# Calculation and Measurement Methods for RCS of a Scale Model Airplane

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***Abstract*—The radar cross section (RCS) of an airplane is very important subject in a military use. As for a RCS estimation object, a scale down model is often employed for the ease of measurements. Recently, electromagnetic simulations of RCS become very convenient because of developments of high speed calculation methods such as MLFMM and HOBF in electromagnetic simulators employing MoM algorithm. As for measurements, high resolution measurements by time domain analysis are employed. In this paper, important characteristics with a scale model are briefly explained. As for calculation, comparisons between actual calculation abilities of MoM, MLFMM and HOBF are made at 18 GHz for 1/48 scale model. As for measurement, a high resolution measurement system employing a compact range and time domain analysis that is used in this study is explained. Next, calculated and measured results are compared in order to show the accuracies of obtained results. Moreover, the effective calculation method in increasing frequency is also investigated in order to estimate the actual RCS value.**

***Keywords*—radar cross section, method of moment, compact range measurement**

## I. INTRODUCTION

In stealth designs of military airplanes, estimations and reductions of radar cross sections (RCS) become very important. Many researches on estimating mono-static RCS are reported by employing scale models [1], [2]. As for calculations, high performance algorithms in method of moment (MoM) such as multilevel fast multipole method (MLFMM) [3] and higher order basis functions (HOBF) are utilized [4]. However, calculation abilities are not sufficient in order to estimate real airplane at X-band by a personal computer. As for measurements, a high resolution measurement is achieved by utilizing time domain analysis of a vector network analyzer.

In this paper, firstly overview electrical performances of a scale model. Next, calculation abilities of MoM, MLFMM and HOBF of FEKO simulator [5] are investigated thorough obtaining calculated data of a personal computer for a 1/48 scale model at 18 GHz. As for measurement, brief explanations of our measurement system employing a compact range and vector network analyzer. Then, measured and calculated data are compared to understand the accuracies of achieved results. Moreover, some trials to increase estimation frequency are conducted.

## II. ELECTRICAL CHARACTERISTICS OF A SCALE MODEL

A configuration of a scale model for calculation is shown in Fig. 1. When the size of an object is reduced to $1/\alpha$, according to miniaturizations of mesh sizes to $1/\alpha$, the estimation frequency should be increased α times. Then, the angular responses of RCS results become the same between a real object and a scale model. However, the RCS value ($\sigma$) itself is reduced to $1/\alpha^2$.

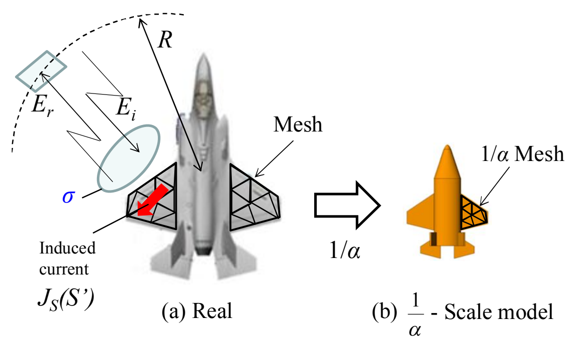


Fig. 1. Scale model configuration.

In order to realize above mentioned RCS ($\sigma$) characteristics, $\sigma$ is explained through equations. $\sigma$ is defined by the next expression in Fig.1 (a) case.

$$\sigma = 4\pi R^2 \frac{|E_r|^2}{|E_i|^2} \tag{1}$$

And the reflected electric field ($E_r$) is given by the next equation.

$$E_r = \frac{-j\omega\mu e^{-jkR}}{4\pi R} \iint_s J_S(S') e^{jkr'} ds' = \frac{-jk\eta}{4\pi R} e^{-jkR} \iint_s J_S(S') e^{jkr'} ds' \tag{2}$$

Then, $\sigma$ of Eq. (1) is expressed by the next equation.

$$\sigma = \frac{k^2\eta^2}{4\pi} \frac{\left|\iint_s J_S(S') e^{jkr'} ds'\right|^2}{|E_i|^2} \tag{3}$$

Here, $J_s$ is related with $E_i$ in the next expression.

$$J_S = 2H_i = 2E_i/\eta \tag{4}$$

Then, the integral part becomes $(E_iS)^2$ in the case of a flat plate having the area $S$. Therefore, for the flat plate, $\sigma$ is given by the next expression.

$$\sigma = \frac{4\pi S^2}{\lambda^2} \tag{5}$$

In the case of scale model of having a scale factor $1/\alpha$, $\lambda$' becomes $\lambda/\alpha$ and $S$' becomes $S/\alpha^2$. When these values are inserted in Eq. (5), RCS value ($\sigma$') of a scale model is obtained.

$$\sigma' = \frac{4\pi S'^2}{\lambda'^2} = \frac{4\pi S^2}{\lambda^2}\frac{1}{\alpha^2} \tag{6}$$

## III. Calculation Method

### A. Structure of a Calculation Model

The calculation structure is shown in Fig. 2. This structure is a simplified model of a jet fighter. The intake of a jet engine and canopy are eliminated. Wings and tail part are composed of flat plates for fabrication ease. The scale down ratio is 1/48. The length of a model becomes 310 mm. This size is very convenient to handle. And, all surfaces are perfect conductors.

