Analysis Methodology of Unusable Fuel Supply for Large Rotorcraft Airworthiness Certificate

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Abstract. The unusable fuel quantity plays a key basis for calibration of aircraft fuel gauge and fuel measurement system. Using large helicopter fuel tanks as case study, the paper described airworthiness requirements for fuel system design and current research development. In particular, the paper presented an analysis method can be utilized and referenced as means of compliance for airworthiness requirements. This method will reduce the qualification time and save money for physical and dynamic bench test/flight test in the future.

Keywords: Large Rotorcraft, Unusable Fuel, Airworthiness Certificate, Methodology

1. Introduction
Unusable fuel is the fuel stored in the aircraft fuel tank and cannot supply to the engine for consumption. Unusable fuel supply is very important for aviation safety and economic robust, because unusable fuel quantity will be used for calibration of aircraft fuel gauge and it is part of the operating weight, in order to reduce the operating fuel consumption cost. Unusable fuel has received a great deal of attention among aircraft designers and operators [1-2].

The current development of aircraft fuel tank requires a prolonged and costly activity to develop and qualify the fuel system, including fuel system design and flight test programmers, culminating in system qualification, due to

The characteristic of aircraft during flight, the tank cannot always keep in the normal pitch and roll attitude. It will be nose-up and down during the flight phases and make the tank unable to maintain horizontal level.

Real full range flight test will introduce more safety risks to get the final unusable fuel quantity in the extreme configuration.

Generally, to improve the qualification process and to reduce the need for full range dynamic physical testing, it needs to take into account the analysis method as a reference for final flight test during the early development phases of the aircraft fuel system.

1.1 Background
From airworthiness certificate side of view, Federal Aviation Authority (FAA), USA and Civil Aviation Administration of China (CAAC) had published unusable fuel standards in FAR/CCAR Part25 and Par29 as basis for Large transport aircraft and rotorcraft (Helicopter).
§29.959 Unusable fuel supply. The unusable fuel supply for each tank must be established as not less than the quantity at which the first evidence of malfunction occurs under the most adverse fuel feed condition occurring under any intended operations and flight maneuvers involving that tank [3-5].

§29.1337 Powerplant instruments (b) (1): Each fuel quantity indicator must be calibrated to read “zero” during level flight when the quantity of fuel remaining in the tank is equal to the unusable fuel supply determined under §29.959 [3-5];

The design and certificate activities must show the compliance with national civil aviation regulation basis as described in §29.959 and §29.1337.

1.2 Current Research Status
In US and Europe, computing technology have been achieved used for recent unusable fuel tank design by Tookey, R and Karnopp, D.S [6-7]. The challenge is to develop the corresponding integrated processes to support this technology and to establish a Synthetic Environment that can provide credible qualification evidence. In China, the airworthiness requirements and methods to identify unusable fuel for Commercial Transport Aircraft were synthesis by Zhao [8]. The unusable fuel quantity for a civil aircraft fuel system determined by flight research was carried out by Chen Zhanbin, Wei Jinzhou, Lv Meixi [9]. The comparison of different measurement methods and future tendency for unusable fuel tank was presented by Lv [10]. Final, Yang [11] synthesis the fault analysis and maintenance of aircraft fuel system.

1.3 Analysis Method for Unusable Fuel Quantity
The paper first reviews the current process for designing and analyzing unusable fuel supply by using the large helicopter as case study. An analysis method presented to calculate the maximum unusable fuel quantity at extreme height nose-up attitude based on flight performance configuration. Compared with real full range dynamic bench test and flight test, this method can reduce the scale of full range dynamic physical testing as a reference for final flight test during the early development phases of the aircraft fuel system.

