Research on Guillotine Test of Fuselage Fuel Hose of Civil Aircraft Auxiliary Fuel System

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Abstract. If the fuel Hose in the fuselage of a civil aircraft is damaged in a survivable crash accident, the fuel leaked from the fuselage fuel pipe may cause an uncontrollable fire. The guillotine test is a test to verify the deformation and tension capability that the fuselage fuel pipe should remain free of oil leakage. However, different aircraft have different configuration and layout, and the structure in the fuselage and other system equipment are very complex, it is very difficult for the airworthiness authority to formulate unified verification test requirements. Considering that the guillotine test is one of the large-scale compliance verification tests perplexing the civil aviation field at home and abroad, this paper studies the guillotine test of the fuselage fuel hose of a domestic civil aircraft auxiliary fuel system, so as to provide a reference for the guillotine test of the fuselage fuel hose of civil aircraft at home and abroad.

1. Introduction
Clause CCAR25.993 (f) of civil aircraft airworthiness authorities[1] at home and abroad requires that "the fuel pipeline in the fuselage shall be designed and installed to allow reasonable deformation and tension without oil leakage". The fuselage fuel pipeline of the auxiliary fuel system of civil aircraft is divided into metal pipe configuration and hose configuration. For the metal pipe configuration, due to the known material parameters, the calculation and analysis method can be used to show the compliance, and there is no need to carry out test verification, which is not within the research scope of this paper. The material parameters of the hose and the strength limit without leakage due to impact are unknown, so the compliance cannot be verified by analysis. Guillotine test is a widely accepted verification method in the industry. Although the guillotine test is widely accepted, the selection of test configuration needs to consider the actual configuration of the aircraft. Therefore, the confirmation of guillotine test configuration needs to comprehensively consider not only the methods widely accepted by the industry, but also the actual configuration of the aircraft, which is used for clause compliance verification after being confirmed by the airworthiness authority.

Taking the auxiliary fuel system of a domestic civil aircraft as an example, this paper analyzes the layout and configuration of the fuel hose near the fuel hose in the aircraft fuselage, decomposes the important elements of the guillotine test, uses the simulation method to predict the response of the hose under the guillotine test condition, and verifies the compliance of the hose in this case through the guillotine test.

2. Origin of Guillotine Test
In the process of aircraft crash, the landing gear damaged due to overload and other fuselage structures near the pipeline may fall off and impact the fuel pipeline, resulting in oil leakage. The guillotine test
is used to verify the scene that the body structure that may fall off impacts the fuel pipe, so as to verify the compliance of the body fuel pipe with Clause 25.993 (f).

On November 11, 1965, flight United Airlines flight 227, a B727 crashed during landing at Salt Lake City Municipal Airport due to pilot error\textsuperscript{[2]}. After the aircraft touched down, the right main landing gear pierced the fuselage fuel pipeline, and a large amount of fuel leakage caused a cabin fire, resulting in 43 of the 91 passengers on board. On June 7, 1966, the Civil Aeronautics Board (CAB) released the accident investigation report 1-0032, which characterized the accident as a survivable crash accident\textsuperscript{[3]}.

In order to clarify the requirements for aircraft crashworthiness, FAA officially issued amendment 25-15 standard for crashworthiness and emergency evacuation of transport aircraft on September 20, 1967. 25.993 (f) is added in the amendment to increase the flexibility requirements from the perspective of fuel conduit, and 25.721 is added to ensure that the fuel system components, pipelines and fuel tanks located in the fuselage are unlikely to be damaged due to the failure of the landing gear due to overload in the vertical plane from the Perspective of landing gear design. At the same time, an aircraft manufacturer has developed a set of test procedures and test devices specially used to test the impact resistance of hose, which is the predecessor of guillotine test. The original intention of the test is to consider the damage of the damaged landing gear to the hose.

3. Research Status of Guillotine Test
In order to ensure the compliance of civil aircraft fuselage fuel pipe with Clause 25.993 (f) and avoid fire caused by fuel pipeline leakage after aircraft crash, several aircraft manufacturers around the world have carried out relevant research on the guillotine test of fuselage fuel hose\textsuperscript{[4]}. However, due to the different body structures and fuel hose materials and configurations of different aircraft, the deformation requirements of the body structure for the fuel pipe are also similar. Figure 1 lists the configurations of the fuselage fuel hoses of two well-known civil aircraft. The illustration shows that the fuselage fuel hoses of these two aircraft configurations are arranged along the belly or installed below the cabin floor, Located in the impact area.