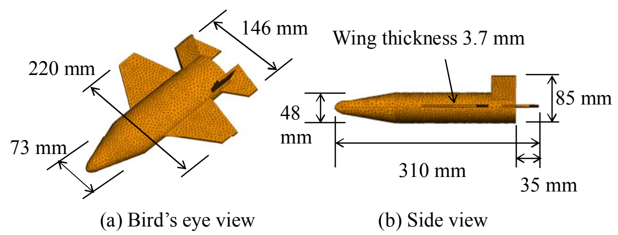


Fig. 2. Structure of 1/48 scale model.

### B. Requested Computer Resources

Mono-static RCS calculations are performed at 18 GHz by MoM, MLFMM and HOBF algorithms of a FEKO simulator [5]. In Table 1, requested computer resources are shown. Here, it is ensured that calculated results of these three algorithms become the same. In the case of MLFMM, small mesh size of 0.1 wavelengths is needed. Memory size is 5.4 GB. Calculation time becomes approximately 5.6 hours.

TABLE I. Requested Computer Resources

| Algorithm | Mesh size | Mesh number | Unknown number | Memory amount | Calculation time |
|---|---|---|---|---|---|
| MoM | 0.1 $\lambda$ | 83,160 | 124,740 | 116.336 GB | 282,293 seconds (78 hours) |
| MLFMM | 0.1 $\lambda$ | 83,160 | 124,740 | 5.430 GB | 19,999 seconds (5.6 hours) |
| HOBF | $\lambda$ | 790 | 14,207 | 1.527 GB | 4,168 seconds (1.2 hours) |

In the case of HOBF, large mesh size of one wavelength can be allowed. Hence, calculation memory is reduced to 1/3 and calculation time is reduced to 1/5 compared to the MLFMM.

## IV. Measurement Method

### A. Measurement Setup

RCS measurement configuration is shown in Fig. 3. A compact range configuration by an off-set parabolic reflector is used. A vector network analyzer (VNA) is used for transmission and reception of radio waves. In transmission, the frequency is swept from 12 GHz to 19 GHz. In reception, at each rotated angle $\theta_i$ ($i$ = 1, 2, ⋯), RCS levels of swept frequency are obtained. And, the swept frequency intensities are converted to time domain signals by the Fourier transformation function. The resultant time domain signals are shown in Fig. 4. Here, the 3 dB time spread is denoted by $\Delta\tau$. The frequency sweep range is expressed by $\Delta f$. The relation of $\Delta\tau$ and $\Delta f$ is given by the next expression.

$$\Delta\tau = \frac{1}{\Delta f} \tag{7}$$

In the measurement, $\Delta f$ becomes 7 GHz. Then, $\Delta\tau$ becomes 0.14 ns. And, time period of 0.14 ns corresponds to wave propagation distance of 4.2 cm. Therefore, by selecting the target signal with time gate function, influences of all surrounding reflected waves are deleted. As a result, high resolution measurement is achieved.

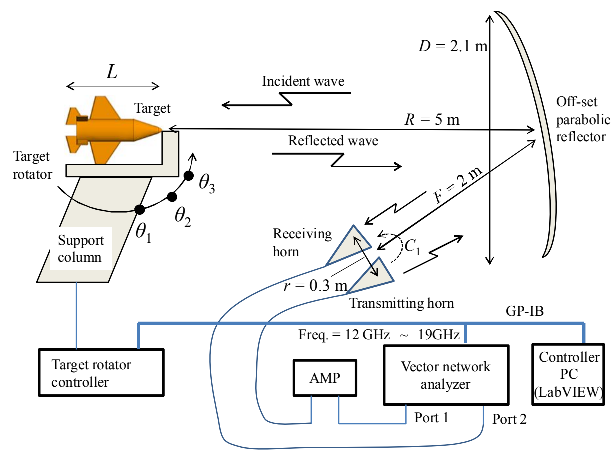


Fig. 3. Experimental setup.

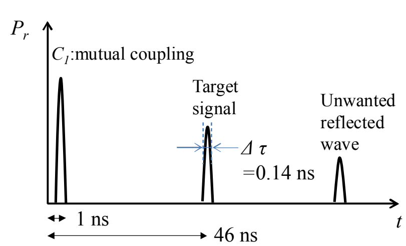


Fig. 4. Generation of time domain waveform.

