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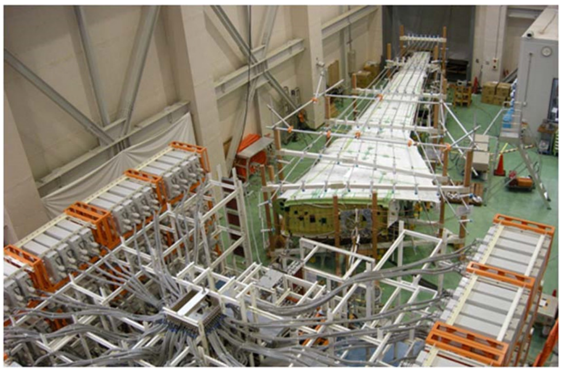
Evaluation by Full Wing Model Test to Ensure Aircraft Safety Against Wing Fuel Tank Explosion by Lightning Strike



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Recently, safety requirements to prevent fuel tank explosion have become stricter. To show compliance with these requirements, Mitsubishi Aircraft Corporation designed the wing fuel tank of the Mitsubishi Regional Jet (MRJ) with a sufficient margin of safety based on three-dimensional electromagnetic simulation and coupon tests. To build further confidence in the safety of the MRJ, which is not yet in service, and to obtain data supporting the type certificate, the occurrence of ignition sources causing fuel ignition in wing fuel tanks is investigated by lightning tests using a full wing model, and the potential difference and current are also measured. The full wing model includes the majority of the MRJ wing structure and is manufactured by the same process as actual wing manufacturing. Such a large-scale test is a rarity around the world. In the tests, lightning current (200kA max.) specified by ARP5412, which is one of the standards for aircraft lightning tests, is injected to the full wing model. In all cases that were tested, it was confirmed that no ignition sources are generated inside the wing fuel tank and that the potential difference and current inside the tank are sufficiently low.

1. Introduction

Mitsubishi Heavy Industries, Ltd. (MHI) and Mitsubishi Aircraft Corporation have been developing the next-generation domestic regional jet, the Mitsubishi Regional Jet (MRJ), toward its first flight in 2015 and the first delivery in 2017. Various tests and analyses are ongoing toward type certification.

For the development of an aircraft, to ensure flight safety, the aircraft must be designed and manufactured according to the safety requirements of the regulations of Japan and other countries. The Japanese regulations are the Airworthiness Standards of the Civil Aviation Bureau of the Ministry of Land, Infrastructure, Transport and Tourism. In addition, compliance with the regulations must be demonstrated. The scope of the regulations is wide, including factors such as strength, structure, environmental performance and safety, and one of the regulations is the prevention of fuel tank explosion. The explosion prevention regulation became stricter because of the TWA800 accident in 1996. It is required to demonstrate that no ignition sources will occur under all situations that should be considered. To show compliance for lightning protection is believed to be one of the most difficult issues.

2. Characteristics of the evaluation by tests using the full wing model

Generally, the main wing of an aircraft is used as fuel tanks. Sparks generated at structural joints inside the main wing and interfaces between components and structure are ignition sources causing fuel tank explosion when the aircraft is struck by lightning. Lightning coupon tests for various joints in the wing will be conducted as “certification tests” to show compliance with

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regulations. For the certification tests, various activities to show no ignition sources considering manufacturing variability and failures are ongoing.

To build further confidence in the actual wing, tests using the full wing model were conducted by injecting the lightning current (200 kA max.) specified by the ARP5412[*1] aircraft lightning test standard. The purposes of the tests are to confirm the following for actual wing configuration: i) sparks causing fuel vapor ignition will not occur inside the fuel tank; ii) sufficient current and potential differences causing sparks will not be generated inside the fuel tank; and iii) an evaluation of analysis accuracy for three dimensional electromagnetic simulation. The full wing test model is a test specimen that includes the majority of the MRJ right wing structure, but does not include a winglet, control surfaces, an engine pylon, etc., that are not members of the wing fuel tank structure[*2]. The full wing model is manufactured by the same process as actual wing manufacturing. The size of the full wing model is as large as a test specimen, and is about 14 m in total length and about 4 m in width (**Figure 1**). The lightning current generator[2] (**Figure 2**), which is owned by MHI and is installed at the Lightning Technology Center of Otowa Electric Co., Ltd., was used to inject lightning current to the full wing model. The generator is a unique system in Japan that has been used for lightning tests satisfying the requirements of the FAA[*3]. A complex wave (200 kA max.) synthesized from multiple components specified by ARP5412 was injected in the tests.

