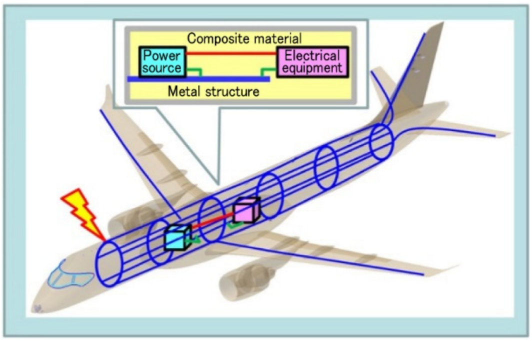
Development of Analytical Design Techniques for Ground Lines to Prevent Effects of Inflow of Current into Composite Structures on Power Sources



TATSUFUMI AOI[*1] HIROOMI MIYAHARA[*1]
AKIO IKEDA[*2] HISASHI SHIMIZU[*2]
KAZUKI YAMAWAKI[*2] YUKI MANDO[*2]

The development of products, in which carbon fiber-reinforced plastics with higher electrical resistivity than metals (hereafter referred to as "composite materials"), has been progressing in recent years. They used extensively and require the design of groundlines to reduce electromagnetic effects (current inflow, interference through groundlines between electrical devices) caused by disturbances such as lightning. Therefore, Mitsubishi Heavy Industries, Ltd. has developed an analytical evaluation technology to reduce the electromagnetic effects of groundlines in composite structures. The developed analytical evaluation technology for groundline structures divides the target frequency range into two and utilizes two complementary methods corresponding to them: quasi-static electromagnetic field analysis plus circuit analysis (low frequency range) and electromagnetic field analysis based on the FDTD (Finite Difference Time Domain) method (high frequency range). We performed the evaluation of the measures to secure current paths and against the effects of induced magnetic fields and the evaluation of the effects of interference between power sources sharing groundlines, and confirmed the validity of the analytical evaluation technology through test and analysis using a mock-up.

1. Introduction

Mobile products such as aircraft are becoming more electrically powered and have more sophisticated onboard electronic systems. To reduce the weight of such products, composite materials have been increasingly used in their structures. Since composite materials have a high resistivity (three orders of magnitude higher than metal), groundlines need to be installed in the structure as current returning paths. In such cases, analysis technology to evaluate electromagnetic characteristics is required to prevent lightning currents from affecting the operation of electrified and sophisticated on-board electronic system equipment. This time, we have developed an analytical evaluation technology for groundline structures that utilizes commercially available electromagnetic field analysis tools. This report describes on the results of the verification of the developed analytical evaluation method by testing and evaluating the effects of electromagnetic noise and lightning current inflow on the power source system using a mockup with simulated wiring installed.

2. Requirements and issues (background)

(1) Requirements for electrical systems and targets to be handled with design tools

Mobile products such as aircraft are equipped with systems to drive and control them, and the electrification of these systems has been progressing in response to initiatives such as the reduction of CO_2 emissions.

For the electrical equipment systems installed in such products, it is necessary to (i) reduce the weight, (ii) maintain and secure the quality of the power source, (iii) take electrical measures against the effects of lightning current inflow, (iv) take measures against the effects of

*1 Chief Staff Researcher, Electron・Physics Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.
*2 Electron・Physics Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.

ground fault currents, and (v) take measures against the effects of electromagnetic interferences and external electromagnetic fields (including induced lightning). This report discusses an analytical evaluation technology which is related to the requirements of (i), (ii), and (iii) above.

The standards related to (ii) maintaining and securing the quality of the power source include, in the case of aircraft, MIL-STD-704 (MIL standard for aircraft electrical power characteristics). Regarding the target frequency range, the operating frequency range of electrical equipment power sources is direct current (DC) to several hundred Hz, and the standard requirements range is DC and 10 Hz to 1 MHz. The standards related to the effects of (iii) lightning current and (iv) ground fault current include MIL-STD-464 (electromagnetic environment requirements for equipment systems) and MIL-STD-461 (lightning immunity test requirements at the equipment level). Considering the frequency components of lightning and ground fault currents, the target frequency range is several Hz to 1 MHz. Therefore, the target total frequency range is DC to 1 MHz.

