Application of De-embedding Approach on Numerical Simulation of Reverberation Chambers

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Abstract— **Reverberation Chambers (RCs) are measurement facility used for electromagnetic compatibility (EMC) tests and antenna measurements. They have stirrers which rotate and scatter electric fields to make distribution of internal field of chambers statistically isotropic and uniform. However, electric field distribution depends on dimensions of a chamber, structure of stirrers, etc. So designing reverberation chambers is not easy and a lot of measurement and numerical simulation are necessary to estimate the effects of individual design parameters. In this paper, to reduce computational load of numerical simulations and to characterize the effects of stirrers, de-embedding approach for reverberation chambers is proposed and an application result is exhibited.**

I. INTRODUCTION

Reverberation chambers (RCs) are type of measurement facility used for electromagnetic compatibility (EMC) tests and antenna measurements, and are standardized by IEC 61000–4–21.

In RCs, it is possible to obtain a statistically uniform and isotropic electromagnetic field [1]. To obtain such environment, stirrers are installed in the space surrounded by the metal wall, and the electromagnetic field inside are agitated according to the time.

In [2], there is a comparison between RC and anechoic chamber (AC) with respect to the radiation immunity test. As an advantage of RC, it is easy to investigate the immunity of complex devices, and it is said that a high electric field can be realized with low electric power because of its high quality factor of resonance.

For RCs, it is difficult to obtain analytical solution of electromagnetic field distribution as its structure is not simple, so it is necessary to evaluate it by measurements or numerical simulations. Also, there are many design elements which mutually influence such as the dimensions of the chamber, the shape, position and number of the stirrer. Thus to design RCs is important reserch topic.

In [3], regarding on stirrer's structute, an investigation which optimizes basic shapes using genetic algorithm was stuied. It is pointed out that change of the stirrer's shape was more effective than optimizing with the same shape. In [4], a method of evaluation of stirrer by means of plane wave's reflection with respect to field asymmetry was presented. In [5], giving design criteria of stirrer, its effect was shown by comparison conventional stirrer and new ones which is designed with the criteria. As a novel concept, in [6], a structure with a movable wall as a stirrer was proposed. As described above, the structure of the stirrer is important but it is difficult to estimate its effect.

Meanwhile, in WBAN (Wireless Body Area Network), the Antenna De-embedding method was proposed [7]. Generally, in analysis of radio propagation, antennas and scatterers are embedded in calculations and simulations. On the other hand, in the Antenna De-embedding method in the WBAN, the influence of the antenna is separated from the channel including the human body by the spherical wave functions technique to improve calculation efficiency. Applying this de-embedding approach on RC, it is expected that the calculation efficiency of design and analysis of RCs would also be improved.

In this study, de-embedding the stirrer's influence from RC regarding the electromagnetic field distribution is aimed. This paper proposes a novel concept of de-embedding approach, explains calculation algorithm. Finally, numerical result is shown.

II. PROPOSED METHOD

A. Outline of De-embedding Approach

Fig. 1 shows the overview of the proposed method in this study. Applying a method similar to the Antenna De-embedding method to 2D RC, separating the influence of the stirrer is considered. As a concrete approach, reflection characteristic of a stirrer is calculated from a reflected wave when cylindrical wave enters a stirrer, and a method of separating it from a chamber is studied. It will be possible to improve the efficiency of the stirrer design by optimizing the reflection characteristics if the analysis with the effect of the stirrer being able to de-embed becomes possible.

B. Fomulation

Fig. 2 shows problem setting in this study. It is assumed that time dependence is $e^{j\omega t}$, 2D TE mode (electric field has only z-direction component) which is uniform in the z direction, and the input of this system is the ideal line current whose amplitude is I_z. To de-embed the effect of stirrer, the region is divided into two: inside and outside the virtual circle, and the electric field is expressed in each region.