Tests where full-threat lightning current specified by ARP5412 is injected to a full size wing build confidence in safety, and such a large-scale test is a rarity around the world.

*1 Aerospace Recommended Practice
Aircraft standards issued by an association (SAE International) formed by engineers and specialists in technologies related to the aircraft, automobile and commercial vehicle industries.

*2 The fuel tanks of the MRJ are the wing box structure used as integral tanks. The wing box structure, which includes the outer wings and center wing, consists of upper/lower skins and front/rear spars and is sealed inside to prevent fuel leakage.

*3 Federal Aviation Administration
The Federal Aviation Administration is one of the agencies belonging to the United States Department of Transportation and is responsible for the type certification of aircraft in the U.S.

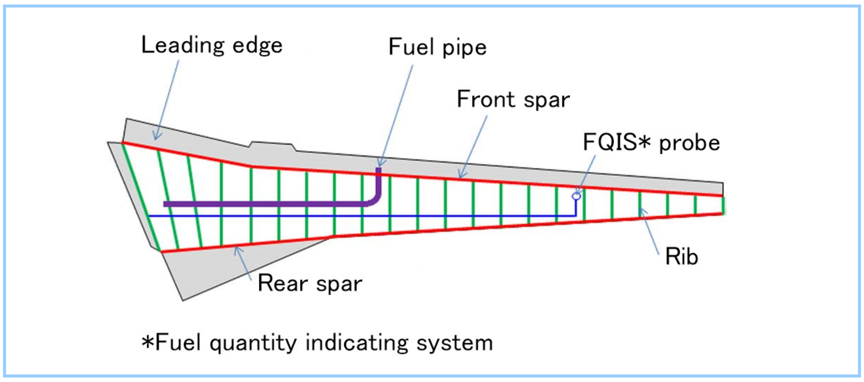

Figure 1　Structural schematic of the full wing model

Figure 2　Exterior view of the lightning current generator

To confirm the effectiveness of the lightning protection design, the following items are conducted for the inside of the wing fuel tank.

(1) Confirmation of no sparks causing fuel ignition
(2) Measurement of potential difference
(3) Measurement of current

3. Test configuration and conditions

3.1 Test configuration

(1) Overall configuration of the test

An overview of the test configuration is shown in **Figure 3**. To inject steep waveforms, the full wing model, which is load for the generator, must be connected to the lightning current generator with low impedance. Furthermore, to minimize the difference between the electromagnetic environment of an actual aircraft lightning strike and the tests, the influence on the magnetic field on the wing surface by the current flowing in the conductor that connects the full wing model and the lightning current generator (i.e. outer circuit) needs to be minimized. To satisfy the requirements described above, the outer circuit was laid out around the full wing model. One end of the output terminal of the lightning current generator is connected to the fuselage side of the full wing model (hereinafter described as the wing root), and the other end is connected to the outer circuit. Lightning current can be injected to any location by connecting the intended location on the full wing model (lightning attachment location) with the outer circuit.