## *B. Calculated and Measured Results*

Comparisons of calculated and measured RCS results at 18 GHz are shown in Figs. 5 and 6 for vertical and horizontal planes, respectively. Here, HOBF algorithm is used to obtain calculated results. In Fig. 5, measured and calculated results agree very well from high value to small value of −40 dBsm. At the top direction (0 deg.), measured result becomes too small. The reason is insufficient alignment of the measured model setting. In Fig. 6, measured and calculated results agree very well from -4 dBsm to −40 dBsm. As a result, high resolution and reliable results are achieved in this measurement.

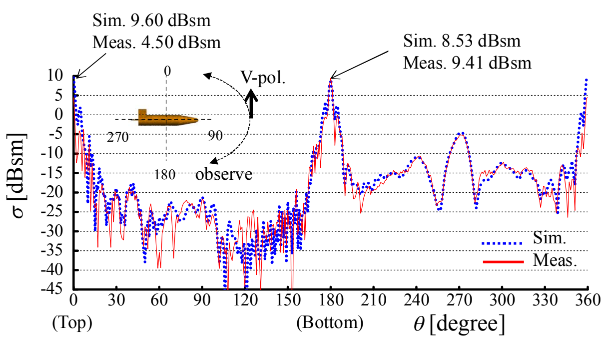


Fig. 5. Monostatic RCS (vertical plane) of Simulation versus Measurement.

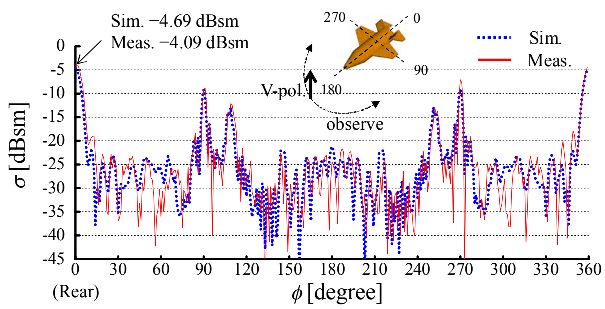


Fig. 6. Monostatic RCS (horizontal plane) of Simulation versus Measurement.

## V. INCREASING OF CALCULATION FREQUENCY

## *A. Calculation Abilities at 70 GHz*

RCS values at higher frequencies are requested in order to estimate actual RCS values. So, the exact method of HOBF and the most simple method of GO (geometrical optics) are investigated at 70 GHz. In Table 2, calculation resources are shown.

TABLE II. COMPUTATIONAL DATA AT 70 GHZ

| Algorithm | Mesh size | Mesh number | Unknown number | Memory amount | Calculation time |
|---|---|---|---|---|---|
| MLFMM | Calculation is impossible. | | | | |
| HOBF | $\lambda$ | 9,092 | 163,656 | 199.811 GB | 684,574 seconds (190 hours) |
| GO | $\lambda$ | 12,536 | - | 91.466 MB | 64,716 seconds (18 hours) |

At HOBF, very large computer memory of 199.8 GB is requested. This is nearly the limit of our PC. Moreover, calculation time becomes 190 hours. In the case of GO, computer memory is very small. However, calculation time becomes 18 hours.

In Figs. 7 and 8, angular responses of RCS of the vertical and the horizontal planes are compared, respectively. In the vertical plane, GO results agree very well to HOBF results except the front direction. In the angular region from 100 deg. to 150 deg., GO results become smaller than HOBF results. In this direction, RCS of tapered shape becomes dominant. In Fig. 8, GO results become smaller than HOBF results at 30 to 80 deg. and at 280 to 330 deg.. These angular regions correspond to reflections from the vertical and tail wings. Rather complicated diffractions arising in these angular regions.

As a result, GO can be used as rough estimations except such directions accompanying with special reflections and diffractions.

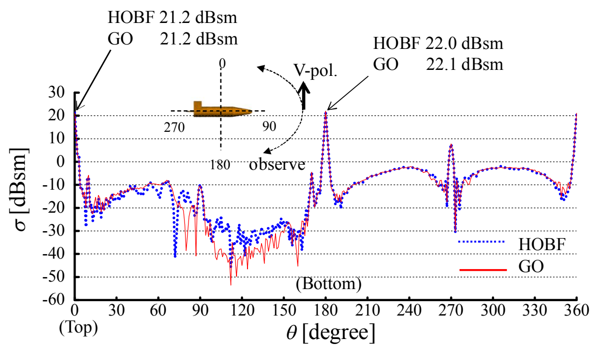


Fig. 7. Monostatic RCS in the vertical plane.

