Measurement of Absorption Cross Section of a Lossy Object in Reverberation Chamber without the Need for Calibration

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***Abstract*—A reliable and simple procedure is proposed to measure the averaged absorption cross section (ACS) of a lossy object in a reverberation chamber (RC). This procedure is based on the time-domain measurement of the ACS in an RC. In the time-domain, to obtain the ACS, the chamber decay time needs to be known. Conventionally, the ACS is normally measured in the frequency domain, and a full two-port calibration must be carried out before collecting the *S*-parameters, which is tedious and time-consuming. In reality, the chamber decay time depends on the diffused loss of the RC, not the insertion loss of the cables. In this paper, by making use of this fact, the ACS can be measured accurately without calibration, which will simplify the measurement process and shorten the measurement time at the same time.**

***Keywords*—Absorption cross section; reverberation chamber; time domain measurement**

I. Introduction

The reverberation chamber (RC) can be characterized as an electrically large shielded metallic enclosure with stirrers, which is designed to work in an "over-moded" condition. Typically, an asymmetric rotating stirrer is installed in the RC to change the boundary conditions of the chamber [1]. Thus, a statistically uniform environment is created inside. The RC is currently used for a wide range of electromagnetic and electromagnetic compatibility (EMC) measurement applications, such as antenna efficiency measurement [2]-[4], shielding characterization of equipment and materials [5]-[8] and EMC radiated emission and immunity tests [1], [9].

Recently, it has been shown that the RC is becoming prevalent as a test facility for the measurement of the average absorption cross section (ACS) of a lossy object, which is averaged over all angles of incidence and polarization [10], [11]. The measurement of the ACS of a lossy object is required for many applications, including the characterization of lossy objects on electromagnetic wave propagation used for communications in multipath environments such as interiors of mass transit vehicles or aircraft loaded with cargoes or passengers [9], biometrics electromagnetic exposure studies such as human's specific absorption rate [12], [13].

The ACS of a lossy object is defined as the ratio of the power dissipated in the object to the power density of the incident plane wave. In the frequency domain, the averaged statistical power transfer function of an RC is proportional to its quality factor. The ACS contribution to the quality factor was derived mathematically in [14], which offers an opportunity to measure the averaged ACS of an object from the quality factor of the reverberation chamber. It has been shown that the ACS can also be measured in the time domain [14], [15]. The loaded and unloaded chamber quality factors can be determined from the chamber decay time which can be extracted from the power delay profile of the RC. The chamber decay time only depends on the diffused loss in the RC and not on the insertion loss and antenna efficiency.

In this paper, we show that the ACS can be measured accurately without calibration. This is realized by making use of the fact that the chamber decay time is independent of the insertion loss of cables in the measurement. Measurements have been done to verify the proposed procedure. It has been shown that the measurement process is simplified and the measurement time is shortened at the same time.

This paper is organized as follows. Section II contains the theory for the measurement of ACS in the time domain. Section III presents the measurement setup and comparison of measured ACS under calibrated and uncalibrated scenarios. The discussions and conclusions of this work are given in the final section.

II. Theory

The quality factor (Q) of the RC is a key quantity in calculating the ACS of lossy objects. Generally, in an electrically large cavity, Q is defined as [14], [16]:

$$Q = \omega U_s / P \quad (1)$$

where ω is the angular frequency, U_s is the steady state energy in the cavity and P is the dissipated power.

The averaged ACS $\langle \sigma_{\text{ACS}} \rangle$ can be written in terms of measurements of loaded and unloaded chamber Q [14]:

