Development of Electromagnetic Simulation Supporting Lightning Protection Design of Mitsubishi Regional Jet

Courtesy of Mitsubishi Aircraft Corporation

KOJI SATAKE*1 SYUSAKU YAMAMOTO*2
HIDEO YAMAKOSHI*3 TATSUFUMI AOI*4
ATSUHIRO IYOMASA*5 KOICHI MURAKAMI*6

Explosion prevention proofing of wing fuel tanks against lightning strikes is one of the important safety verification aspects for the development of the next-generation Mitsubishi Regional Jet (MRJ). In order to comply with recently tightened standards, all fuel tank joints must be provided with fault tolerant lightning protection, and its validity must be demonstrated. However, the traditional approach based only on experience and testing could be a bottleneck to the development of the MRJ, as it requires a huge amount of work. Accordingly, Mitsubishi Heavy Industries Ltd. (MHI) developed an electromagnetic simulation technique that can predict the strike current distribution in each portion of a wing fuel tank accurately to support efficient and rational lightning protection design and the obtainment of type certification. This paper outlines the development of the electromagnetic simulation.

1. Introduction

MHI established Mitsubishi Aircraft Corporation for the MRJ project and has been promoting development toward the first flight in 2013 and the first delivery in 2015.

Passenger aircraft must be designed, manufactured and issued with type certification in accordance with Airworthiness Inspection Manual of Japan Civil Aviation Bureau (JCAB) for flight safety. Provisions related to type certification cover various aspects such as strength, structure, environment performance and safety, and the prevention of fuel tank explosions is included therein. As this provision has been tightened since the occurrence of a fuel tank explosion accident in the United States, it demands that the aircraft to be verified has no risk factors that could lead to a fuel tank explosion by assuming every possible situation.

One of the factors that should be considered is a spark produced by a large current flowing through the fuel tank when lightning strikes the aircraft. The fuel tank makes up the wing box consisting of the upper/lower skin and the front/rear spar of wing. The enclosed space composed of metal structures keeps the current from entering inside and provides a safe current route under normal conditions. However, considering failures such as damage or aging of joint components, the fuel tank must be provided with a fault tolerant lightning protection design, including enhancement of conductivity and spark containment at each joint in accordance with the magnitude of current at each joint location. At the same time, it is necessary to demonstrate that there is no possibility of ignition by means of tests. Since several tens of thousands of fasteners and bolts are used in the joints, resulting in hundreds of fastener type and failure combinations, there was concern that the traditional approach based on experience and the presumption of estimating the current route and magnitude would become a bottleneck in MRJ development, as it requires a huge amount of time for development and verification.

*1 Research Manager, Yokohama Research & Development Center, Technology & Innovation Headquarters
*2 Takasago Research & Development Center, Technology & Innovation Headquarters
*3 Research Manager, Advanced Technology Research Center, Technology & Innovation Headquarters
*4 Research Manager, Hiroshima Research & Development Center, Technology & Innovation Headquarters
*5 Advanced Technology Research Center, Technology & Innovation Headquarters
*6 Manager, System design department, Mitsubishi Aircraft Corporation

To solve this problem, MHI developed an electromagnetic simulation that can accurately predict the strike current distribution in each portion of a wing fuel tank and lead to efficient and rational lightning protection design and the obtainment of type certification. This technology was developed toward state of the art level with the support of; Lightning Technologies, an NTS Company, an authority on lightning protection for aircraft; U.S. Electro Magnetic Applications, Inc. (EMA), the developer of the analysis code; and Kazuo Yamamoto, an associate professor at Chubu University who has significant experience in lightning analysis.

The following sections describe the outline of the electromagnetic simulation.

2. Verification of Analytical Model using Wing Model

2.1 Analysis Method

Electromagnetic analysis for lightning strike simulation uses the Finite-Difference Time-Domain (FDTD) method[1], which is a direct solution of Maxell's equation. We selected EMA3D produced by EMA from several general-purpose electromagnetic simulation software packages that use the FDTD method, in consideration of the fact that it is commonly used for lightning strike simulation for aircraft and is recommended by Society of Automotive Engineers, Aerospace Recommended Practice 5415A (SAE ARP5415A)[2], one of international standards for land transportation and aerospace instruments.