In addition, in order to (i) reduce the weight, electrical systems of moving products may share current returning paths in the power lines, and it is necessary to be able to consider these requirements in actual system design.

(2) Issues

Conventional metal structures mainly use aluminum or titanium alloys, which have low resistivity (about $3x10^{-8}$ to $6x10^{-7}$ Ωm) for the structural frame, so the resistance and reactance are usually low, at levels of 1mΩ or less, resulting in a small voltage drop generated when current flows through them. Therefore, metal structures are often used as direct current return paths.

On the other hand, the resistivity of a composite structure is approximately 100 to 1,000 times larger, ranging from $1x10^{-5}$ to $3x10^{-5}$ Ωm, causing a large voltage drop when current flows through the structure. Therefore, there is a problem that using a composite structure as current return paths causes significant interference between power sources and is difficult to apply. For this reason, it is necessary to install metal-based groundlines on the structure as current return paths.

Therefore, composite structures and metal groundlines coexist in the system, i.e., multiple current paths with significantly different resistivities exist, which make it difficult to easily identify the current paths. To address this issue, it is necessary to perform the evaluation of (1) securing current paths against large current inflows, such as lightning, and of the effects of electromagnetic fields. In addition, multiple power sources are connected to one shared groundline, affecting the operation of one power source on another power source. To address this issue, it is necessary to (2) develop an analytical evaluation technology that takes into account the effects of interference between power sources sharing groundlines.

3. Analysis model

3.1 Analysis Method

It is necessary to simultaneously evaluate the current paths of currents at several Hz to 1 MHz, which correspond to the frequency characteristics of lightning currents, and the interference at DC to several hundred Hz, which correspond to the operating frequency of electrical equipment power sources. However, it is difficult to perform the evaluation accurately in a practical calculation time with a single analysis method, so we considered the complementary use of two methods: quasi-static electromagnetic field analysis plus circuit analysis (for low frequency range) and electromagnetic field analysis based on the FDTD method (for high frequency range). The low frequency range method was applied to the frequency range of (1) DC to 100 kHz and the high frequency range method was applied to the frequency range of (2) 100 kHz to 1 MHz.

(1) Low frequency analysis (DC to 100 kHz)

The quasi-static electromagnetic field analysis (electromagnetic field analysis method applicable where no displacement current flows with respect to time variation) analyzes electromagnetic fields using the finite element method or the moment method. Based on the analysis results obtained, electrical circuit parameters (R: resistance, L: inductance, C: capacitance, G: conductance) between the components are output as S-parameters, and the current and voltage are calculated by circuit analysis. We used Ansys Q3D Extractor, a commercially available analysis tool.

(2) High frequency analysis (100 kHz to 1 MHz)

Electromagnetic fields are analyzed using the FDTD method. The voltage and current of the target section are output directly from the integral calculation using the outputs of the electric and magnetic fields. We used Ansys EMC Plus, a commercially available analysis tool.

3.2 Verification items

For the issues described in chapter 2, we performed the following verifications. For (1) securing current paths and the effects on electromagnetic fields, we evaluated the current distribution through the structure containing composite materials when lightning current flows into the structure. For (2) the effects of interference between power sources sharing groundlines, we set up two power source systems that share groundlines and supply power to the power source on one side (disturbing side) to evaluate the voltage and current generated at the terminal of the other side (disturbed side).

3.3 Test specimen and test Setup

(1) Test specimen

Figure 1 shows an overall view of the test specimen, which is composed of composite, resin, and metal elements. While the target mobile products such as aircraft and transportation systems have structures in the size of several tens of meters, the test specimen was fabricated at approximately 1/10 scale. The frequency band is up to 1 MHz (300m wavelength), and the effects of standing waves are negligible for both the actual object and the test specimen, so this dimension was determined to be not particularly problematic. In addition, two power lines sharing groundlines were installed in the test specimen. **Figure 2** shows section A-A of the test specimen. The test specimen is a three-dimensional structure with a hexagonal cross-section. The frame is made of resin, and an aluminum panel is attached to the bottom. The evaluation was conducted in the case where only composite panels were installed on the surface and in the case where composite panels with a Cu mesh for lightning protection were installed. The panels were electrically connected to each other using groundlines composed of a metal conductor cable with a conductor cross-sectional area of 50 mm^2.