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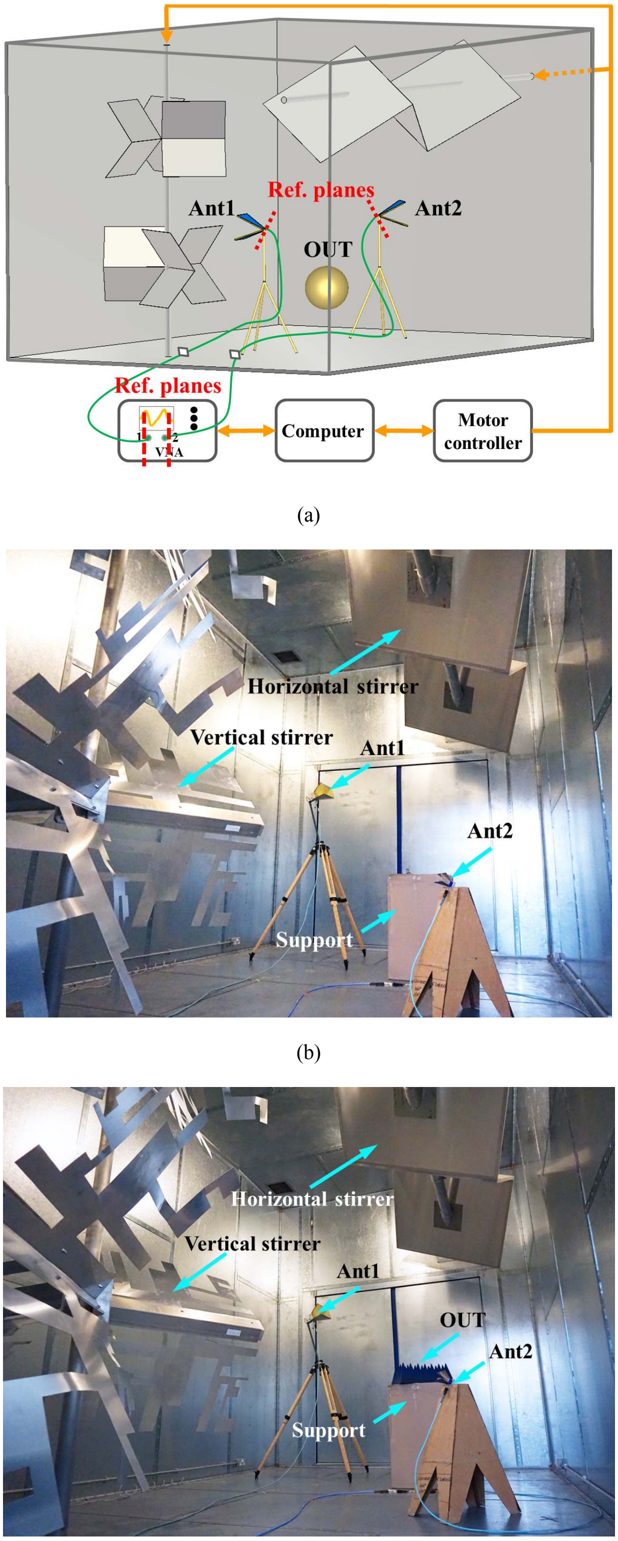

Fig. 1. ACS measurement setup in the RC: (a) measurement system, (b) unloaded scenario, (c) loaded scenario.

$$\langle\sigma_{\mathrm{ACS}}\rangle = \frac{2\pi V}{\lambda}\left(Q_l^{-1} - Q_u^{-1}\right) \quad (2)$$

where V is the chamber volume, λ is the wavelength, Q_l is the chamber quality factor when there is an object under test (OUT) in the RC and Q_u is the chamber quality factor when there is no OUT in the RC.

Basically, the chamber Q can be measured in the time domain - the loaded and unloaded chamber Q can be determined from the chamber decay time. [2] and [14] have shown, in the time domain, $Q = \omega\tau$, ω is the angular frequency and τ is the chamber decay time. The loaded and unloaded Q (Q_l and Q_u, respectively) can be written as [14]:

$$Q_l = \omega\langle\tau_l\rangle \text{ and } Q_u = \omega\langle\tau_u\rangle \quad (3)$$

where $\langle\tau_l\rangle$ is the average loaded chamber decay time and $\langle\tau_u\rangle$ is the average unloaded chamber decay time. If we substitute (3) into (2), we obtain the ACS in the following form [14]:

$$\langle\sigma_{\mathrm{ACS}}\rangle = \frac{V}{c}\left(\langle\tau_l\rangle^{-1} - \langle\tau_u\rangle^{-1}\right) \quad (4)$$

where c is the speed of light in free space. This technique requires the knowledge of the chamber decay time τ. To obtain τ, we first need to obtain the time-domain power response of the RC from the inverse Fourier transform (IFT) of S_{21}. Because the time domain power in the RC decays exponentially, τ can be obtained from the slope of ln(power) in the time domain. The details of the extraction of τ from the *S*-parameters can be found in [17] and [18].