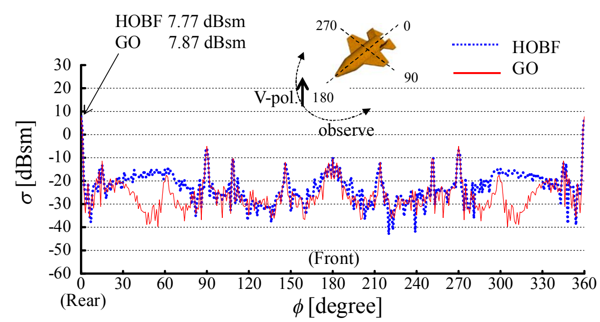


Fig. 8. Monostatic RCS in the horizontal plane.

## *B. GO Calculations in Increased Frequencies*

In order to understand computational difficulties in increasing calculation frequency, computer memory sizes and calculation times are shown in Fig. 9. HOBF comes to the limit of memory size at 70 GHz. In higher frequencies, GO can be applicable. Although the memory amount is very small, large calculation times are requested. At 96 GHz which corresponds to 2 GHz of a real airplane, calculation time becomes 64 hours. At 144 GHz that corresponds to 3 GHz at a real airplane, calculation time becomes 314 hours. This frequency seems the highest in the present electromagnetic simulation operated on a personal computer.

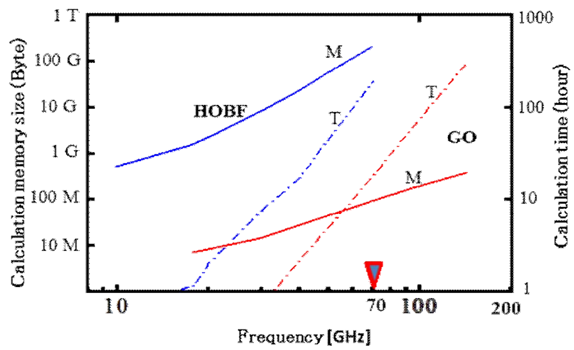


Fig. 9. Computational limits.

Calculated GO results are shown in Figs. 10 and 11 in the vertical and the horizontal planes, respectively. In the vertical plane, angular dependences of $\sigma$ become similar at all frequencies. Except the direction at the front of the air plane, σ increases depending on frequency increases are adequate. In the front direction from 100 deg. to 170 deg., $\sigma$ value are less than −30 dBsm and frequency dependences of $\sigma$ are not observed. Because the structure corresponding to this direction is tapered cone, frequency dependence does not occur.

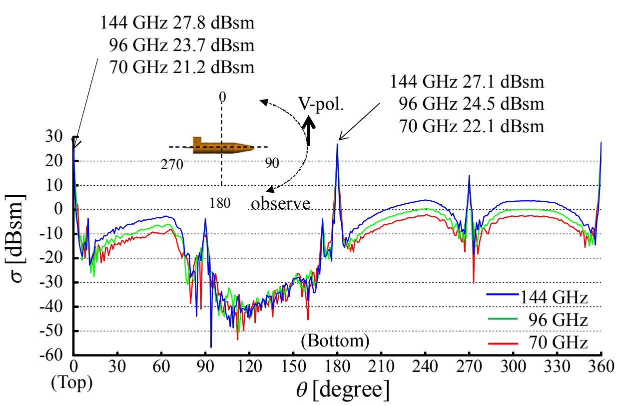


Fig. 10. Monostatic RCS in the vertical plane.

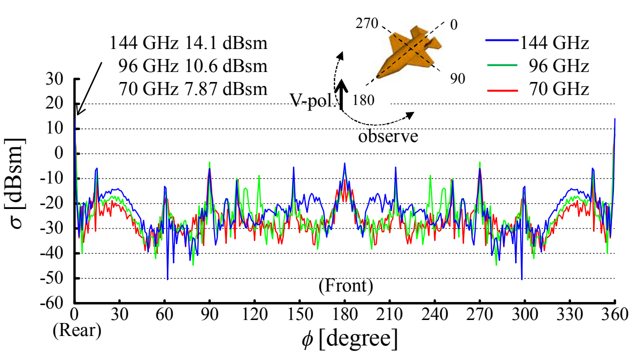


Fig. 11. Monostatic RCS in the horizontal plane.

In the horizontal plane, at the rear directions from 0 deg. to 50 deg. and 310 deg. to 360 deg., frequency dependences of $\sigma$ value become adequate. In the other angular regions, $\sigma$ value changes in frequency increases do not have typical rules. In these angular regions, complicated reflections and diffractions are relating. As a result, unusual frequency characteristics occur.

## VI. Conclusion

Simulations and measurement are achieved at 18 GHz for a scale model airplane of 1/48 down sized. In calculation, usefulness of HOBF is shown. In measurement, usefulness of the time domain function of a vector network analyzer is ensured. Very accurate results of calculated and measured are shown. Moreover, GO calculation results at higher frequency of 144 GHz are shown.

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