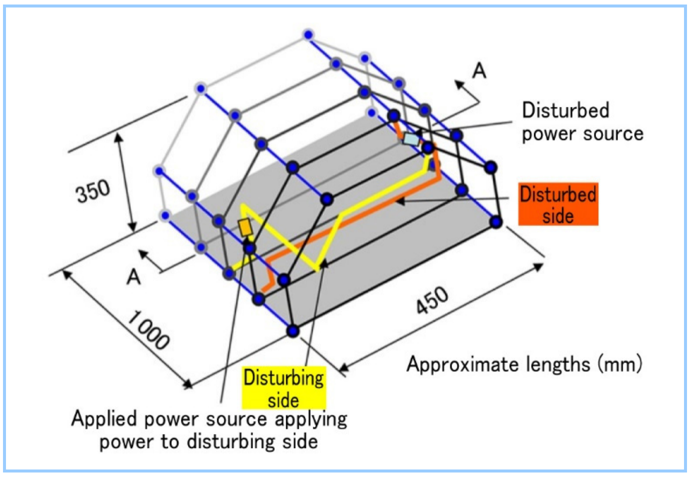


Figure 1 Overall view of test specimen

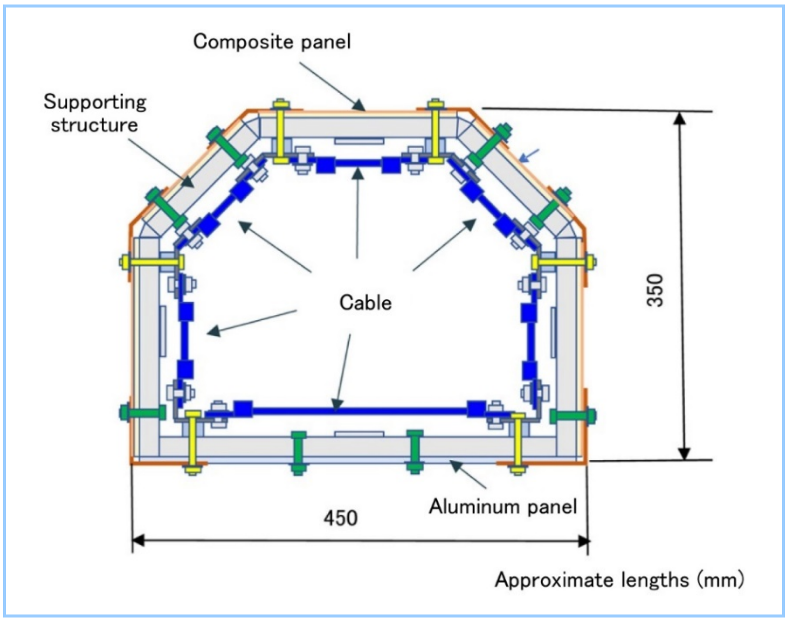


Figure 2 Test specimen (section A-A)

(2) Test setup and test conditions

Figure 3 illustrates the current application test setup and shows the test status. We applied current from the power source to the test specimen and performed evaluation. For the evaluation of frequency characteristics, a single frequency current (0.1Hz to a maximum of 1 MHz) was applied. In addition, for the evaluation related to lightning current waveforms, a simulated lightning current waveform (Component A: 1kA peak) based on the test standards used in the aircraft field [(1)] was applied to evaluate the transient characteristics. In consideration of design applicability, five cases were tested with different cable types (50mm^2 cable, 15mm-wide copper braided cable), with and without Cu mesh, and with different combinations of current draw in/out (single point/equalized, equalized/equalized, etc.) **Figure 4** shows an example of the applied waveform used in the test.