Conventionally, in order to extract the chamber decay time, a full two-port calibration must be carried out before collecting the S-parameters of the antennas. In such measurements, the reference planes are calibrated at the end of the cables, as shown in Fig. 1(a) with dot lines. However, it is tedious and time-consuming. Nowadays, some VNAs are pre-calibrated with the reference planes at the output connectors of the VNAs, when the VNA is preset the reference planes are restored [19]. This offers an opportunity to perform the measurement without the need for calibrations. The antennas and the cables after the reference planes can be regarded as integrated antennas. As mentioned in Section I, the chamber decay time does not depend on the insertion loss of cables used in the measurement and it is only determined by the diffused loss in the RC. Therefore, the ACS can be measured accurately without calibration, which will simplify the measurement process and shorten the measurement time.

III. MEASUREMENTS

To validate the proposed methods, measurements were performed from 4 to 5 GHz in our RC which has a size of 3.6 m × 4 m × 5.8 m. It has two mode-stir paddles: the vertical one is mounted in a corner while the horizontal one is set close to the ceiling. Two double-ridged waveguide horn antennas were used as antenna 1 (SATIMO® SH 2000) and antenna 2 (Rohde & Schwarz® HF 906). Antenna 1 was connected to port 1 of a VNA via a cable running through the bulkhead of the chamber, and antenna 2 was connected to port 2 of the VNA via another cable through the bulkhead of the chamber. During the measurement, the two stirrers were moved simultaneously and stepwise to 120 positions (3 degrees for

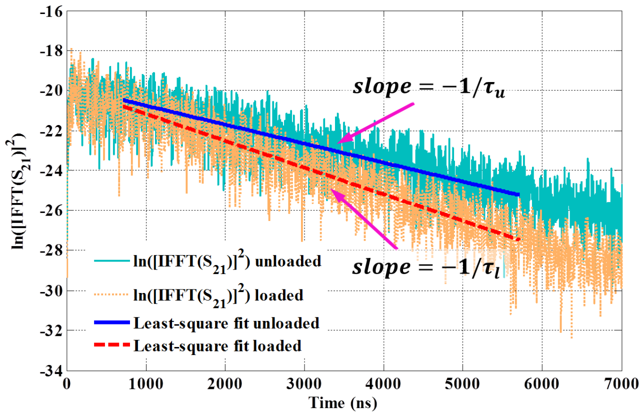

Fig. 2. Time domain response with calibration: ln([IFFT(S_{21})]^2) and least-square fit under loaded and unloaded scenarios.

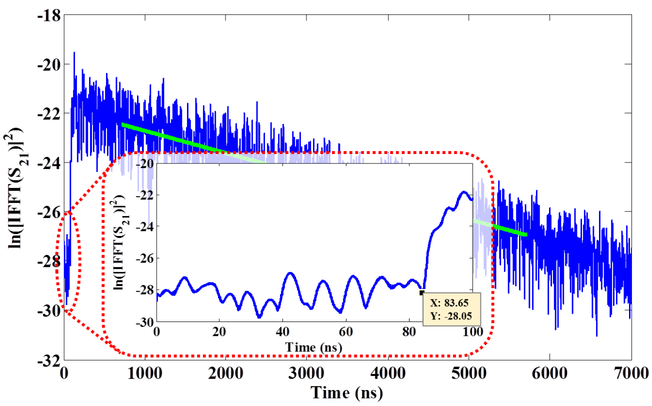

Fig. 3 Time domain response with no calibration and the close-up of the early time behavior.

