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Reverberation-Chamber Performance of the Oscillating-Wall Stirrer for Estimating Antenna Efficiency

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***Abstract*—Mode-stirring mechanisms play a critical role in randomizing the fields in a reverberation chamber such that, on average, the chamber provides a uniform field everywhere in the working volume. Recently, a new type of quasi-wall stirring mechanism, the so-called oscillating-wall stirrer was introduced to increase the working volume, without reducing chamber performance. For the first time, we analyze the performance of that stirrer above 1 GHz, for the application of testing antenna efficiency. We investigate this by analyzing the coherence distance of the oscillating-wall stirrer, and the spatial uniformity. We conclude that, for the most stringent threshold, the oscillating-wall stirrer can provide sufficient samples for a single measurement of antenna efficiency above 1 GHz, with uncertainty due to lack of spatial uniformity better than 0.15 dB.**

***Index Terms*—Antenna Efficiency, Coherence Distance, Oscillating-Wall Stirrer, Reverberation Chamber, Spatial Uniformity, Stirrer Mechanisms, Wireless Testing**

I. INTRODUCTION

The type of mode-stirring mechanism plays a critical role in the performance of a reverberation chamber (RC). Mode-stirring mechanisms such as paddles or moving walls randomize the fields in the chamber, which, when averaged over multiple positions, should provide a uniform field everywhere in the working volume. This allows an RC to accurately measure metrics used in EMC (e.g. radiated emissions/immunity, shielding effectiveness) and in wireless testing (e.g. antenna efficiency, total radiated power, total isotropic sensitivity) [1]–[3]. Whether or not this uniformity is achieved with enough uncorrelated samples depends on the geometry and material properties of the stirring mechanism in combination with the losses and volume of the chamber.

Recently, a new type of stirring mechanism has been introduced, the so-called 'oscillating wall stirrer' (OWS) [4]–[6], as shown in Fig. 1 and illustrated in Fig. 2. This type of stirrer has been classified as a 'quasi-wall' stirrer, since it acts as a moving wall, but space is left between the side walls of the cavity such that the fields can propagate behind the stirrer so the volume does not change, and its movement is not completely linear. To clarify the latter, the stirrer is attached to a linear bi-slide, but folds in and out for various positions, as is illustrated for three positions in Fig. 2. The large surface area of this stirrer should allow for a larger change of the fields when moved to a new position, while keeping a working volume that is significantly larger than in a chamber with a more generally used rotating stirrer [4], [5]. For antenna-testing purposes, this can be beneficial when the antenna is integrated in a large device, or for purposes where the antenna itself has a large volume (such as reflector antennas, radar, etc.).

The performance of the OWS up to 1 GHz for EMC testing has been shown to be according to the IEC 61000-4-21 standard [1], [4], [5]. However, in antenna-efficiency testing different procedures are generally used, with a focus on other metrics of interest. For example, more focus on correlation between paddle positions (coherence angle or distance), and the uniformity is often computed differently [2], [3], [7]. Many RCs are equipped with two of more paddles, which often results in more independent samples. Since the OWS is a single stirring-mechanism, the question arises whether it can provide sufficient independent samples for the measurement of antenna efficiency without position-based stirring. Besides that, a previous work that used the OWS for antenna-efficiency testing has shown that a significant spatial variation can occur in enhanced backscattering, which may be linked to lack of spatial uniformity [8].

To answer these questions, we analyze in this work for the first time the performance of the OWS above 1 GHz for the purpose of antenna-efficiency testing. We mainly focus on spatial uniformity and coherence distance, as lack of spatial uniformity and correlation are often among the most significant contributors in the measured estimate of antenna efficiency [3], [7]. Note that the performance of any mode-stirring mechanism inherently links to the surrounding cavity, so the performance metrics we focus on in this work describe the behaviour of the full RC with OWS. In Section II, we describe the theory behind these metrics, we show experimental results in Section III, and the work is concluded in Section IV.