As the evaluation of the effects of interference between power sources sharing groundlines, we supplied power to one power source (disturbing side) of the two power lines sharing groundlines in the test specimen and evaluated the voltage and current generated at the terminal of the power source on the other side (disturbed side) (Figure 1).

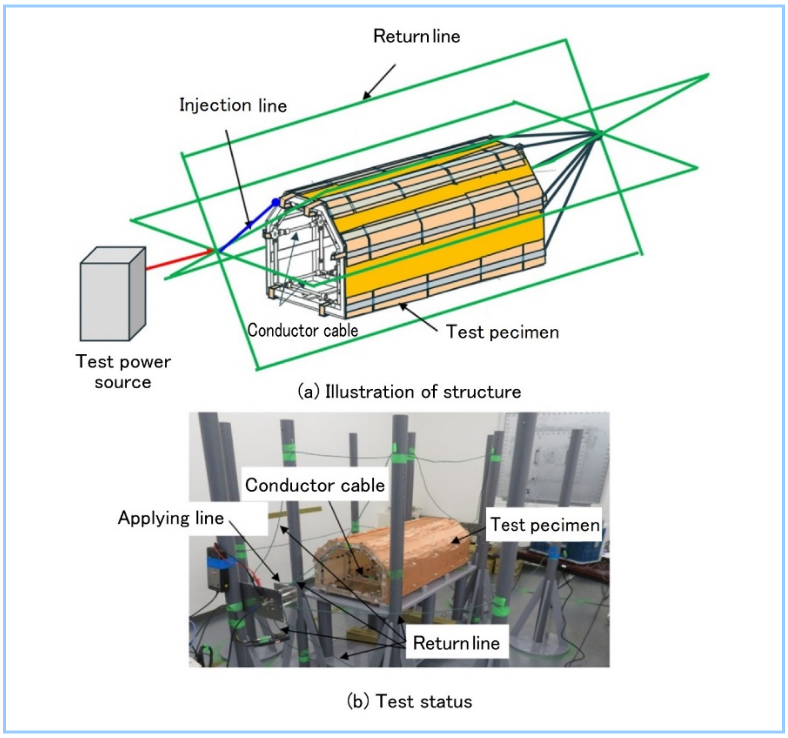


Figure 3 Test set up

	Standard waveform	Test waveform
Peak time	6.4μs	6.0μs
Half peak time	69μs	79μs

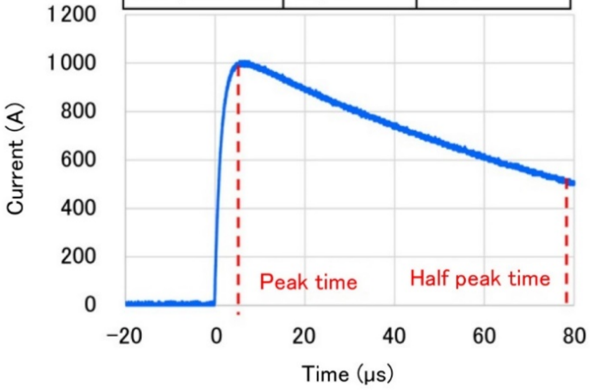


Figure 4 Example of simulated lightning current waveform

3.4 Analysis model

(1) Ansys Q3D Extractor model

Figure 5 shows the model. Cable diameters and fittings were modeled according to the dimensions of the test specimen. For the resistance values of components and contact resistance points, the values measured with DC were used and reflected in the conductivity of the model elements in the relevant areas. We evaluated the frequency characteristics of the impedance between two points by analysis and compared them with the measured results to confirm the validity of the model. The analysis was performed at frequencies of 0.1Hz, 10kHz, and 1MHz.