2.2 Verification Purpose

Although EMA3D is proven software as described above, the various modeling methods must be validated for an analysis of current and voltage in the wing fuel tanks of the MRJ. We prepared a wing structure (a test specimen for verification (hereafter 'unit cell') simulating the metal structure including wing structure (Skin, Stringer, Spar, Rib, Leading Edge (LE), Trailing Edge (TE) and joint structure (fasteners and bolts)) that is composed of a fuel tank and also created a model of this specimen for analysis. The specimen was used to measure the current, voltage and magnetic field in the essential portion by applying the strike current specified by the test standards. By comparing the measurements and the results obtained by analysis, the validity of the modeling method was confirmed.

2.3 Test Specimen and Analytical Model

Figure 1 shows the overview of the unit cell without the skin on the upper wing surface. Three rib sections including Rib 7, 8 and 9 in the longitudinal direction of the wing are simulated, and a LE and a TE are provided as wing forward and rearward, respectively. The space separated by three ribs corresponds to the fuel tank space. After the unit cell was placed on a wooden frame one meter from the ground, a strike current was applied to the desired portion from the pulsed power supply through a cable while keeping ample distance to avoid electromagnetic induction to the unit cell. Aluminum plates were set to surround the unit cell so the current distribution would be symmetric in the design of the return circuit of the current. The surface magnetic field, current and voltage were measured as an electromagnetic field of each portion.

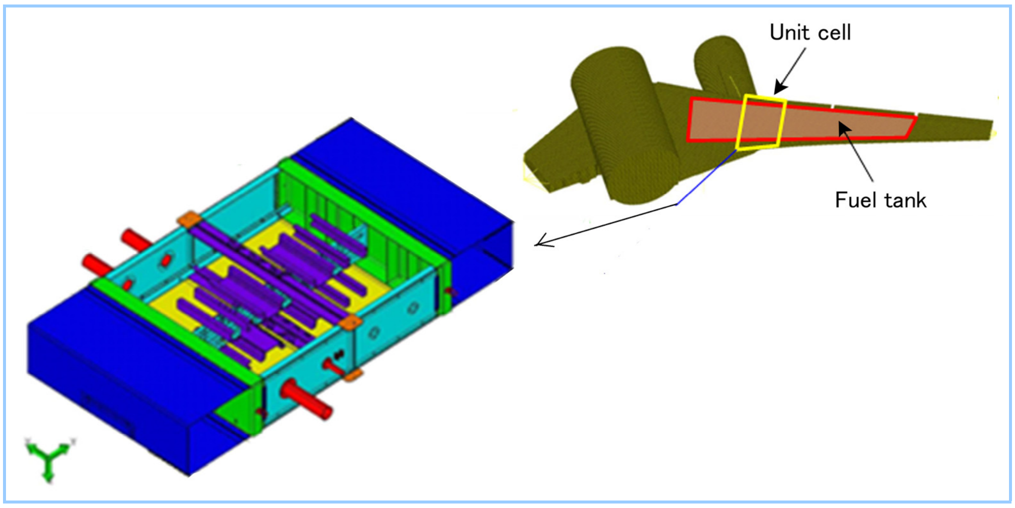

Figure 1 Unit cell overview

Figure 2 shows an example of the standard current waveform applied in the test. This waveform has the highest peak current of 200kA among the standard current waveforms with 6.4μs for time to peak and 69μs for time to half value. Since the application of 200kA current damages the unit cell and will require repair, various data are acquired at 3kA after confirming the linearity of current distribution from 3kA to 200kA. The linearity of the current distribution was confirmed by checking the current flow corresponding to the current applied to the unit cell in a step-by-step manner from 3kA to 200kA.