II. THEORY

In this section, we describe the theory used in this work to estimate spatial uniformity and coherence distance.

A. Spatial Uniformity

For EMC testing, the IEC standard dictates that the uniformity is assessed by measuring the electric field (E-field) using an E-field probe, sampled in multiple orientations and locations within the working volume [1]. The standard deviation of the E-field with respect to the mean of all samples is then defined as the field uniformity. However, when it comes

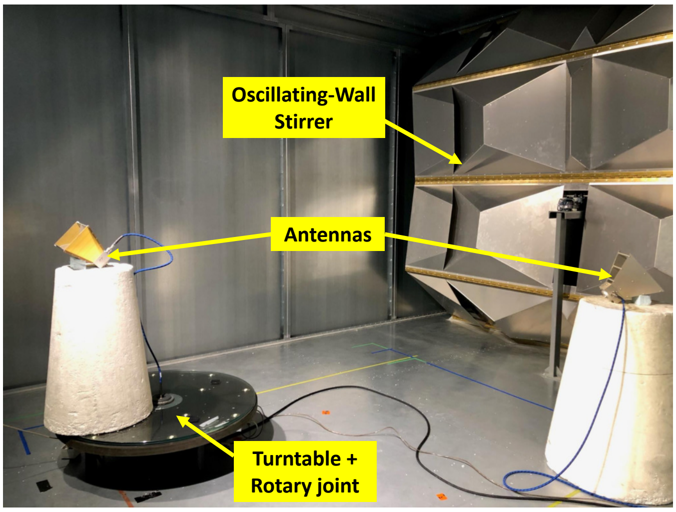

Fig. 1. The RC setup used in this work with two dual-ridge horn antennas, the OWS used for paddle stirring and the turntable used to obtain independent measurement for various positions.

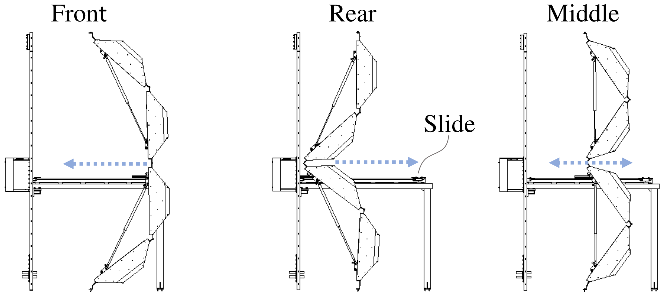

Fig. 2. Illustration of the movement of the OWS (from left to right) for the maximum, minimum, and middle position [4].

to assessing uncertainty due to lack of spatial uniformity for applications such as antenna efficiency, a different approach is more suitable [2]. In such cases, it is useful to know the deviation over position for the chamber contribution to S_{21}, as that metric is used in both the antenna-replacement method given in [1], and in the widely-used non-reference one-, two-, and three-antenna methods presented in [9]. Since these measurements are performed using a Vector Network Analyzer (VNA), they can also be performed accurately. This is also necessary, since the allowed limit above 1 GHz for spatial uniformity in EMC testing of 3 dB ([1]) translates in many cases unacceptable deviation in the estimate of antenna efficiency (up to 100 % deviation).

For antenna-efficiency measurements, lack of spatial uniformity is estimated using the chamber transfer function given by [2]

$$G_{\text{ref}} = \frac{\langle\langle|S_{21}|^2\rangle_N\rangle_F}{\eta_1^{\text{tot}}\eta_2^{\text{tot}}}, \tag{1}$$

where N is the number of mode-stirring samples, F the frequency-averaging bandwidth, and η_1^{tot} and η_2^{tot} the total-antenna efficiency as defined in [9] of the two antennas used. The standard deviation in G_{ref}, which defines lack of spatial uniformity, is then given by [2]

$$\sigma_{G_{\text{ref}}} = \sqrt{\frac{1}{P-1}\sum_{p=1}^{P}(\langle G_{\text{ref},p}\rangle_N - \hat{G}_{\text{ref}})}, \tag{2}$$