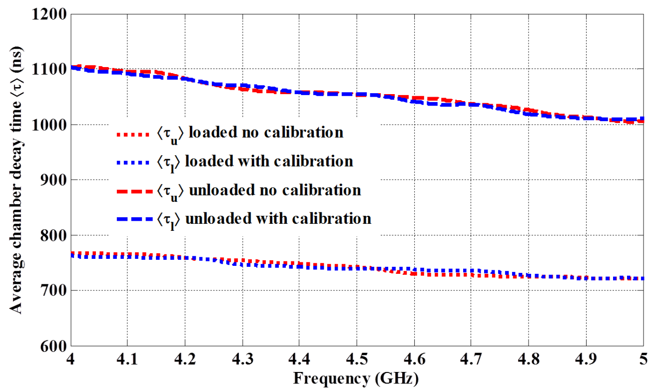

Fig. 4 The comparison of the average chamber decay time with and without calibration under loaded and unloaded scenarios.

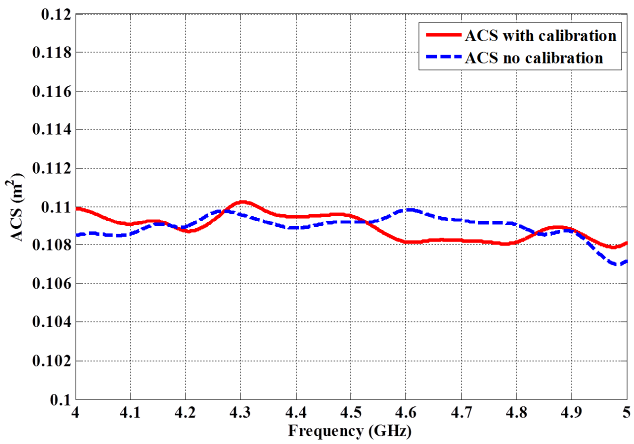

Fig. 5 The comparison of the measured ACS with and without calibration.

each step). At each mode stir position, a full frequency sweep was performed by the VNA and the full *S*-parameters were collected. A piece of RF absorber was selected as an OUT. The measurement setup is shown in Fig. 1 (a). The measurement setups without and with the OUT are shown in Fig. 1 (b) and Fig. 1 (c), respectively.

The measurement procedure is given as follows.

Step 1: Calibrate the VNA including the cables according to the standard calibration procedure.

Step 2: Place the two antennas and the support (excluding the OUT) inside the RC.

Step 3: Connect antenna 1 to port 1 of the VNA and antenna 2 to port 2 of the VNA, and collect the full *S*-parameters for each stir position.

Step 4: Keep the previous measurement setup unchanged and place the OUT on the support, and repeat *Step 3*.

Step 5: Preset the VNA to shift the reference planes, and repeat *Step 3* without calibration.

Step 6: Move the OUT out of the RC, and repeat *Step 3* without calibration.

In this measurement, 10 001 points were sampled in the frequency range from 3.8 to 5.2 GHz. The ACS of the OUT was calculated using (4). We use a band-pass elliptic filter of order 10 to filter S_{21} with 200 MHz bandwidth, and then the inverse fast Fourier transform (IFFT) is applied to the filtered S_{21}. Since the time domain power decays exponentially ($e^{-t/\tau}$) in the RC, the least-square fit is applied to ln(power) to obtain the slope, and τ can be extracted by getting the negative inverse of the slope. To avoid the fit error caused by the noise level, only part of the signal is used for least-square fit, as shown in Fig. 2. The average chamber decay time $\langle\tau\rangle$ is then obtained from the ensemble average of the τ for different stir positions. The early time behavior is depicted in detail in Fig. 3. As can be seen, in the first 83.65 ns, the chamber is not charged, this is the time that the wave travels in the cables. In our case, the total length of the two cables is about 16 m and the travelling speed of the wave inside the cables is about 2×10^8 m/s [20]. Thus, the 83.65 ns corresponds to 16.73 m which agrees well with the total length of our cables used in the measurement (our VNA is pre-calibrated with the reference planes at the output connectors of the VNA, when the VNA is preset the reference planes are restored). By sweeping the center frequency of the filter, τ at different center frequencies are obtained. The measured chamber decay time with and without calibration under loaded and unloaded scenarios is shown in Fig. 4. As expected, the chamber decay time is reduced when the chamber is loaded. The chamber decay time with calibration and that without calibration agree well, i.e., the

