Calibration and Validation of Wideband Complex Excitation Coefficients for a Low Frequency Plane Wave Generator

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Abstract— **Plane Wave Generators (PWG) have proven to be an effective solution for testing antennas and active devices in compact anechoic environments. Precise control over excitation coefficients is critical for achieving uniform amplitude and phase in the Quiet Zone (QZ), as excitation errors can adversely impact measurement accuracy. This paper investigates different calibration techniques to minimize excitation discrepancies in a 19-element PWG subarray operating at UHF/VHF frequencies. The array was characterized using the Pulsar by AGC spherical near-field automotive range, employing different post-processing techniques to determine the realized excitation when all elements are excited simultaneously. An excellent correlation was observed between conducted measurements of individual components, such as phase shifters, and full radiated array measurements analyzed using a field expansion method. This approach requires a single measurement of the fully excited subarray and the measurements (or accurate modelling) of the individual sub-arrays, streamlining the calibration process while maintaining high accuracy.**

I. Introduction

Plane Wave Generators (PWG) employ an array of elements that are strategically arranged and excited to approximate a plane wave and establish a far-field condition within a Quiet Zone (QZ), located in the near-field region of the array[1]-[4]. Their compact design allows to achieve a closer approximation of far-field conditions than comparably sized Compact Antenna Test Range (CATR) systems. However, the discrete sampling of the radiating aperture by the PWG's array elements inherently limits the maximum achievable electrical size of the QZ. Consequently, PWGs are predominantly used in lower-frequency measurement applications, such as UHF and VHF, where system size is a critical design consideration [4], [5]. As a result, PWGs are often employed as a practical alternative or, more frequently, as a complement to traditional CATR-based systems, particularly for low-frequency testing scenarios.

The PWG concept has demonstrated its effectiveness as a solution for testing antennas and devices in compact anechoic environments [1], [2], [4]. Technology advancements have brought the PWG concept from a theoretical framework to the industrial-grade testing solution of today, with notable applications in testing antennas and active devices at frequencies ranging from VHF/UHF to millimeter waves [3], [1].

To fully realize its potential to approximate the ideal far field condition of uniform amplitude and phase within the QZ, the excitation of the PWG must be meticulously controlled across the entire operational frequency band as excitation errors will give rise to deviations from the ideal far field condition. For this reason, a proper calibration of the array is needed. The goal of the calibration is to minimize discrepancies in array excitation caused by imperfections in the Beam Forming Network (BFN) in particular to compensate for error in the amplitude/phase shifters, but also cable variations, individual element responses, and inter-element coupling within the array.

This paper examines the effectiveness of various calibration techniques suitable for UHF/VHF band frequencies, focusing on their ability to quantify errors in the realized excitation of an array. The study evaluates these techniques using a 19-element sub-array, which forms part of a larger PWG, as illustrated in in Fig. 1. By comparing the performance of different approaches, this investigation aims to identify the most effective calibration methods to effectively compensate and minimize excitation errors and to provide an estimate for achievable calibration accuracy.

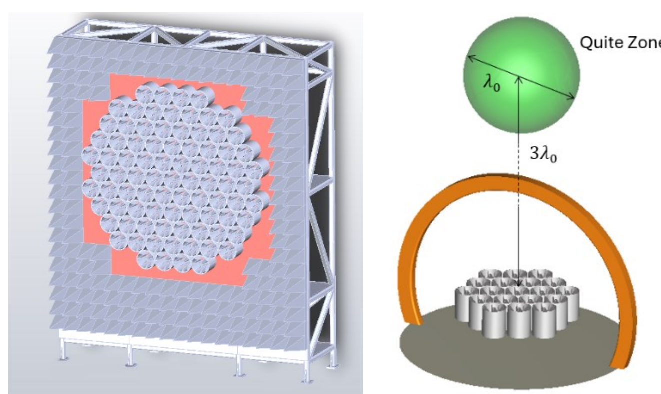

Fig. 1. Full PWG array solution for measurements of wide band antennas and active decives at VHF/UHF frequencies (left). Skecth showing the investigated 19-element PWG sub-array measured in the Pulsart by AGC spherical near field automotive range (right).