2. Fuel Transfer System and Jet Pumps System in Large Helicopter under FAR/CCAR Part 29
As shown in Fig.1, each group of tank Ti (i = 1, 2, 3, 4, 5, 6) with its fuel volume Vi (i = 1, 2, 3, 4, 5, 6) is equipped with a jet pumps system continuously transferring fuel from the main tanks T4 and T3 to the feeder tanks T2 and T1 (inside which the electrical pumps feeding the engines are installed). The flow in excess entering the feeder tanks returns to the main tanks through an overflow communication. Doing so, the feeder tanks are kept full as long as fuel remains in the main tanks. However, due to installation constraints, tanks shape or aircraft attitudes, some fuel cannot be pumped by the jet pumps. This quantity is part of the unusable fuel V unusable.

Fig. 1 Configuration with six tanks – Top view
Due to symmetry of helicopter/aircraft, the Right-Hand (RH) feeder tank T2, main tank T4 and auxiliary tank T6 were taken as example. The total quantity of Fuel will be

\[ V_{total} = V_2 + V_4 + V_6 \]  

(1)

3. Design of Low-Level Alarm System and Extreme High Nose-Up Attitude Configuration

3.1 Low-Level Alarm System

As shown in Fig. 2, Helicopter fuel gauge always set low-level sensor to warn the Low-level fuel \( V_{low-level} \) in T2. When the alarm warning, pilot will know the quantity of fuel in T2.

\[ V'_{2} = V_{low-level} \]  

(2)

The Total RH group fuel quantity is

\[ V'_{total} = V_{low-level} + V'_{4} + V'_{6} \]  

(3)

3.2 Extreme High Nose-Up Attitude Configuration

During flight phase, the helicopter will be nose-up and down and make the tank unable to maintain horizontal level. This characteristic makes the measurement of maximum unusable fuel quantity in each tank to be very difficult. Dynamic tests under bench for each pitch and roll configuration would be a prolonged and costly activity. Thanks to the flight performance analysis and simulator analysis, the extreme conservative configuration at high nose-up attitude obtained in Fig. 3.

4. Maximum Unusable Fuel Quantity at High Nose-Up Attitude

To obtain the Maximum Unusable Fuel Quantity \( V_{Max_{-}UFQ} \), the strategy is to keep the RH feeder tank fuel consumption working and to drain out the fuel in T2 with low-level alarm activated. Then the
fuel quantity V’4 and V’6 in Eq.(3) will be obtained. The figures below in Fig.4 illustrate how the maximum unusable fuel quantity can reach VMax_UFQ although the low level warning is activated when the fuel quantity in the RH feeder tank falls below Vlow-level.

![Figure 4](image)

**Fig.4** Maximum Unusable fuel distribution at high nose up attitude (with level alarm activated).

In this case, the Feeder tank T2 fuel quantity is V’2, and the fuel quantity in tank T4 and T6 is the same as the fuel quantity V’4 and V’6 in fig.3. The mathematical expression of Maximum Unusable Fuel Quantity VMaxUFQ is as follows:

\[
V_{\text{Max}_\text{UFQ}} = V'2 + V'4 + V'6
\]  

(4)

The low-level warning is therefore not linked to the maximum unusable quantity in the RH group obtained at high pitch nose-up attitude but the fuel quantity remaining inside the feeder tank. Indeed, according to the flight manual, the fuel potentially remaining in 6th tank (at high nose-up attitude) can be recovered after resuming normal aircraft attitude as shown in Fig.5. That was needed to be confirmed for instance during flight test at high nose-up pitch attitude where low level warning was raised before total fuel quantity inside right group fell to VMax_UFQ.

![Figure 5](image)

**Fig.5** Unusable fuel conditions at normal pitch attitude

5. **Conclusion**

Flight performance analysis and simulator analysis can play a better guidance for final flight test during the early development phases of the aircraft fuel system. An analysis mythology as means of compliance for airworthiness requirements presented in the extreme conservative configuration at high pitch nose-up attitude. The maximum unusable fuel quantity obtained. In fuel system design, when the low-level warning activated, the remaining fuel quantity in the RH fuel tanks should be greater than maximum unusable fuel quantity obtained. It is conservative and acceptable.
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