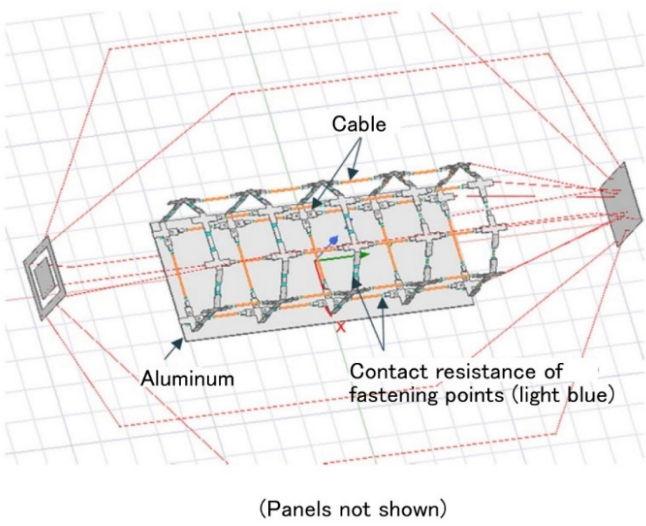


Figure 5 Analysis model (Ansys Q3D)

(2) Ansys EMC Plus model

Figure 6 shows the model. The bottom panel and copper mesh were modeled with plane elements, while the rest were modeled with line elements. The conductivities of the elements and contact resistance points were converted from measured values, taking into account a mesh size of 20mm. The branch currents flowing through each element of the metallic conductor cables were output. The frequency characteristics at only high frequency (100kHz, 1MHz) conditions were analyzed and evaluated because analysis in the low frequency range with the FDTD method requires a longer time.

The encircled numbers 1 to 6 in Figure 6 show the longitudinal conductors, while number 7 shows the internal first-row conductor placed longitudinally to the direction of current application. The results of the analytical evaluation of the current flowing through these conductors are described later in chapter 4.

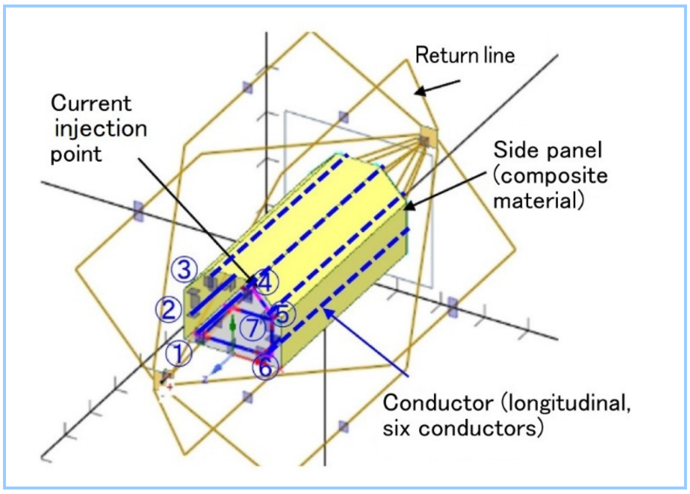


Figure 6 Analysis model (Ansys EMC Plus)

4. Verification result

4.1 Evaluation of measures to secure current paths and against effects of induced magnetic fields

Figure 7 to **Figure 9** show the evaluation results of the analysis accuracy with respect to the measured current distribution values through the structure when currents of 0.1Hz, 10kHz, and 1MHz frequency components flowed into the test specimen. As a result of the evaluation in five cases where the tests described in chapter 3 were conducted, the analysis error was almost within a ±6dB range. Safety-critical equipment on aircraft is often given a design margin of 6dB or more [(2)]. Hence, it was confirmed that the analytical evaluation could be made with sufficient accuracy allowing the consideration of excessive design margins to be avoided. In addition, in terms of frequency characteristics, the accuracy of Ansys Q3D Extractor was worse than that of Ansys EMC Plus at 1MHz as shown in Figure 9. Therefore, it was confirmed that evaluation with an accuracy of within about a ±6dB range is made possible by using Ansys Q3D Extractor in the low frequency range and Ansys EMC Plus in the high frequency range when applying the analytical design method.