![Figure 1](image_url)  
Figure 1  Configuration of fuselage fuel hose of two well-known civil aircraft in Europe and America

Therefore, in order to unify the test requirements, after a lot of research and analysis, FAA issued issue paper ip-23 for aircraft in August 2011. It is recommended to verify clause 25.993 (f) through guillotine test. Install the fuel pipe on the test bench according to the installation mechanism. The test shall ensure that the fuel pipe is consistent with the mounting mechanism, and the test article sleeve and clamp shall also be consistent with the mounting mechanism. Since the layout of fuel duct is easily affected by the direct impact of damaged and separated landing gear and the tensile, extrusion and shear effects caused by fuselage deformation and separation, analysis shall be carried out to support that the test is the most severe configuration, or multiple configurations shall be used for the test.
The fuel pipe should be pressurized with water to the maximum working pressure of the fuel supply system. A 1/8 inch (about 3.18 mm) thick steel plate with a total weight of 34.5 kg was tested. The drop hammer falls freely from a height of 37.5 feet (about 11.43 m) and strikes the thinnest weakness of the conduit test article (obtained by analysis). In the test, the conduit is deformed at least 18 inches (0.457 m) in the vertical direction after being impacted, as shown in Figure 2. There shall be no liquid leakage after the test.

4. Configuration of Hose Guillotine Test of Auxiliary Fuel System of a Civil Aircraft

According to the schematic diagram of the guillotine test, the important factors of the guillotine test are the weight of the falling hammer, the falling height of the falling hammer, the thickness of the cutter head, the test article and its installation configuration, and the height and distance between the test article and the buffer sandbag. This meets the requirements of "the design and installation of the fuel pipeline in the fuselage will deform without oil leakage under the impact of the maximum possible structural weight of the fuselage in the case of aircraft crash".

Based on this, according to the actual configuration of auxiliary fuel system of a domestic civil aircraft, the factors of fuselage fuel hose guillotine test are as follows

4.1. Selection of Test Configuration
The installation arrangement of the auxiliary fuel system of a civil aircraft listed in this paper is shown in Figure 3, that is, the front auxiliary fuel tank and rear auxiliary fuel tank are added on the basis of the basic aircraft fuel system, and the new auxiliary fuel system hoses (shown in Figure 4) are used for refueling, ventilation and fuel transfer between fuel tanks respectively.
Figure 4  New pipeline layout of auxiliary fuel system

The purpose, material and length of the new fuel hose are shown in Table 1.

| No. | Hose Name                  | Qty of Hose | Hose Length (mm) | Hose Material                                   |
|-----|---------------------------|-------------|------------------|-------------------------------------------------|
| 1   | Front auxiliary tank transfer hose | 1           | 1950             | MIL-DTL-83797 as Fuel Hose, MIL-DTL-6000 as Protect outer Hose. |
| 2   | Front auxiliary tank filler hose | 1           | 1520             |                                                 |
| 3   | Front auxiliary tank breather hose | 1           | 1650             |                                                 |
| 4   | Rear auxiliary tank transfer hose | 1           | 3700             |                                                 |
| 5   | Rear auxiliary tank filler hose | 1           | 3650             |                                                 |
| 6   | Rear auxiliary tank breather hose | 1           | 4200             |                                                 |

The fuselage pipes are double-layer pipes, and the inner pipe is mil-dtl-83797, which is protected by the outer pipe to prevent fuel leakage into the fuselage structure from causing harm. The outer pipe includes hose mil-dtl-6000 and metal hard pipe (the metal hard pipe meets sae-ams-4081, sae-ams-4083 or other equivalent standards).

The refueling pipeline is used on the ground. The ventilation pipeline is a pipeline to ensure the ventilation between the auxiliary fuel tank and the basic fuel tank on the ground. There will be no fuel after the aircraft is running. After the refueling pipeline and vent pipeline complete their respective functions on the ground, there will be a cutting device to cut off the functional connection between them and the fuel tank.

During flight, the fuel consumption sequence of the aircraft is the fuel in the auxiliary fuel tank first, and then the fuel in the basic fuel tank. The pipeline realizing the fuel transmission function between the auxiliary fuel tank and the basic fuel tank is the fuel tank transfer pipe. The transfer pipeline is located at the upper part of the fuel tank. After the transfer, the remaining fuel in the fuel pipeline will flow to the auxiliary fuel tank or basic fuel tank due to gravity. Therefore, there may be fuel in the transfer pipeline before the fuel in the aircraft auxiliary fuel tank is exhausted, and the position of the rear auxiliary fuel tank group is located in the area affected by the disconnection of the landing gear. Therefore, the rear transfer hose is selected as the test object.