where P is the amount of antenna positions, p is the antenna-position number, and $\hat{G}_{\text{ref}}$ is the chamber-transfer-function average over all positions. Independence between positions was verified using Pearsons cross correlation, often referred to as ‘between’ correlation [3]. Note that (2) is similar to the equation for the E-field standard deviation in the IEC Standard, but that generally less samples are needed in this definition (9 instead of 24), and G_{ref} is used instead of the measured E-field. In this work, we report $\sigma_{G_{\text{ref}}}$ in dB, which is estimated by [2]

$$\sigma_{G_{\text{ref}},\text{dB}} = 10\log_{10}\left(\frac{\hat{G}_{\text{ref}} + \sigma_{G_{\text{ref}}}}{\hat{G}_{\text{ref}}}\right), \tag{3}$$

similar to equation B.7 in [1].

B. Coherence distance

The coherence distance is defined as the minimum distance that a linear mode-stirring mechanism such as the OWS should be moved to produce a new independent sample [3]. Samples are defined as independent when correlation between them is below a certain threshold. Note that these samples are not truly independent, but rather weakly correlated. Correlation can introduce errors into the measurement [7], which can directly translate to an error in the estimated antenna efficiency. The coherence distance can be extracted for each frequency f by the normalized linear sample autocorrelation of an S_{21} measurement as [10]

$$R(f,i) = \frac{\sum_{j=1}^{N-i} S_{21}(f,n_j)S_{21}^{*}(f,n_{j+i})}{\sum_{j=1}^{N} S_{21}(f,n_j)S_{21}^{*}(f,n_j)}, \tag{4}$$

where $S_{21}(f,n_j)$ corresponds to the measured transmission coefficient for mode-stirring sample n_j, for a lag shift $i \in \mathbb{Z}$. Note that this formulation does not subtract the mean or unstirred energy (different from [3], [10]), since the IEC antenna-replacement method does not either. Unstirred energy introduces correlation in the measurement, and should therefore be taken into account in the coherence distance. Linear autocorrelation shifts the entire sequence over a copy of itself for various ‘lags’, where each lag corresponds to a shift of one mode-stirring sample. The autocorrelation is then calculated for each of these lags.

Fig. 3 shows an example of the normalized autocorrelation for a single frequency with two thresholds, for a measurement with $N = 1500$ paddle steps, which corresponds to 1500 lag shifts. Note that we do not show the negative lag shifts for clarity, as the autocorrelation is symmetrical. The coherence distance can be extracted from the amount of lags that the sequence needs to be shifted for the autocorrelation to drop below a certain threshold. Thresholds vary significantly between fields and applications [11], but often 0.3, 0.5 and 1/e are used

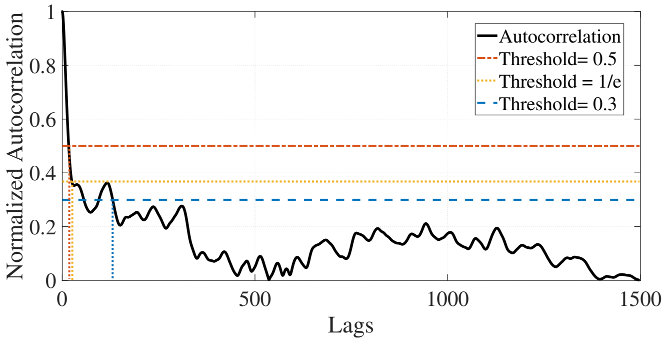

Fig. 3. Example of half the normalized autocorrelation for a single frequency including various thresholds. For more stringent thresholds, a larger lag shift is needed for the autocorrelation to drop below the threshold, which corresponds to a larger coherence distance.