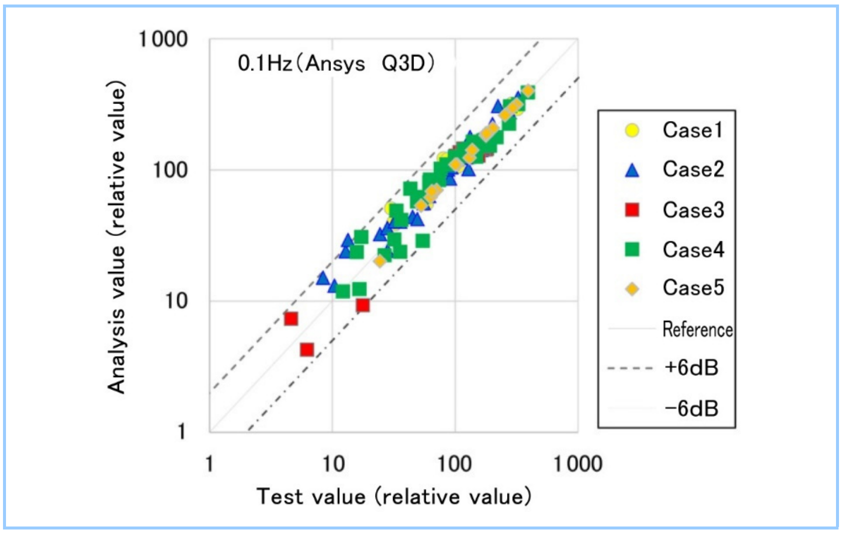


Figure 7 Evaluation result of single frequency characteristics (0.1Hz)

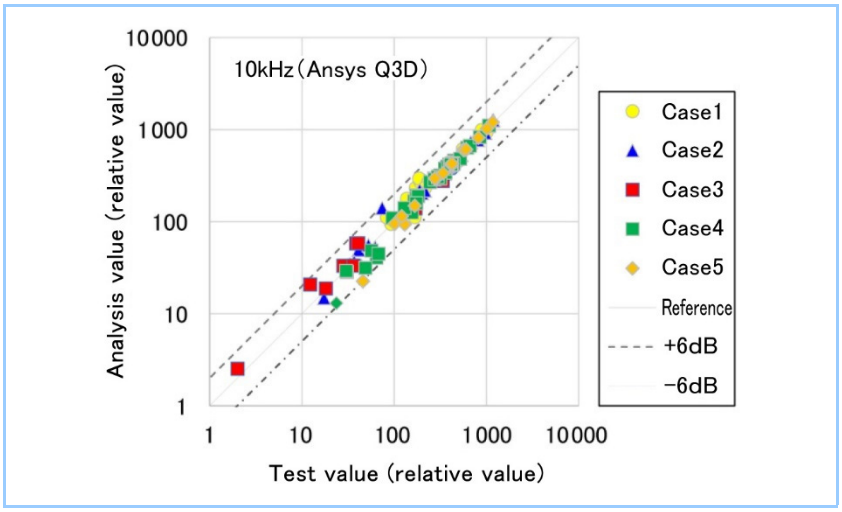


Figure 8 Evaluation result of single frequency characteristics (10kHz)

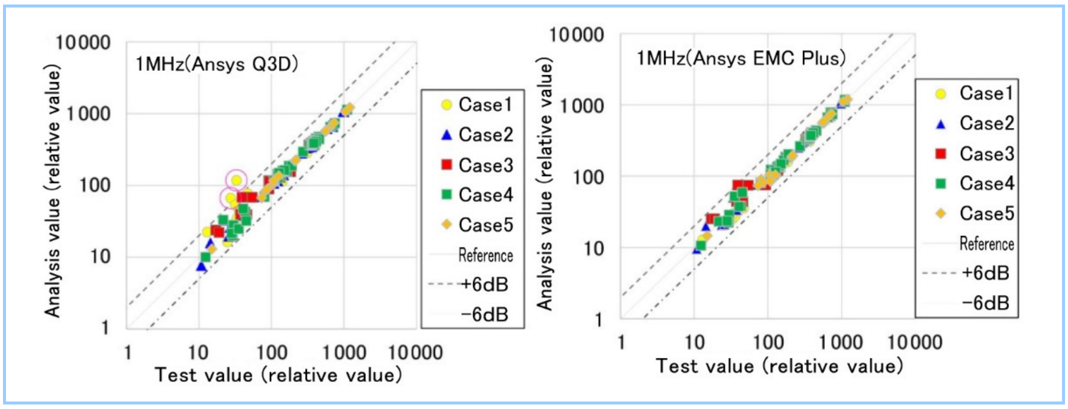


Figure 9 Evaluation result of single frequency characteristics (1MHz)