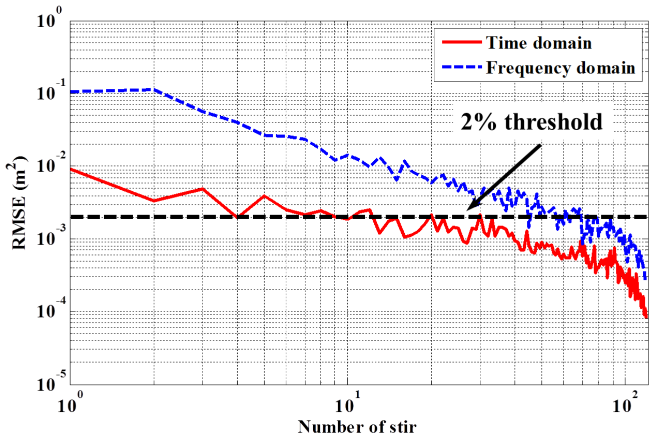

Fig. 6 The RMSE with the increase of the number of stir positions for time-domain method and frequency-domain method.

chamber decay time can be measured accurately without calibration. The measured ACSs with and without calibration are depicted in Fig. 5. As we can see, they agree well and the maximum difference is within 2%, which manifests the effectiveness of the proposed method.

IV. Measurement Efficiency Comparison

The measurement efficiency of the proposed method and the conventional method is studied and compared. The root-mean-square-error (RMSE) of the measured ACS from 4-5 GHz with different numbers of stir positions to the ACS measured with 120 stir positions is adopted to evaluate the convergence, and the algorithm is expressed as:

$$\mathrm{RMSE}_i = \sqrt{\frac{\sum_{j=1}^{N}\left(\mathrm{ACS}_{i,j} - \mathrm{ACS}_{M,j}\right)^2}{N}} \quad (i = 1,2,\cdots,M) \tag{5}$$

where i is the number of stir positions, M is the maximum number of stir positions, j is the frequency sampling point number, N is the number of frequency sampling points in 4-5 GHz. In our case, M = 120 and N = 7143. The calculated results are shown in Fig. 6. As can be seen, the proposed time-domain method converges faster than the conventional frequency-domain method. This is because the chamber decay time τ is not sensitive to the boundary conditions and only depends on the overall loss of the RC. While the chamber transfer function depends on how well the RC is stirred. Thus, $\mathrm{ACS}_{\mathrm{TD}}$ (ACS measured in the time domain) converges faster than $\mathrm{ACS}_{\mathrm{FD}}$ (ACS measured in the frequency domain). It is worth mentioning that, in the time domain, the RMSE is always below 10% (compared with the averaged ACS in the full frequency span, about 0.1 m^2 from Fig. 5) and drops below 2% after 15 stir positions. However, in the frequency domain, the RMSE is always above 10% before the first 15 stir positions and drop down slowly afterwards. They are below 2% after 80 stir positions, which means the time domain measurement is much more efficient than the frequency domain method. The comparison of the two measurement methods is shown in Table I. It is demonstrated that the proposed method is much more efficient and its measurement procedure is simpler than the conventional method.

TABLE I
Comparison of Different Measurement Methods

Measurement method	Stir number needed	Measurement complexity	Measurement time
Conventional frequency domain method	80	Need calibration	approx. 2 hrs
Proposed time domain method	15	No calibration	approx. 20 mins

V. Discussions and Conclusion

In this paper, a reliable and simple method is proposed for the measurement of the averaged ACS of a lossy object in an RC. This procedure is based on the time-domain measurement of the ACS in an RC. By making use of the fact that the chamber decay time is independent of the insertion loss in the system, the ACS can be measured accurately without calibration, which will simplify the measurement process and shorten the measurement time at the same time. Measurement has been done to validate the proposed method. The results show that the averaged ACS of the OUT can be accurately measured using the proposed method with simpler measurement process and much less time. It should be noted that the antennas used in the measurement should be of high efficiency i.e., the losses in the RC are dominated by the chamber wall loss and OUT loss rather than by the losses of the antennas used in the measurement. Otherwise, the power will not decay exponentially and chamber decay time cannot be extracted correctly.

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