Figure 3 shows the analytical model. All structures that conduct current, such as the main body of the unit cell, the return circuit and the line for injecting strike current were modeled. The analytical space has been divided into a mesh to create cells of 19.5 mm in the X direction, 14 mm in the Y direction and 19 mm in the Z direction. It is preferable for the cell size to be as large as possible to the extent that the relevant phenomenon can be reproduced in terms of calculation time, because it determines the upper limit of time step Δt defined by the following Courant conditions.

$$\Delta t \leq \frac{1}{c\sqrt{\Delta x^{-2} + \Delta y^{-2} + \Delta z^{-2}}} \qquad (1)$$

The c in the above formula represents light speed.

It is assumed that the cell size affords the reproduction of a geometric configuration with the pitch of the fastener bolts included and without interference between each structure. The preferred cell size is less than roughly one-tenth of the wavelength in terms of calculation accuracy, and because the wavelength based on the current waveform shown in Figure 2 is several kilometers long, it is small enough for this wavelength.

On the other hand, for the part where the thickness is different from the actual structure in regard to the cell size, we modeled all of the structures to have no significant differences in impedance from the actual configuration while adjusting the electric conductivity to make the apparent electric conduction of the relevant structure equal to that of the actual structure. In addition, the inductance of structures such as Skin, Spar, and Rib that compose the unit cell depends on the width of the structure. Consequently modeling a structure of 1mm thickness to 20mm thickness produces an error of only a few percent. Therefore, it is believed that the scale of the cell size in the direction of thickness does not have a significant impact on inductance.

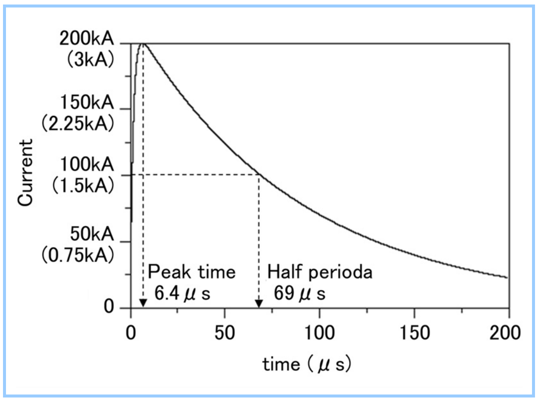

Figure 2 An example of strike current waveform
Items in parentheses indicate the current level used to acquire data in the test

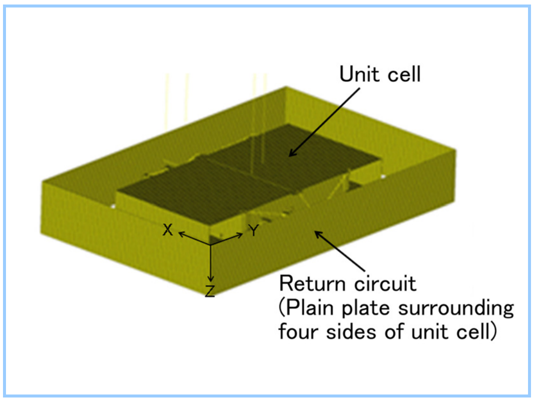

Figure 3 Analytical model

2.4 Comparison of Actual Measurement Results and Analysis Results

We tested dozens of cases assuming typical lightning strike points on an actual aircraft. **Figure 4** shows the time response of the surface magnetic field corresponding to the surface current distribution of the unit cell as an example. These surface magnetic fields describe the amount and direction of current flow at the structure surface points. This case assumes the passing of current flowing in the structure caused by a lightning strike. According to Figure 4, the peak value and time constant are almost perfectly the same between the experiment and the analysis.

Since the strike current spreads concentrically, the current at the P1 point has a greater -X directional component and thus the Hy component becomes a principal component for the surface magnetic field. The P2 point is the surface magnetic field of the TE side surface. As this point is largely affected by the current flowing on the LE surface or the return circuit, the Hz component becomes significant.