The obtained analysis accuracy resulted from improvements made by taking into account the variation of contact resistance and the refinement in modeling of form-dependent inductance. **Figure 10** shows the analysis results of the frequency characteristics of current flowing through conductor encircled number 7 (Figure 6) constituting the groundline for the case where the contact resistance is given uniformly and for the case where the resistance variation is considered by giving the measured resistance value of each structural element, which indicates an improvement in the analysis accuracy. Current values closer to the measured values were obtained by considering the resistance variation. This variation in resistance is mainly due to the variation in contact resistance at the points where the cable conductor is connected. The metal cables in this test specimen are arranged at intervals of about 25cm. When they are designed in the actual product structure size (meters order), the resistance of the structure itself is larger than that in this test. So, the effect of resistance variation is relatively small. Thus, it is expected that the effect observed in this test verification would be small.

Next, **Figure 11** compares the test results of current distribution measurements obtained by applying the simulated lightning current (Component A: 1kA peak) shown in Figure 4 to the test specimen with the results of analysis using Ansys EMC Plus, which can handle the high frequency of lightning as confirmed in the previous section. The waveforms matched well, verifying the applicability of the analytical model to the design, not only in terms of frequency response but also in terms of transient characteristics. Therefore, the current paths can now be identified by this analysis.

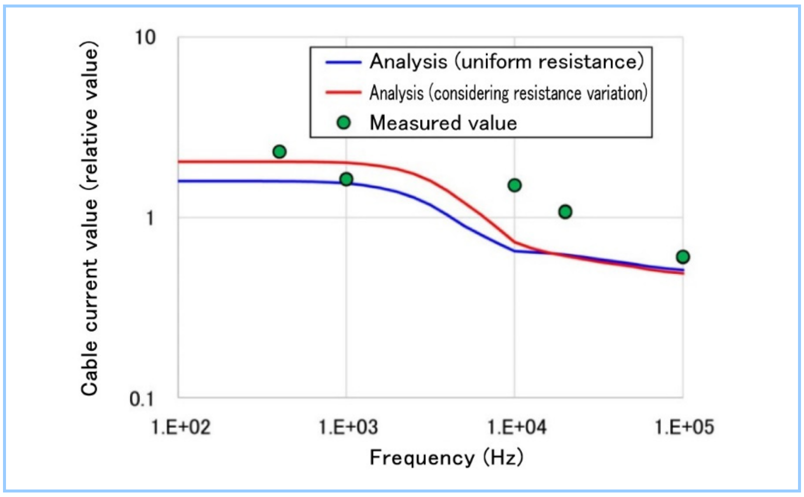


Figure 10 Improvement in analysis accuracy (effects of resistance)