4.2. 1 Test Article

The total length of the test article is 3700mm, and the installation is shown in Figure 5. The left and right ends are respectively connected with the oil tank through joints, and the middle is fixed on the support through clamps, which is used to support the pipeline; The pipeline consists of inner and outer double layers. The inner pipe is a transfer hose conforming to mil-dtl-83797 specification. The outer pipe is used to protect the inner pipe, which is composed of three sections. The middle section is a rubber hose conforming to mil-dtl-6000 specification, with a length of 2310mm. Both sides are aluminum alloy hard pipes. The rubber hose and aluminum alloy hard pipes are connected together through a throat clamp. In order to show the compliance of fuselage fuel pipe with Clause ccar25.993 (f), the inner hose (about 3700mm long fuel transfer hose conforming to mil-dtl-83797 specification) is selected as the test article to carry out the guillotine test.
4.3. Deformation Requirements from Aircraft Level

The calculation and analysis results of aircraft crash at 0 ° pitch angle of 17 ft/s (this data is the survivable crash condition approved by the airworthiness authority) show that under the survivable crash condition, the deformation of fuselage fuel pipeline extracted by support nodes is shown in Figure 6, and the tensile length and tensile percentage between nodes are shown in Table 2. The test results show that the deformation at the possible maximum deformation position of the hose is about 10.2 mm, and the calculated elongation of the whole hose is less than 4%.

4.4. Impact Energy Screening

The structure and equipment layout around the aircraft hose are shown in Figure 7. The analysis results show that there is no other equipment around the hose except cables and steel cables. There are 7 structural parts that may impact the hose, with a total weight of 23.5 kg. Thus, the maximum weight that may impact the fuel pipeline is 23.5 kg.

The factors determining impact energy include impact weight and impact height, which can be inferred from impact velocity. When the aircraft falls at the speed of 17 ft/s, the maximum relative speed between the fuel pipeline and the surrounding structure is 17 ft/s at the moment when the belly contacts the ground. It is inferred that the initial height of the free fall of the heavy object is no more than 1.5 m.
In conclusion, when the aircraft studied in this paper crashes at 0° pitch angle of 17ft/s, the energy factor of impacting the fuel hose is the impact weight of 23.5kg and the impact height of 1.5m.

In addition, the selection of impact energy also needs to consider the ip-23 generally recognized in the industry. Ip-23 is specially released by FAA for this model. This document proposes that the aircraft is equipped with fuel pipes in the fuselage and fuel tank, which will be affected by the survivable crash process. This paper is based on the B727 aircraft crash incident (the scene after the crash is shown in Figure 8, which requires that the fuel pipeline will not leak and cause fire after the aircraft crash). The applicant must demonstrate that these fuel ducts have sufficient flexibility and deformation capacity to reduce the possibility of fuel leakage during a survivable crash. Possible cases include the impact of landing gear on the guide tube, the tensile effect of structural extrusion on the guide tube, and the shear effect of fuselage structural deformation and/or separation on the guide tube. The guillotine test described below is considered as a compliance method to prove that the fuel pipe has sufficient resistance to foreign object impact, sufficient flexibility and sufficient tensile properties.

In order to verify the effectiveness of the design of the fuel pipeline for this problem, the applicant shall use the guillotine test to verify the compliance of the fuel pipeline, and the fuel pipe shall be pressurized with water to the maximum fuel supply pressure of the fuel supply system. The total weight of the drop hammer tested was 76 pounds (34.47 kg), including a 1/8 inch thick steel plate. The drop hammer fell from a height of 37 feet (11.2776 meters) and impacted the thinnest weakness of the conduit test article. The installation of fuel pipe must ensure sufficient tensile capacity. This capability shows that the conduit test article has at least 18 inches (0.4572 m) deformation in the test, and there shall be no fuel leakage after the test. Figure 9 is the test installation schematic diagram.
5. Configuration Confirmation of Guillotine Test
After comprehensively considering the actual configuration of the aircraft and the requirements of ip-23, a guillotine test is carried out on the fuselage fuel hose of an auxiliary fuel system of a civil aircraft under the most severe conditions. The drop weight, height and cutter head width of ip-23 are used for the test, and the rear auxiliary fuel tank transfer hose with a length of 3.7m is used for the test article (the drop weight directly impacts the inner hose). The installation of the test article shall be consistent with the installation on the aircraft. The drop hammer impact position is located at the middle point between the nearest edges of the hard pipes at both ends of the outer layer. At this position, the inner transfer hose is impacted to simulate the most severe impact state of the aircraft configuration.

6. Simulation of Guillotine Test
Before the test, the design team used the simulation method to simulate the guillotine test. The model is shown in Figure 10. The model uses solid element modeling for the outer pipe, inner pipe, drop weight and test tooling of fuel pipeline, and shell element modeling for clamp and throat clamp. The number of simulated units and nodes is shown in Table 3.