The following section briefly describes the formulation of the method. In 1), reflection characteristics of the stirrer are defined. In 2) and 3), expression of E-field in each region is

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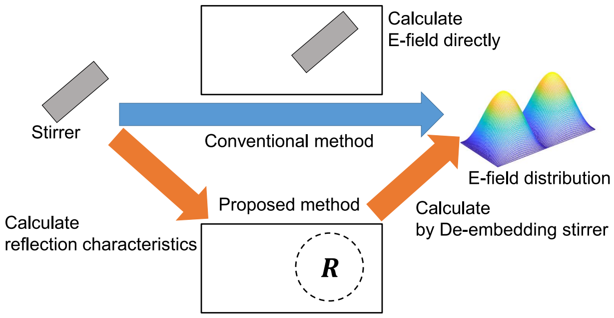

Fig. 1. Overview of De-embedding method in this study

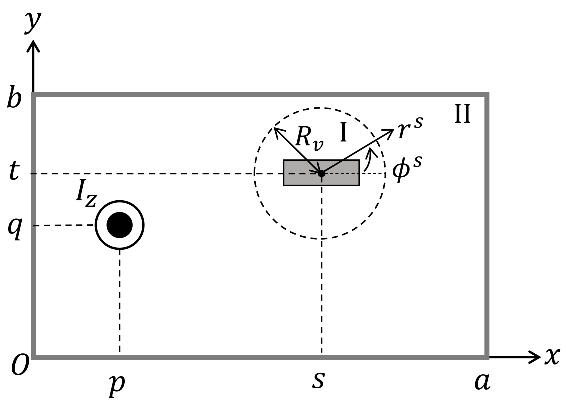

Fig. 2. Problem setting

described. In 4), boundary conditions are described in this problem.

1) Reflection Characteristics Matrix $\boldsymbol{R}$ *of the Stirrer:* Let us consider a case where an nth order cylindrical wave enters a stirrer placed in free space. The incident wave E_z^{inc} is represented by

$$E_z^{inc}(r^s, \phi^s) = B_n^{inc} H_n^{(1)}(k_0 r^s) e^{jn\phi^s} \quad (1)$$

where k_0 is the wavenumber in free space, $H_n^{(p)}$ is the Hankel function of the p th kind, n th order, B_n^{inc} is amplitude, r^s and ϕ^s are the distance and the angle from the center of stirrer, respectively.

At this time, the electric field distribution E_z including the stirrer is represented by cylindrical wave expansion [8]

$$E_z(r^s, \phi^s) = B_n^{inc} H_n^{(1)}(k_0 r^s) e^{jn\phi^s} + \sum_{m=-N_s}^{N_s} \left[A_m^{r_n} H_m^{(2)}(k_0 r^s) e^{jm\phi^s} \right] \quad (2)$$

where N_s is the truncation order, $A_m^{r_n}$ are the expansion coefficients.

Then, $\boldsymbol{r}_n = \boldsymbol{A}^{r_n} / B_n^{inc} \in \mathbb{C}^{2N_s+1\times 1}$ is defined. Repeating this caluclation by $(n = -N_s \sim N_s)$, $\boldsymbol{R}$ is defined as follows:

$$\boldsymbol{R} = \{\boldsymbol{r}_{-N_s}\, \boldsymbol{r}_{-N_s+1} \dots \boldsymbol{r}_{N_s-1}\, \boldsymbol{r}_{N_s}\} \in \mathbb{C}^{2N_s+1\times 2N_s+1} \quad (3)$$

It can be said that $\boldsymbol{R}$ obtained in this way corresponds to the reflection coefficient of the stirrer. Therefore, in this study, $\boldsymbol{R}$ is called reflection characteristics matrix.

2) Region I: In the region I, E-field E_z^I is the sum of the incident wave to the stirrer E_z^{inc} and the reflected wave by the stirrer E_z^{ref} which are expressed by cylindrical wave expansion

$$E_z^{inc}(r^s, \phi^s) = \sum_{p=-N_s}^{N_s} \left[B_p^{inc} H_p^{(1)}(k_0 r^s) e^{jp\phi^s} \right] \quad (4)$$

$$E_z^{ref}(r^s, \phi^s) = \sum_{q=-N_s}^{N_s} \left[A_q^{ref} H_q^{(2)}(k_0 r^s) e^{jq\phi^s} \right] \quad (5)$$

$$E_z^I(r^s, \phi^s) = E_z^{inc}(r^s, \phi^s) + E_z^{ref}(r^s, \phi^s) \quad (6)$$

where B_p^{inc} and A_q^{ref} are expansion coefficients. Also, the following relationship can be known from the reflection characteristics.

$$\boldsymbol{A^{ref}} = \boldsymbol{RB^{inc}} \quad (7)$$

3) Region II: In the region II, there are E-field E_z^{tr} by the line current, the reflected wave E_z^{sc} from the chamber wall and the equivalent wave E_z^{eq} from the virtual circle.