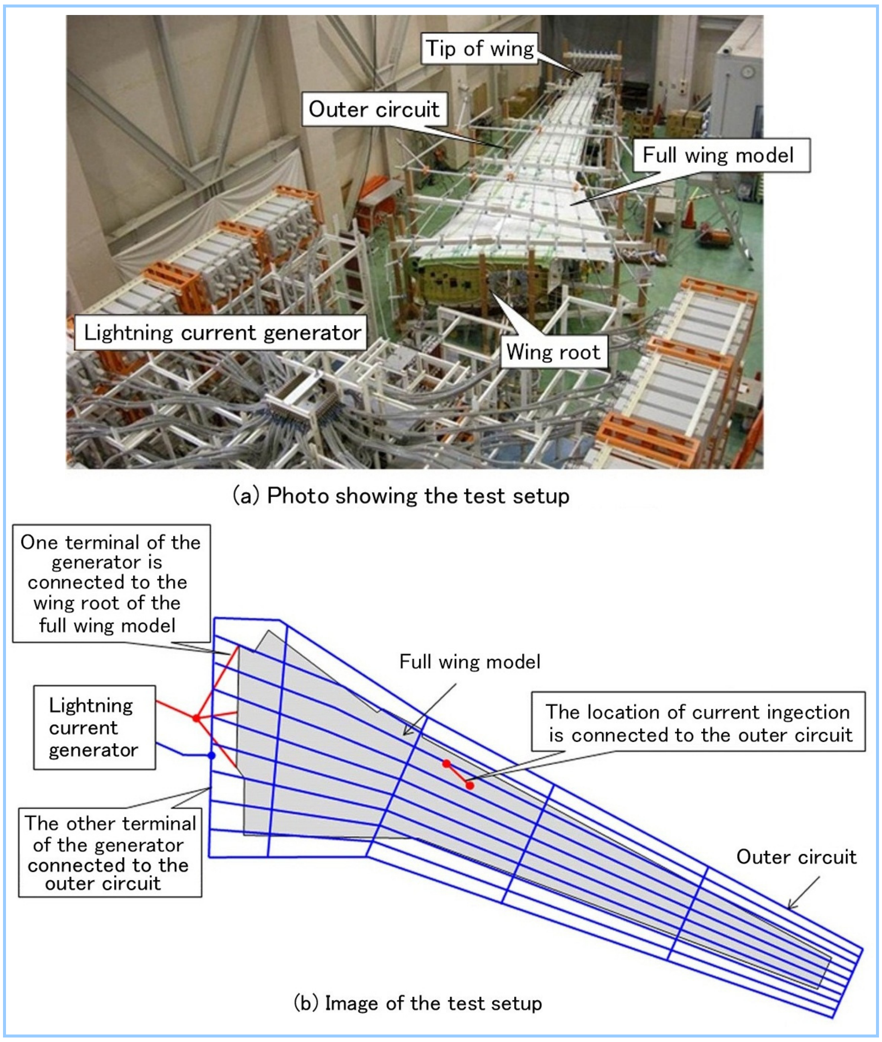

Figure 3 Overview of the test configuration

(2) Confirmation method of no sparks causing fuel ignition

To confirm that sparks causing fuel ignition are not generated when the aircraft is struck by lightning, up to 15 cameras were laid out all over the inside of the wing fuel tank (**Figure 4**). To be able to detect sparks causing fuel ignition by printed photos, the sensitivity of the cameras, including the aperture, image processing for photo data and printing method, were calibrated in advance according to the Lightning Test Standard[3, 4] for aircraft. The cameras were exposed for several seconds including the timing of lightning current injection by synchronizing with optical signals from the lightning current generator at just a few seconds before injection. The pictures will be absolutely dark if sparks are not generated, because external light does not intrude inside the wing fuel tanks. To conduct the tests safely and correctly by reducing the influence of high voltage and large current, a remote control system was constructed. By converting the USB signals from the cameras installed inside the wing fuel tank to optical signals, the system can perform many processes, such as communication, shutter operation, taking photos with illumination, etc., for multiple cameras simultaneously from the control room, which is electrically isolated from the cameras