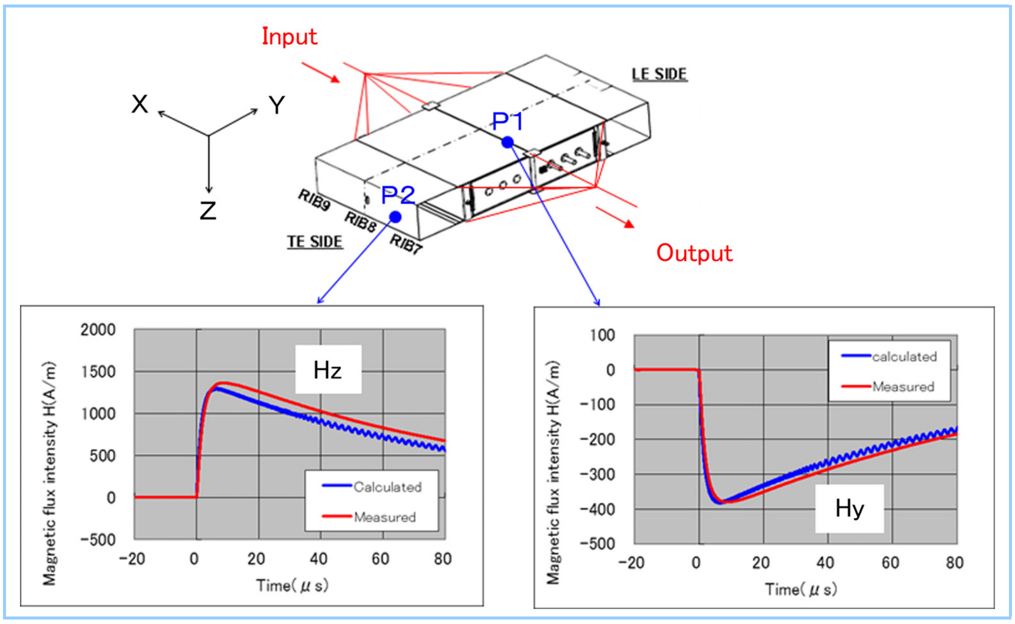

Figure 4 Analysis results of unit cell model (Comparison of actual measurements of external magnetic field)

Figure 5 shows the current waveform flowing on Rib 8 in the tank. The inside of the tank is a space surrounded by metal except for the joint sections. A current is observed because a slight electromagnetic field enters from the joints, but it is very small at less than 1% for the applied current of 3kA. The waveform seen in the beginning is believed to be noise.

The results of the analysis and measurement agree with each other, and the validity of the modeling was confirmed.