E_z^{tr} is expressed by the following fomula [8].

$$E_z^{tr} = -\frac{\omega\mu}{4} I_z H_0^{(2)}\left(k_0 \sqrt{(x-p)^2 + (y-q)^2}\right) \quad (8)$$

E_z^{sc} and E_z^{eq} are unknown to be solved.

For example, considering a moment method with a pulse function as an expansion function [9], E_z^{sc} is represented by

$$E_z^{sc} = \sum_{n=1}^{N_{c1}} \left[-\frac{\omega\mu}{4} \int_{\Delta C_n} a_n H_0^{(2)}(k_0 |\boldsymbol{\rho} - \boldsymbol{\rho}'_n|)\, dl' \right] \quad (9)$$

where N_{c1} is the truncation order, ω is the angle frequency, μ is the permeability in free space, a_n are weighting coefficients, ΔC_n is length of the n th segment of conducter's shape, $\boldsymbol{\rho}$ and $\boldsymbol{\rho}'_n$ are the position vector from the origin of xy plane and the nth element, respectively.

In addition, E-field due to the equivalent wave source from the virtual circle, when using cylindrical wave expansion

$$E_z^{eq}(r^s, \phi^s) = \sum_{l=-N_{c2}}^{N_{c2}} \left[C_l H_l^{(2)}(k_0 r^s) e^{jl\phi^s} \right] \quad (10)$$

where N_{c2} is the truncation order and C_l are expansion coefficients. And, total E-field E_z^{II} in the region II is represented by

$$E_z^{II} = E_z^{tr} + E_z^{sc} + E_z^{eq} \quad (11)$$

4) Boundary Conditions: A virtual circle is a boundary given for convenience, not a material boundary. Since the tangential components of the electric field and the magnetic field are continuous,

$$E_{\parallel}^{I} = E_{\parallel}^{II} \quad (on\ virtual\ circle) \tag{12}$$
$$H_{\parallel}^{I} = H_{\parallel}^{II} \quad (on\ virtual\ circle) \tag{13}$$

are two boundary conditions. Here, $H_{\parallel}^{I}$ and $H_{\parallel}^{II}$ represent the tangential component of magnetic field on virtual circle in region I and region II, respectively.

Next, the boundary conditions on conductors are considered. The region I has a stirrer, but $E_z^I = 0$ on the stirrer is considered because of in the reflection characteristic (7). Therefore, only the cavity of the region II should be considered.

$$E_{\parallel}^{II} = 0 \quad (on\ chamber\ wall) \tag{14}$$

The unknown sequences B^{inc}, a_n and C_l can be solved by formulating the system of linear equations with the above (12), (13), and (14) as boundary conditions.

III. NUMERICAL SIMULATION AND RESULTS

In this paper, a circular conductor with a radius of R_{str} which makes it possible to calculate reflection characteristics analytically were verified as a stirrer. The frequency f is determined by

$$f = c_0 \sqrt{\left(\frac{3}{2a}\right)^2 + \left(\frac{2}{2b}\right)^2} \tag{15}$$

where c_0 is speed of light in free space. This frequency is resonance frequency of TE32 mode. Detailed parameters are summarized in table I.

TABLE I
SETTING PARAMETERS

a	6.36 m
b	4.0 m
p	0.636 m
q	2.0 m
s	3.816 m
t	2.4 m
R_{str}	$0.14b$ =0.56 m
R_v	0.6 m
I_z	1 A
f	103 MHz (TE32)
N_{c1}	216
N_{c2}	19
N_s	19

Fig. 3 shows the electric field strength distribution calculated by applying de-embedding of the stirrer by the proposed method. Further, Fig. 4 shows calculation results by the conventional moment method.