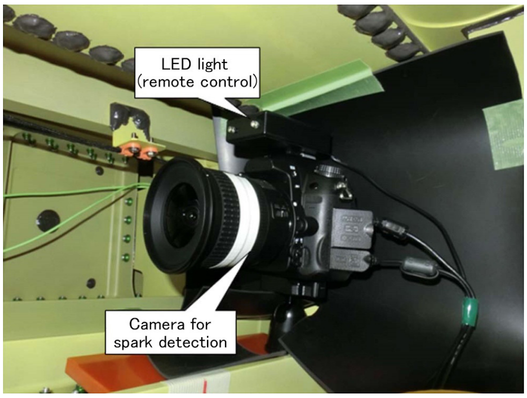

Figure 4 Example of camera layout for spark detection

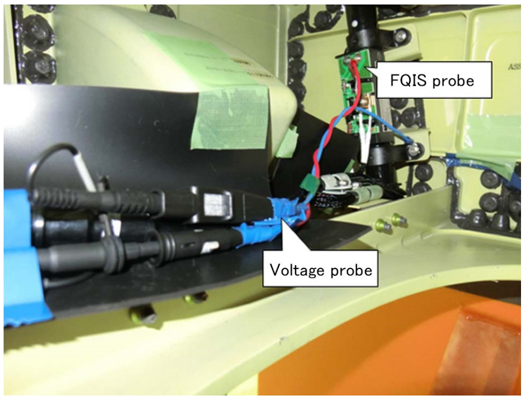

Figure 5 Example of voltage probe layout

(3) Measurement method of potential difference

An FQIS (Fuel Quantity Indicating System) probe was selected as the measurement point of potential difference in the tests. FQIS probes are sensors to measure fuel quantity. The signal cable connected to the FQIS probe installed near the wing tip is the longest signal cable in the wing fuel tank. Therefore, the potential difference between the FQIS probe and the wing structure near the probe must be the highest among FQIS probes in the wing fuel tank. To simulate the electrical conditions of the actual wing, one end of the cable connected to the FQIS probe was connected electrically to the main wing fuel tank structure at the wing root. The potential difference between the FQIS probe near the wing tip and the structural member of the main wing fuel tank near the probe was measured by a voltage probe (**Figure 5**). The voltage probe was connected to a battery-powered oscilloscope to prevent the influence of other measurement devices and ground potential. Similar to the remote control system for the cameras, a remote control system to perform the setting and data acquisition of the oscilloscopes was constructed by converting the LAN signals from the oscilloscopes to optical signals to electrically isolate the oscilloscopes from the control room.

(4) Measurement method of current

To measure the currents that flow into the wing fuel tank when lightning current is injected, optical fiber current sensors were wound around the joints. A shear tie, with which a skin and a rib are fastened by fasteners including the fastener struck by lightning (lightning strike fastener), was one of the measurement points (**Figure 6**). The optical fiber current sensor used in the tests utilizes the magneto-optical effect. The instrument[5] was developed for lightning tests jointly by MHI, Tokyo Electric Power Company and Showa Electronics, Co., Ltd. It can measure a current ranging from about 10 A to 100 kA and a DC frequency up to 1 MHz. The sensor uses optical signals for measurement and can be electrically isolated from the measuring object. Therefore, the sensor is not affected by the high-voltage and large current environment in the lightning tests, and can measure accurately. The output signals from the sensors are transmitted to the control room by optical fiber and are converted to electrical signals by the signal processor installed in the room for the acquisition of data by the oscilloscope.

