velocity of working fluid in the inlet section of the mixing chamber.

4.2 Failure solution

Reconfigurable logic of fuel system management must ensure the safety of aircraft flight. Fault reconstruction strategy of fuel system is shown in Table2 and Table3.

| Fault Name            | Fault Phenomenon                        | Reconstruction Strategy                        | Level |
|-----------------------|-----------------------------------------|-----------------------------------------------|-------|
| Engine Fire           | Pilot observed the engine fire          | Close corresponding shut-off valve            | A     |
| Scavenger blocked     | Liquid level of collector tank decrease | Open cross feed valve                          | B     |
| Fuel pump fault       | Outlet pressure sensor detect lower value than ever | Close fault pump, open back-up pump            | B     |
| Imbalance between left tank and right tank | Great value between left tank and right tank of liquid level | Close fuel pump of lighter tank, open cross feed valve, match the mass between left and right tank | C     |
| Imbalance between forward and after tank | Great value between forward tank and after tank of liquid level | Open trim valve and trim fuel pump           | C     |
| All of fuel pump for one side failure | All outlet pressure sensor of one side detect lower value than ever | Close all of the fault fuel pump, open cross feed valve | A     |

| Fault Name            | Fault Phenomenon                        | Reconstruction Strategy                        | Level |
|-----------------------|-----------------------------------------|-----------------------------------------------|-------|
| electric self-test    | Fault component information display on LCD | Stop refueling and change corresponding component | B     |
| Cannot open shut-off valve | One of fuel tank liquid level is zero, inlet pressure increase | Stop refueling and change corresponding component | A     |
| Cannot close shut-off valve | One of fuel tank liquid level increase | Close corresponding tank by float shut-off valve | A     |
5. **Application of fuel system simulation platform**

Aircraft flight time account for the most time of total work time for fuel system. Simulation platform is built according to former fault model. The curves of pressure and flow rate of pumps and valves could be easily observed in platform. When fault of components inject simulation platform, failure of component will be located and the information about fault will be displayed in integrated interface, and related caution LCD will be lighted. The position of center of gravity of aircraft is shown in the left part of platform when fuel system meet trouble[8].

For example, when bearing fault of left forward pump is injected, the left forward pump fault is detected by fault inference engine. The curves of pressure and flow rate of fault pump is shown in the bottom of platform. The information “the bearing of left forward pump fault” is shown in the top of platform. The alarm light will become yellow.

When bearing fault is injected, normal model is switched from to failure model. The outlet pressure of pump is changed from 3.8bar to 2.7bar shown in Fig 2. The outlet flow rate of pump is changed from 4.5L/S to 3.7L/S shown in Fig 3.

![Pressure Drop](image1)

**Fig 2** The variation of outlet pressure

![Flow rate Drop](image2)

**Fig 3** The variation of outlet flow rate

The information of bearing fault generally occurs in the vicinity of fundamental frequency which is 1001Hz in this example. If the threshold value which is the difference value between maximum and mean value in the section, it can be determined as a bearing failure of the fuel pump, as shown in Fig 4.
6. Conclusion

The basic conception of airworthiness and health management are introduced in this paper. The airworthiness regulations about fuel system is classified and summarized. The simulation platform of health management based on airworthiness is built to simulate all the function of aircraft fuel system. Take an example of bearing fault of fuel pump during flight. Simulation platform could detect the fault through real-time reasoning machine. The results show that the health management based on airworthiness could protect the aircraft flight safety and improve the economics of the aircraft.

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Appendix A Detail requirements of airworthiness for fuel system
i. Feed Engine Requirement
   a) It must be constructed to ensure a flow rate and pressure of fuel for proper engine.
   b) Do not interruption power for more than 20 seconds.
   c) Prohibit ice block occur under extreme cold circumstances.
   d) Fuel system has an appropriate manual switching capability for each engine.
e) Supply fuel to each engine through a system independent of each part of the system supplying fuel to another.

ii. **Fuel flow Measurement Requirement**
   a) The quantity of fuel in the tank may not exceed requirement.
   b) The fuel must flow through its bypass when the flowmeter blocked.
   c) Unusable fuel is able to supply engine at any circumstances.

iii. **Fuel Tank**
   a) Each fuel tank must be able to bear the vibration, inertia, fluid, and structural loads that it may occur in operation.
   b) Fuel tanks within the fuselage contour must be able to resist crack and to retain fuel, by the inertia forces in emergency landing conditions.
   c) Fuel tanks must be in a perfect position so that exposure of the tanks to scraping action with the ground is impossible.
   d) All covers must be fire-proof and prevent to penetration by tire fragments and low energy engine debris.
   e) Fuel tank must bear 125% of the maximum air pressure.
   f) Fuel tanks must be not destructed by fluid pressure developed during the most disadvantage combination of aircraft roll and acceleration.
   g) Fuel tanks must be withstand at the temperature of 43°C.
   h) Every Fuel tank must be designed so that tank loads are not concentrated on non-supported tank surfaces.
   i) Every fuel tanks must be designed an expansion space of 2 percent of the tank capacity.
   j) Every fuel tank must have a sump which its capacity of not less than 0.1% in the normal ground attitude are established to ensure water dropout.
   k) The maximum temperature of the fuel tank must be less than the lowest natural temperature of the fuel in tank.

iv. **Vent System**
   a) Every fuel tank must be vented from the top part of the expansion space so that venting is valid under any normal flight circumstances.
   b) Any vent covers could be blocked by dirty and ice.
   c) The venting capacity and vent pressure levels must maintain acceptable under normal flight, take-off, landing condition.
   d) The vent covers are not distribution in APU, engine, manned cabin.
   e) Vapor from covers must return back to the fuel tank.

v. **Pressure Refuel System**
   a) Every pressure refuel system fuel manifold must have prohibited the escape of hazardous quantities of fuel from the system if the fuel inlet valve is fault.
   b) An automatic shutoff must be built to prohibit the quantity of fuel in any tank from exceeding the maximum quantity certificated for that tank.
   c) It must be checking for proper shutoff operation before refueling the tank.
   d) The temperature caused by failure of component must meet the criterion.

vi. **Critical Component**
   a) Each main fuel pump must have a bypass facility.
   b) Emergency pump must be equipped with to feed engine immediately in any of the main fuel pump failure.
   c) Any fuel line cannot be damaged due to piping vibration.
d) The connection of the pipeline should use flexible hose.
e) Every component cannot be installed in the high temperature places.
f) The fuel filter should ensure fuel supply to engine and prevent engine from damaging.
g) Every fuel pumps must be equipped with a fuel filter.
h) Any critical valve must be designed a redundancy.

vii. Fuel Jettison System
a) Each aircraft must be installed a fuel jettison system and can fly 15 minutes after fuel drop.
b) Fuel or fumes must not enter any part of the aircraft.
c) Jettison system cannot affect operation controllability of the aircraft.
d) Emergency drain valve must be designed to allow flight crew to close the valve during jettison time.
e) It does not appear dangerous with asymmetric discharge of fuel.

viii. Inerting System
a) Corona discharge must not appear at vent cover.
b) There is no ignition source in maximum fuel vapor density in fuel tank.
Each fuel tank average flammability exposure time should not exceed the flammability exposure time’s (defined as the total time during pre-flight, flight, landing and all passengers outside) 3%.