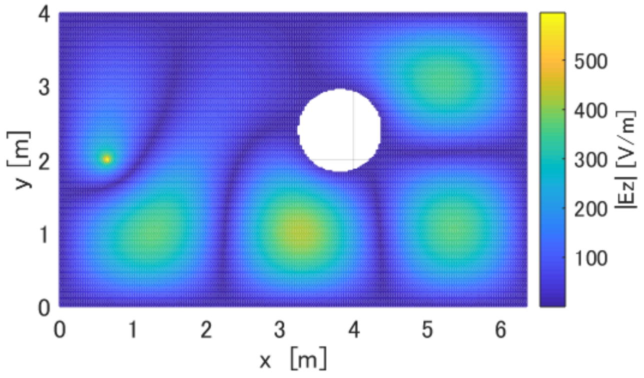

Fig. 3. E-field strength distribution (De-embedding)

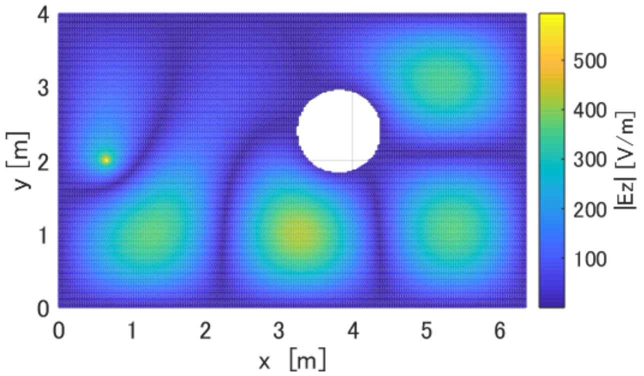

Fig. 4. E-field strength distribution (MoM)

In order to evaluate error between the result of de-embedding approach and MoM, the following formula is defined.

$$error = \frac{\sqrt{\sum |E_{De} - E_{MoM}|^2}}{\sqrt{\sum |E_{MoM}|^2}} \tag{16}$$

where E_{De} is the strength of the E-field by de-embedding, E_{MoM} is the strength of the E-field by the conventional moment method, $\sum$ is calculated over the sampling point N on the xy plane. This error can be considered as a kind of relative error because the difference is divided by the sum of result of MoM.

The table II summarizes the error evaluation of this simulation.

TABLE II
ERROR

	all region ($N = 38470$)	region I ($N = 237$)	region II ($N = 38233$)
error	0.0060	0.2136	0.0059

The error in the region II is smaller than that in the region I. Because the region I is near the stirrer and the region II which is important in practical use. From the result, it is supposed that applicability of de-embedding method on reverberation chambers is exhibited.

To compare the computional loads, calculation time was measured. Calculation time with MoM and de-embedding approach by Intel® Core^{TM} i7-6700 (3.40GHz 3.41GHz). These simulation is programmed in MATLAB®.

TABLE III

CALCULATION TIME

	MoM	De-embedding
time [s]	24.2	28.6

Table III shows that the loads with de-embedding approach is higher than that with MoM. It is considered that de-embedding approach is more complicated algorithm than MoM. In this regard, it can be said that further study is necessary. However, it seems that the computational loads in the entire RC design can be reduced, if optimization of electric field uniformity of the reflection characteristics $\boldsymbol{R}$ is realized.

IV. CONCLUSIONS

In this paper, a novel approach to de-embed the effect of stirrers from characteristics of reverberation chambers is proposed. To show the applicability of the method, a 2D numerical simulation of the proposed de-embedding approach is performed and good agreement is obtained in comparison with the conventional approach by MoM. The followings are left for further study:

- Investigation calculation load of the proposed approach compared to conventional methods
- Investigation of effectiveness by numerical calculation of $\boldsymbol{R}$ for other conductor shapes
- Optimization of $\boldsymbol{R}$ with respect to field uniformity
- Application for 3D and realistic problems

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