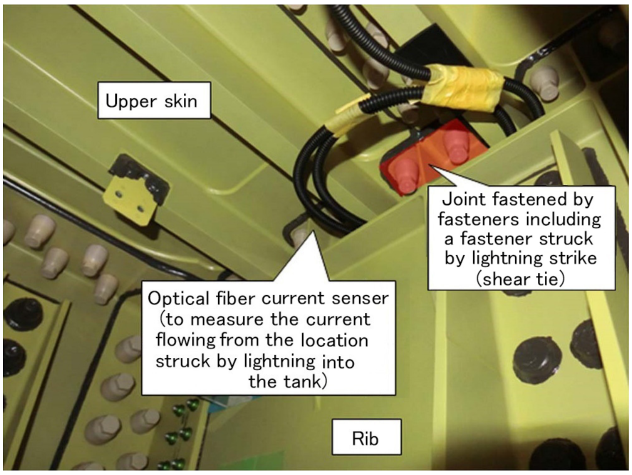

Figure 6 Example of optical fiber current sensor layout

3.2 Test conditions

In this test, lightning current was injected to nine locations by conduction*4 or arc entry*5 (**Table 1**, **Figure 7**). The locations were selected as the typical lightning attachment scenarios according to the scenarios specified by ARP5414.[6] An example of the sensor layout for testing is shown in **Figure 8**.

*4 To simulate the state of the lightning current flowing through a wing from a wing tip or an engine to a wing root when a wing tip or an engine is struck by lightning.

*5 To simulate the direct lightning attachment on a wing surface.

Table 1 Test conditions

Case	Location struck by lightning	Lightning strike zone	Current injection method	Current waveform of lightning
1	Wing Tip	Zone 3 (1A)*	Conduction	Comp. A (200kA) +B+C
2	Fastener 1 fastening upper skins	Zone 3	Arc entry	Comp. A/5 (40kA)+B+C*
3	Pylon	Zone 3 (1A)*	Conduction	Comp. A (200kA)+B+C
4-1	Fastener 2 fastening upper skins	Zone 2A	Arc entry	Comp. D (100kA)+B+C*
4-2	Joint of upper skins	Zone 2A	Arc entry	Comp. D (100kA)+B+C*
5	Fastener 3 fastening upper skins	Zone 2A	Arc entry	Comp. D (100kA)+B+C*
6	Main Landing Gear	Zone 3 (1A)*	Conduction	Comp. A (200kA)+B+C
7	Access Panel	Zone 2A	Arc entry	Comp. D (100kA)+B+C*
8	Fastener fastening lower skins	Zone 3	Arc entry	Comp. A/5 (40kA)+B+C*

* Although the Wing Tip, Pylon and Main Landing Gear are located in Zone 1A, current for Zone 3 was applied to portions where the Wing Tip, Pylon and Main Landing Gear are connected, because the full wing model does not have them.