![Simulation model of broken end test](image)

**Table 3  Number of simulation model elements and nodes for guillotine test**

| Item            | Qty.      |
|-----------------|-----------|
| Solid Element   | 1245724   |
| Shell Element   | 1328      |
| Node            | 1610068   |
| Material        | 8         |
| Tied Connection | 30        |

The drop hammer material is 321 stainless steel. Within the stainless steel range required by ip-23, the outer pipe adopts ordinary rubber parameters, the inner pipe adopts the relationship between tension and deformation obtained from tensile test as the stiffness curve of the inner hose, and both ends of the inner and outer pipes are rigidly connected.

Using the calculation method of impact dynamics, the maximum deformation deflection of the pipeline at the impact point is 457mm, and the pipeline displacement change curve and the state of reaching the maximum deformation after the pipeline is impacted are shown in Figure 11.
The calculation results show that the pipeline just reaches the deformation of 18 inches (457mm) required by the guillotine test, and there is no fuel leakage.

7. Guillotine Test Verification

The guillotine test bench is shown in Figure 12. The 34.5kg drop hammer of the test bench can impact the test article under the guidance of steel cable from the height of 11.43m. The test article is installed according to the actual situation on the machine, and the four clamp positions are fixed and supported on the test tooling; The sleeves at both ends of the hose (mil-dtl-83797) are fixed on the test tooling through plugs; The outer hose and hard pipe of the test tooling are fixed together through a throat clamp; The other end of the hard pipe of the test tooling is connected with the pipeline flange by welding, and then the circular sleeve tooling is connected with the pipeline flange and fixed on the test tooling. The installation control dimensions of test bench and test article are shown in Figure 12.

After the installation and acceptance of the test bench and test article, fill the test article pipeline with liquid, record the pressure, and maintain the pressure for 5 minutes as required to ensure that there is no leakage in the pipeline. After raising the drop hammer with a weight of 34.7kg and a cutter head thickness of 3.18mm for 11.43m, fall freely, and record the process of the drop hammer impacting the hose with a high-speed camera, Observe whether the pipeline leaks within 15 minutes after impact, and record the liquid pressure value in the pipeline at the moment of impact and 15 minutes after impact to ensure that there is no liquid pressure loss.

The test results show that during the impact process, the maximum deformation deflection of the test article is 461.4mm, and there is no fuel leakage. After 15 minutes, the pressure does not drop significantly, which meets the requirements of the test qualification criterion. The maximum deformation in the test is shown in Figure 13.
8. Comparison Between Simulation Results And Test Results
The comparison of simulation and test results is shown in Table 4. The results show that the inputs adopted by the two methods are consistent, and the response trend of fuel hose is basically the same. The maximum deformation deflection value is quite different because the tensile force and deformation curve of the test article used in the simulation calculation are obtained through the tensile test. Affected by the deformation speed, the curve obtained from the tensile test is different from that of the hose subjected to instantaneous impact, resulting in different maximum deformation deflection values. However, the results in FIG. 11 and FIG. 13 show that, The simulation calculation can effectively obtain the hose response, which is basically consistent with the hose deformation trend obtained from the test.

Table 4 Comparison between simulation results and test results of guillotine test

| Verification Method | Drop weight (kg) | Cutter thickness (mm) | Falling height (m) | Max Hose deflection (mm) | Leakage (Y/N) |
|---------------------|-----------------|----------------------|------------------|------------------------|---------------|
| Simulation          | 34.5            | 3.175                | 11.43            | 457                    | N             |
| Test                | 34.7            | 3.18                 | 11.43            | 461.4                  | N             |

9. Conclusions And Outlook
Guillotine test is a widely recognized test method in civil aviation industry to verify the compliance of fuselage fuel hose with Clause 25.993 (f). Taking the fuselage fuel hose of a civil aircraft auxiliary fuel system as an example, considering the actual installed configuration of the aircraft fuselage fuel hose, this paper selects the most severe guillotine test conditions produced by the aircraft configuration, compares the test configurations recommended in the widely recognized requirements ip-23 in the industry, and selects the two more severe configurations as the final test configuration. The test results show that the fuel hose used in the installation mechanism meets the design requirements through the guillotine test.

The combing results of this paper show that the actual configuration of the guillotine test combed out by the fuselage fuel hose of the auxiliary fuel system of a civil aircraft is much lower than that required by ip-23, which indicates that the guillotine test conditions determined by ip-23 may be too harsh. This indicates that by accumulating more fuel hose configurations of civil aircraft fuselage in the future, the actual configuration combing results of the aircraft can be considered to determine the guillotine verification test conditions, so as to avoid unnecessary economic impact caused by the passing design of fuel pipe.

At the same time, considering the economy of aircraft design and verification, the response trend of the test article obtained by the simulation and test methods is basically the same. When the hose deformation accuracy is not high, the simulation method can save the test cost and obtain good economic benefits.
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