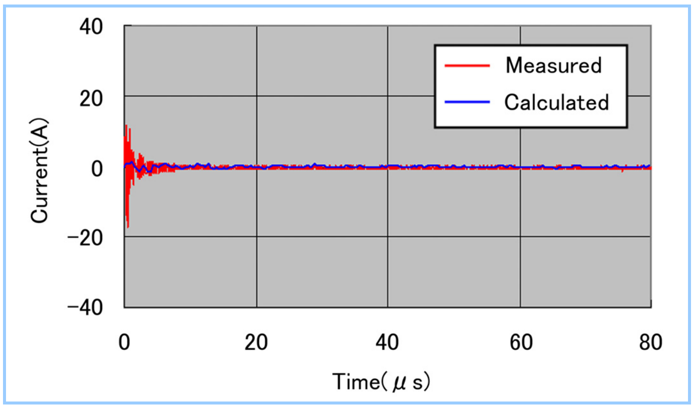

Figure 5 Current response waveform flowing around entire Rib 8

3. Application to Actual Wing

3.1 Model Overview

Figure 6 shows the analytical model. The actual wing model consists of the wing structure, right wing engine, engine pylon, main landing gear and fuel tubing inside the tank based on Computer Aided Design (CAD) data. The fuselage section model was created to cover the center wing beneath the fuselage, and the joints with the outer wing in the direction of the fuselage are included. The front and rear of the fuselage are covered with metal structures in order to prevent the invasion of electromagnetic fields. Because the right and left wings are in a symmetric structure, analyzing the lightning current distribution from the right wing to the center wing reveals the current distribution on the whole wing. Accordingly, the left wing was trimmed from Rib 4 for more efficient calculation on the condition that it does not have any effect on current distribution in the center wing (fuselage). Inner structures such as tubing are terminated at Rib 4. The exit of the strike current is provided by binding up conductor lines that are pulled out from three locations in the upper and lower sections of the end of Rib 4.

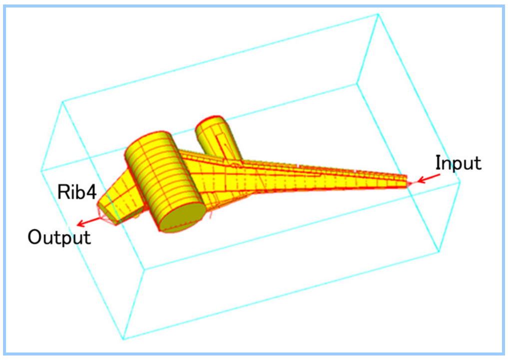

Figure 6 Analytical model

Table1 Conditions for actual scale wing model

Cell size	25mm isotropic cell
Calculation time step	4 x 10^{-11}s
Analytical space	Number of cells in X direction 480 Number of cells in Y direction 800 Number of cells in Z direction 300 Total number of cells 115,200,000
Boundary condition	Absorbing boundary condition: Mur first order
Electromagnetic source	Current source

As for the details of the leading and trailing edges, leading edge has a Fixed Leading Edge (FLE) and slat, and the trailing edge has a Fixed Trailing Edge (FTE), aileron, spoiler and Flap Track Support. The actuator and hinges needed to activate them are also modeled to enable accurate reproduction of the current distribution in the case of lighting strike at the control surface.

Table 1 shows the setting conditions of the analytical model. An isotropic cell of 25 mm was applied to model the aforementioned structure. Models of the fuel tubing, actuator, and part of supporting structure are simplified using line elements that have an equivalent resistance. As the model is on a large scale with about one hundred twenty million cells in total, it takes a significant amount of time for analysis, and promoting the efficiency of lightning protection design and the obtainment of type certification cannot be expected. Consequently, we attempted to shorten the calculation time by applying an approximate method that ignores displacement current and a parallel calculation method. The approximate method without the displacement current satisfies the formula of $\sigma >> \varepsilon\ \omega$ (σ: conductivity, ε: permittivity ω: angular frequency) and is applicable to relatively slow electromagnetic phenomenon.

The strike current waveform meets this condition since its frequency characteristic is generally lower than the 100 kHz order as shown in Figure 2 and is intended for conductive current. Applying this low-frequency approximation of Maxwell's equation made it possible to compress the time axis, resulting in shortened calculation times of 1/10 the original method.

In addition, the overall calculation time was shortened through the use of a parallel calculation method that calculates multiple areas at the same time by dividing the analytical space into multiple areas and assigning the calculation of each area to CPU.

By applying this method and with the use of parallel calculation using 32 CPUs (Intel Xeon 5500 2.93GHz, 8 cores/node, memory capacity 32 GB/node), the calculation could be done in about two days per condition.

3.2 Example of Analytical Results

Figure 7 shows a snapshot of the current density distribution at 4μs and 8μs. when the strike current is applied to the upper surface of the wing skin while setting the edge of the left wing as the current exit. The current spreads in concentric fashion from the lightning strike point, and a large current density area can be seen around the Auxiliary Spar on the trailing edge side because of the edge effect caused by the inductance component. This indicates that attention should be paid not only to the current route depending on the magnitude of resistance value, but also to the spreading of the current route caused by the edge effect.