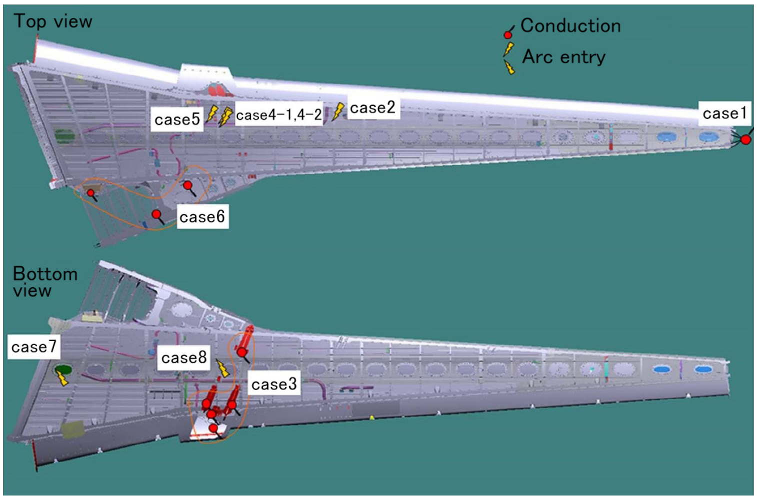

Figure 7 Locations struck by lightning

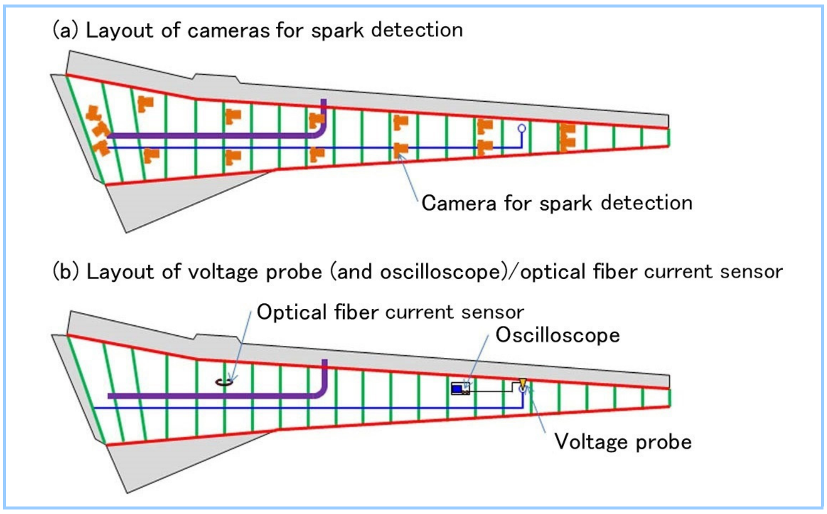

Figure 8 Example of the sensor layout inside the wing fuel tank

Two conditions – case 1 (conduction) and case 4-1 (arc entry) – are explained below as typical conditions.

Case 1 simulates a lightning strike on the wing tip, and the outer circuit is connected to the tip of the full wing model by cables. The lightning current generated by the lightning current generator is injected to the full wing model via the outer circuit, and the current flows through the full wing model to the wing root.

Case 4-1 simulates a direct strike on a fastener at the central portion of the wing. The fastener fastens the upper skins and the rib at the lapped portion of the skins. An arc entry electrode is installed keeping a small gap between the electrode and the fastener. The lightning current is injected from the outer circuit to the full wing model by arc discharge, which is the same phenomena as actual lightning[*6]. A photo of arc discharge at the lightning strike location, which was taken by using an ND filter in case 4-1, is shown in **Figure 9**.

*6 Current was injected according to the method specified by the Aircraft Lightning Test Method (ARP5416).

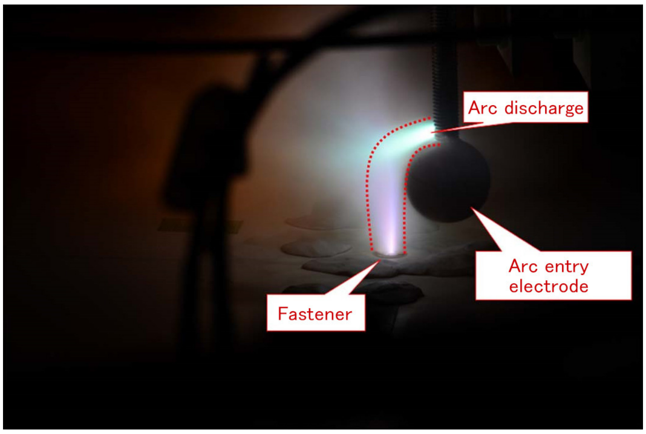

Figure 9 Arc discharge at the location of lightning current injection by arc entry in case 4-1

4. Test results

4.1 Results of confirmation of no sparks causing fuel ignition

Figure 10 (case 1) and **Figure 11** (case 4-1) are photos taken in the tests. The photos on the left in Figure 10 and 11 are background images, which were taken with the illumination on before the test, and the photos on the right were taken in tests by exposing for several seconds including the timing of lightning current injection. The red illumination in the photo on the right is the LED light set in photographing range to confirm that the camera was working normally. Because only the illumination of the LED light is seen in the photo on the right, it was confirmed that sparks causing fuel ignition were not generated. For all photos taken by all cameras in all test conditions, no spark generation was confirmed. Based on the results, it was demonstrated that sparks causing fuel ignition were not generated in the wing fuel tank for various lightning attachment scenarios.