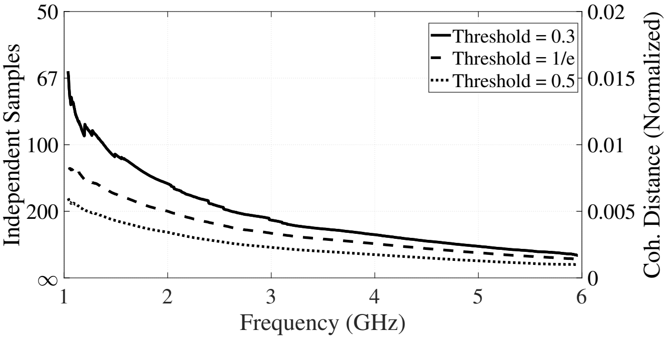

Fig. 4. Normalized coherence distance and the corresponding independent samples that can be extracted over frequency, computed with various thresholds.

for correlation metrics in reverberation-chamber measurements [3], [10]. In some cases, the autocorrelation surpasses the threshold again after it has dropped below it (see Fig. 3 for a threshold of 0.3). In such a case, the maximum lag shift (where all larger lag shifts are below the treshold) is chosen to compute the coherence distance. For thresholds of 0.5 and 1/e, this happens at lag 17 and 25, respectively, and at lag 132 for a threshold of 0.3. If 1500 steps correspond to a movement of 1.5 m, the coherence distance would then be 1.7 cm and 13.2 cm. A similar procedure is carried out to convert lags to a coherence angle, but it should be noted that in case of a rotating paddle, a circular autocorrelation should be used [10]. In this work, for clarity, we do not give the coherence distance in meters, but we normalize the results to show the amount of independent samples that can be extracted. In such a case, the minimum position of the OWS (rear position in Fig. 2) is given by 0 and the maximum position (front position in Fig. 2) by 1. Therefore, a coherence distance of 0.01 can yield 100 independent (or low-correlated) samples. Next, using this approach, we analyze with experimental results how many independent samples the OWS can provide, and the spatial uniformity it yields.

III. EXPERIMENTAL RESULTS

This section describes the setup used to obtain experimental results of coherence distance and chamber spatial uniformity.

A. Experiment Setup

All measurements were performed in a 72.72 m^3 reverberation chamber at the Eindhoven University of Technology, which uses the OWS for mode stirring and a turntable to obtain independent realizations. The setup is shown in Fig. 1. Measurements were performed using a VNA from 1-6 GHz with a 200 kHz spacing, an IF bandwidth of 1 kHz, dwell time of 10 μs, and an output power of 0 dBm. We used two VNA ports connected to two dual-ridge horn antennas operating in the 1-18 GHz band. Note that the measured chamber-performance metrics have a dependence on the antenna used, so we used directive antennas pointed at the stirrer to yield the lowest K-factor possible with this setup. The calibration reference plane was brought up to the connectors using a 3.5 mm precision calibration kit. For the measurement of coherence angle, 1500 samples of the OWS were taken to accurately assess where the correlation passes the threshold, and we used two turntable positions for comparison. For the assessment of uniformity, we used 100 paddle-positions and $P = 12$ turntable positions since, generally, $P = 9$ antenna positions are required to assess $\sigma_{G_{\mathrm{Ref}}}$ [3]. A frequency-averaging bandwidth of 100 MHz was used in post-processing.

B. Coherence Distance

As mentioned before, the coherence distance is a critical metric in assessing the amount of independent samples that can be extracted from a single mode-stirring mechanism. Fig. 4 shows the results for normalized coherence distance and the corresponding number of independent samples for various thresholds. Using the most stringent threshold of 0.3, approximately 100 independent samples can be extracted above 1.3 GHz. This number of samples is often used for a single measurement, or independent realization. Therefore, for a threshold of 0.3, a combination of position and paddle stirring should be used when the antenna efficiency is measured below that frequency. For the thresholds of 0.5 and $1/e$, at least 130 and 190 samples can be extracted, respectively.