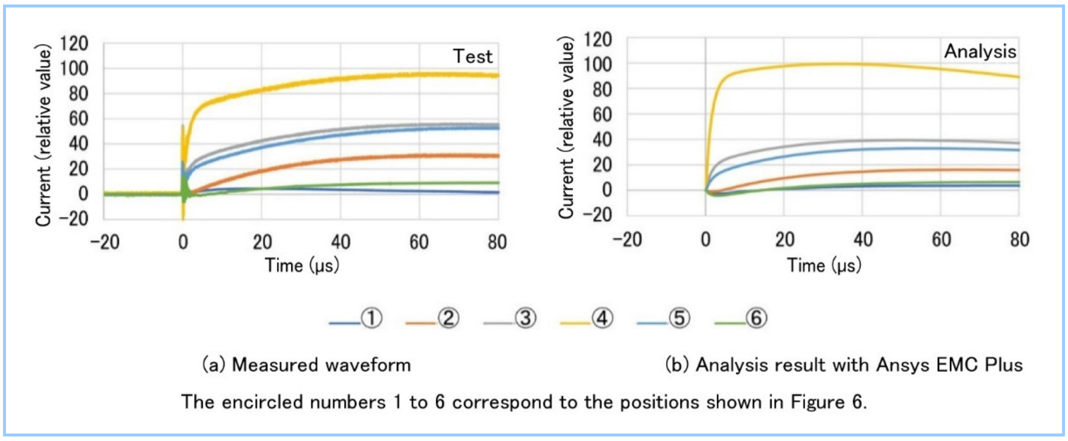


Figure 11 Evaluation result of applying simulated lightning current

4.2 Evaluation of effects of interference between power sources sharing groundlines

In terms of the effects of interference between power sources sharing groundlines, **Figure 12** shows the test and Ansys Q3D Extractor analysis results of the current and voltage values generated in the disturbed side when a sine wave of 50Vpp is applied to the disturbing-side system, with respect to the frequency. The voltage and current increased from the frequency of approximately 10kHz, indicating the effects of interference between power sources. Nevertheless, the test and analysis values showed very good agreement, with the analysis accuracy for the current value of 3.7dB or smaller and the voltage value of 2.4dB or smaller. Although the test verification was conducted in the frequency range of 0.1Hz to 1MHz, there was almost no change in the characteristics below 1kHz, and it is expected that this can be extended to DC. Therefore, the validity of the analytical model for the evaluation of the effects of interference between power sources was confirmed in the frequency range from DC to 1MHz.

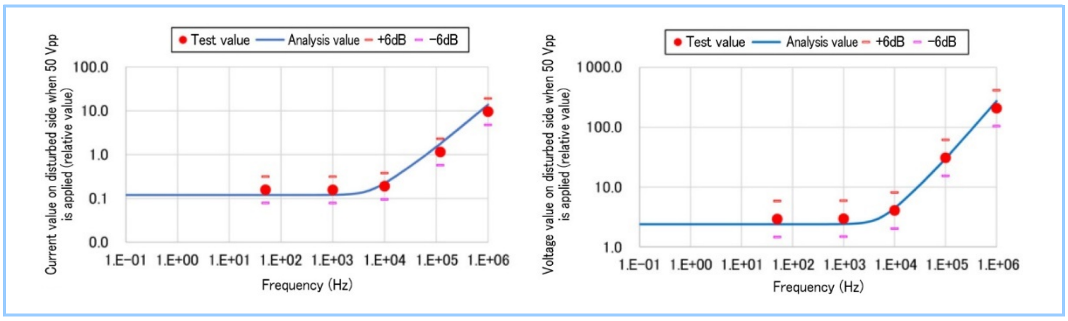


Figure 12 Evaluation results of power system noise effect and voltage drop

5. Conclusion

In order to prevent lightning currents from affecting the operation of onboard electronic system equipment that has been increasingly electrified and sophisticated, analysis technology to evaluate electromagnetic characteristics is needed for mobile products such as aircraft, in which composite materials with high electrical resistance have been increasingly used. We have developed an analytical evaluation technology for groundline structures by utilizing two complementary methods: quasi-static electromagnetic field analysis plus circuit analysis (for low frequency range) and electromagnetic field analysis based on the finite difference time domain method (for high frequency range). We verified the analysis and evaluation technology by conducting the evaluation of the measures to secure current paths and against the effects of induced magnetic fields and the evaluation test of the effects of interference between power sources sharing groundlines using a mock-up. Now, the design of groundlines through analysis is possible, leading to a reduction in the number of prototypes and elemental tests, which is expected to improve the efficiency of the design of electromagnetic field countermeasures.

Moving forward, we plan to apply this technology to product design and establish an analytical design technology for comprehensive effects of electromagnetic fields on composite structures.

References

(1) SAE ARP5412, Aircraft Lightning Environment and Related Test Waveforms
(2) MIL-STD-464, ELECTROMAGNETIC ENVIRONMENTAL EFFECTS REQUIREMENTS FOR SYSTEM