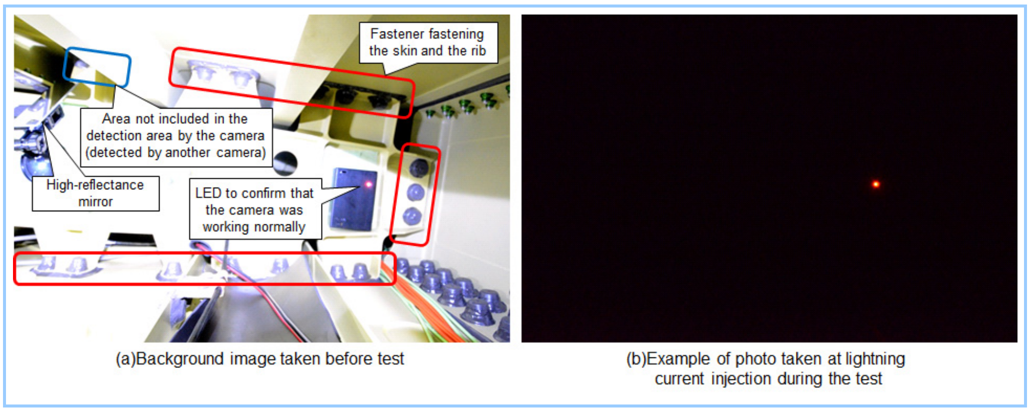

Figure 10　Example of photo by camera for spark detection in case 1

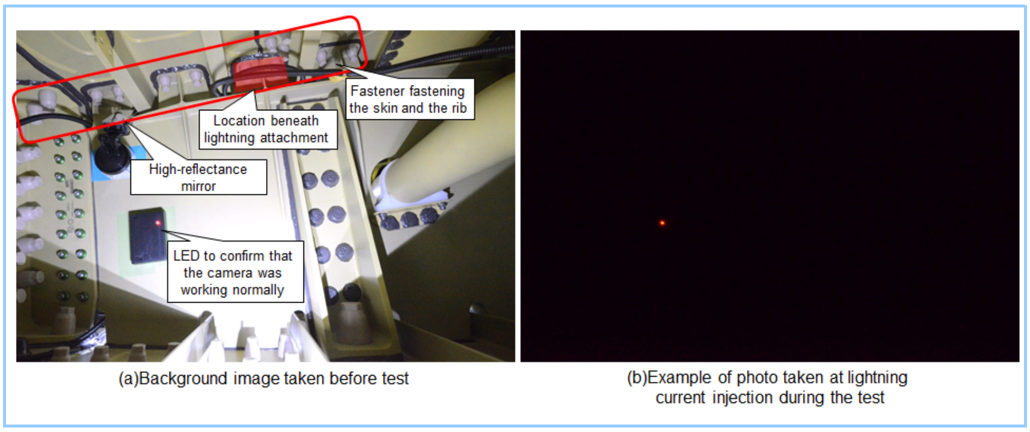

Figure 11　Example of photo by camera for spark detection in case 4-1

4.2　Measurement results of potential difference

The potential difference between the FQIS probe and the wing fuel tank structure was measured in case 1, using a voltage probe attached as shown in Figure 5. The measurement results are shown in **Figure 12**. In this graph, the horizontal axis is time (0 at the start of current injection) and the vertical axis is the potential difference between the FQIS probe and the wing fuel tank structure. For the vertical axis, negative values mean that the potential of FQIS is lower than that of the wing fuel tank structure, while positive values mean that the potential of FQIS is higher than that of the wing fuel tank structure. In Figure 12, the value is negative because the lightning current flows from the wing tip to the wing root in case 1 and one end of the FQIS probe is connected to the wing root, and the potential difference was low at 1 V at most.

If the potential difference is as high as several hundred volts, sparks causing fuel ignition might be generated by dielectric breakdown. However, it was confirmed that the potential difference was very small as shown by the test results, so there is no risk of fuel tank explosion.