Generally, one can extract less independent samples when a single stirring mechanism is used, compared to multiple. However, the OWS in combination with this specific surrounding cavity provides a coherence distance small enough to provide sufficient samples needed for a single independent realization of antenna efficiency. Besides that, likely due to its larger surface area in combination with chamber volume and loss, more independent samples can be extracted in this frequency band compared to other (unloaded) chambers with (rotational) stirrers as presented in [3] for the threshold of 0.3. Therefore, the coherence distance measured in this work shows that the OWS can be a suitable candidate to measure antenna efficiency above 1 GHz. Note that the stirrer impact may vary over the range of positions in Fig. 2, where a non-linear stepping of the stirrer may yield lower correlation. This will be part of future research.

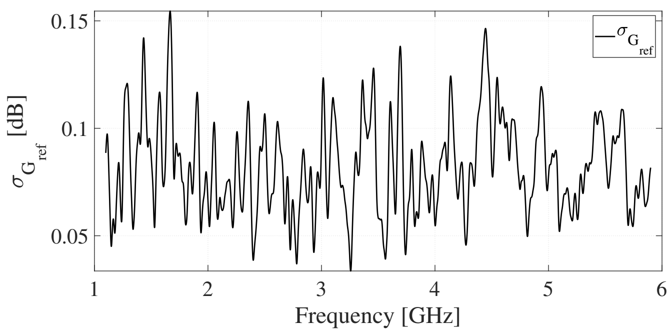

Fig. 5. Standard deviation of G_{ref} over frequency, computed with 12 antenna positions.

C. Uniformity

The chamber component of uncertainty due to lack of spatial uniformity $\sigma_{G_{\text{ref}}}$, as defined in [2], is calculated according to (2). The standard deviation including coverage factor of the best estimate is extracted from twelve positions, where the best estimate is the mean over all twelve positions. Fig. 5 shows the standard deviation, normalized to G_{ref} [2]. $\sigma_{G_{\text{ref}}}$ varies over frequency, but, in a wireless-testing context, the highest value in the band of interest is generally used to assess the uncertainty for that bandwidth [2]. In this case, the maximum standard deviation in the 1-6 GHz band is 0.15 dB, which corresponds to approximately 3.5 % deviation in antenna efficiency. Such deviations in efficiency have been reported before [8], and the uniformity of this chamber is comparable to that of unloaded chambers reported in other works [12]. Therefore, even though only a single mode-stirring mechanism is used, the uniformity of this chamber yields very good conditions for antenna-efficiency testing.

Note that spatial uniformity and coherence distance or angle are directly related, since a higher correlation often corresponds to a higher value of $\sigma_{G_{\text{ref}}}$ [3]. While these metrics contribute to the largest uncertainty in antenna-efficiency measurements [7], this does not mean that there are no other important metrics of interest in characterizing the performance of the OWS, and the entire RC. For example, in a previous work, much larger deviations in positioning have been observed in efficiency when the two-antenna method was used to obtain the efficiency estimate [8], which would not show in the antenna-replacement method. To further investigate the performance of mode-stirring mechanisms such as the OWS, future work will focus on uncovering such effects by investigating different configurations of the paddles of the OWS, and will focus on more performance metrics.

IV. CONCLUSION

In this work, we have investigated the performance of the oscillating-wall stirrer in a reverberation-chamber above 1 GHz for the purpose of measuring antenna efficiency. In doing so, we focused on the performance metrics of coherence distance and uniformity, as these are generally the largest contributors to uncertainty in antenna efficiency. We conclude that, with the most stringent threshold of 0.3, at least 100 samples can be extracted for frequencies above 1.3 GHz, which is more than some other chambers with traditional (rotating) stirring mechanisms and enough to perform an independent antenna-efficiency measurement. The low coherence angle is likely a result of the increased surface area of this type of stirrer. The spatial uniformity, measured from the deviation in the chamber transfer function, was maximum 0.15 dB, which yields a 3.5 % deviation in antenna efficiency. This is an acceptable error bound, and makes the oscillating-wall stirrer a suitable candidate for antenna-efficiency testing with the antenna-replacement method. Future work will investigate additional metrics and the effect of other paddle configurations on those metrics.

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