Figure 8 shows the current waveform flowing in the rib in the tank. The current in the tank responds considerably slowly compared with the applied strike current waveform. The current in the tank is created by the electromagnetic field entering from the joints and is less than 1% of the applied current, the same as in the unit cell test.

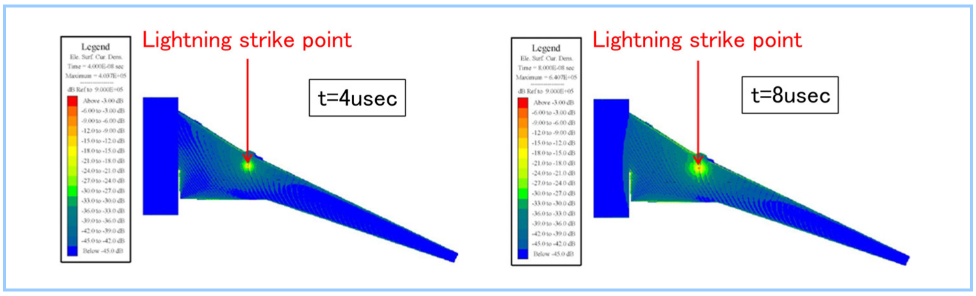

Figure 7　Current distribution at lightning strike on the upper surface skin of wing

Using the analytical model, each maximum current value assumed for all joints can be known by conducting large-scale simulation supposing various lightning conditions with different lightning strike locations and waveforms.

Knowledge pertaining to the current at the joints enabled us to standardize the multiple lightning protection design of fasteners in terms of the structure requirement and current level, and the efficient designing of proper lightning protection became possible. This also allowed us to classify the joint structures systematically and to select the test part and test current conditions based on the current value at the relevant joint in setting the test conditions for the obtainment of type certification. Accordingly, this allows us to reasonably verify the safety of all fuel tank joints without missing anything.

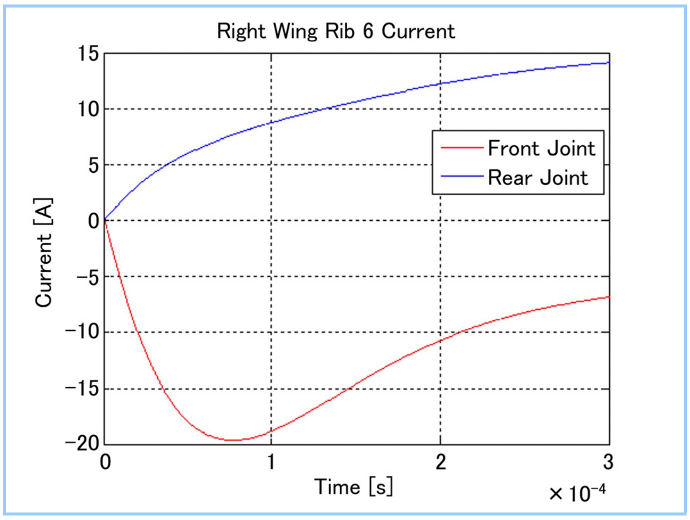

Figure 8　Current-time waveform flowing in ribs in tank
("Front Joint" and "Rear Joint" indicates the current flowing in the joints to Front Spar and Rear Spar, respectively)

4. Conclusion

This paper outlined a large-scale electromagnetic simulation to carry out lightning protection design and the obtainment of type certification to ensure the safety of aircraft.

This technique can be applied not only to metal structures, but also to other structures including composites by modeling the composite as anisotropic material. That means there is a possibility that this technique can be applied to the lightning protection design of next-generation aircraft. We are also planning to expand its application to such as electromagnetic interference to electrical equipment caused by lightning strikes and so on in the future.

References

1. Toru Uno, Finite difference time domain method for electromagnetic field and antenna analyses、Corona Publ. Co. Ltd (1998)
2. SAE ARP5415A User's Manual for Certification of Aircraft Electrical/Electronic Systems for Indirect Effects of Lightning, P152