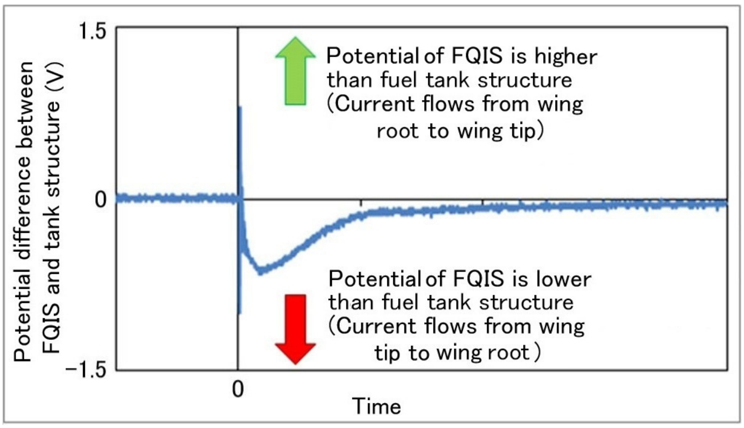

Figure 12　Results of potential difference measurement of FQIS

4.3 Measurement results of current

The current that flows into the wing fuel tank through a fastener which is struck by lightning in case 4-1 was measured. The current was measured by an optical fiber current sensor wound around the joint (shear tie) where the rib inside the wing fuel tank and the skin are fastened by the fastener as shown in Figure 6. The results of the measurement are shown in **Figure 13.**

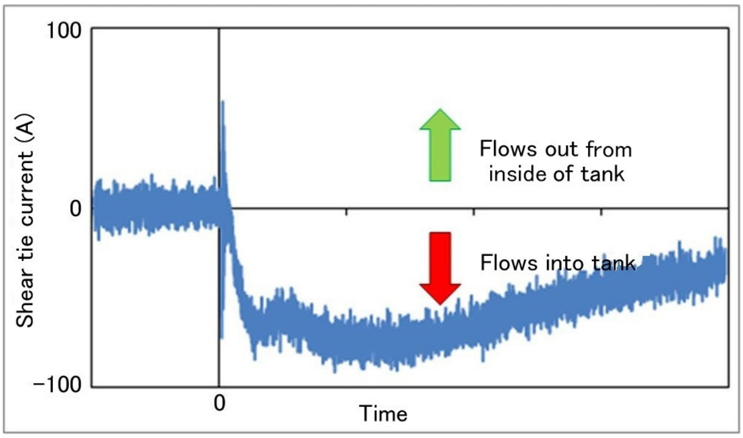

Figure 13 Measurement results of current flowing into the wing fuel tank

The horizontal axis is time (0 at the start of current injection) and the vertical axis is current flowing through the shear tie. For the vertical axis, a negative value means that the current flows into the wing fuel tank, and a positive value means that the current flows out from the inside of the wing fuel tank toward the skin. According to the results, the current flowing into the fuel tank in case 4-1 was up to 90A. In case 4-1, the peak value of injected lightning current is 100 kA, and the current flowing into the wing fuel tank is only about 0.1% of the current injected to the full wing model. Even including other arc entry conditions, the current flowing into the wing fuel tank was also less than 1% of the injected current. Based on the results, we confirmed that most of the lightning current flows on the surface and only a little current flows into the wing fuel tank.

5. Conclusion

To build further confidence in the safety of the MRJ, which is not yet in service, and to obtain data supporting the type certificate, lightning tests using the full wing model were conducted. The full wing model includes the majority of the MRJ wing structure and is manufactured by the same process as actual wing manufacturing. In the tests, lightning current (200kA max.) specified by ARP5412, which is one of the standards for aircraft lightning tests, is injected to locations where lightning may be attached. We obtained data to confirm the safety of the MRJ for the prevention of fuel tank explosion as follows: no sparks causing fuel ignition is generated in the wing fuel tank; the potential difference in the wing fuel tank is sufficiently low; and current flowing into the wing fuel tank is sufficiently small.

For the flight safety of the MRJ, we will utilize the knowledge obtained in the tests for activities toward type certification and the first delivery.

References

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