II. PWG OVERVIEW

The investigated PWG is divided into sub-arrays. The individual antenna elements of each sub-array are configured with identical amplitude and phase coefficients distributed through a uniform feeding network. Phase matched cables of equal lengths are used to ensure minimum amplitude and phase deviation between elements, enabling the array to operate effectively across a wide frequency band. The array excitation, in terms of amplitude and phase coefficients of the sub-arrays, are controlled by analog wideband amplitude/phase modules, which are digitally controlled as described in [3], [1]. This feeding architecture eliminates the need for analog-to-digital or digital-to-analog conversions, and thus distortion of wideband signals. The use of linear components makes the array both bi-directional and reciprocal. Although this implementation does not include distributed signal amplification, the design allows for this feature as an optional enhancement.

Amplitude excitation is achieved by using programmable attenuators, while the phase is controlled by programmable phase shifters. Amplitude weights are controlled in 0.5dB steps on a 0-40dB dynamic range while a phase resolution smaller than 2° can be achieved. The programmable amplitude/phase module is shown in Fig. 2. Also shown is the measured phase response of four different modules. The imposed phase, ranging from 0° to 360°, remains stable across a 10:1 bandwidth, exhibiting minimal frequency dependence. This stability makes the modules ideal for wideband coefficient applications. Variation on the realized amplitude and phase values need to be compensated by means of look-up tables derived from dedicated calibration performed with a Vector Network Analyzer (VNA).

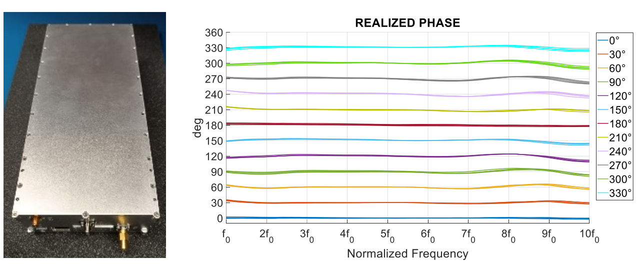

Fig. 2. Wideband programmable amplitude and phase shifter developed for this validation (left). Measured phase response of 4 different phase shifter modules in a 10:1 bandwidth (right).

A representative prototype sub-array, comprising the 19 central elements of the proposed VHF/UHF frequency design, was fabricated and measured to validate the PWG concept. The sub-array has a diameter of approximately $2.1\lambda_0$, with an element spacing of $0.4\lambda_0$, where λ_0 is the wavelength of the lowest frequency (f_0) of the design frequency range. To optimize specific sub-bands, various quiet zone (QZ) syntheses were performed across the frequency range from f_0 to $8f_0$. Additionally, different QZ sizes and QZ distances were analyzed. As shown on the right side of Fig. 1, in this paper the results related to a QZ size of $1\lambda_0$, at PWG aperture to QZ center distance of $3\lambda_0$ are reported. The considered optimized sub-band ranges from f_0 to $2f_0$.

III. MEASUREMENTS AND DIGITAL TWIN PWG

The validation measurements were performed in a MVG multi-probe spherical near-field automotive test range, operating from 70 MHz to 6 GHz, installed in the Pulsart by AGC facility in Belgium. As shown on the right-side of Fig. 1, the sub-array was positioned on the ground, radiating upwards into the hemispherical near-field (NF) system. As part of the validation, the measurements were compared to the full-wave digital twin model of the entire array. The digital twin was also used to generate the array excitation coefficients, which were applied in the BFN. Measurements of have been conducted on the extended 8:1 bandwidth from $0.5f_0$ to $4f_0$, in order to validate digital twin predictions.

The programmable amplitude/phase modules of the BFN were set with excitation coefficients derived from an optimization of the digital twin of the PWG. Hemispherical NF data radiated by the whole array (driven through the BFN from a single input port) was collected at the measurement distance and then propagated to the desired QZ coordinates using NF-to-NF post-processing. This technique is discussed further in [3], [1].

Measured results were then compared to numerical predictions using the digital twin model.

A comparison in terms of 2-dimensional QZ field maps between measurements and predictions is shown in Fig. 3. The down-range (xz-plane cut) at $1.5f_0$ in amplitude and phase is shown [6]. Minimal differences between measurements and predictions are observed confirming the correct implementation and setting of PWG.

The measured and simulated nominal-to-peak amplitude and phase variations within the QZ volume are shown in Fig. 4 and Fig. 5, respectively [6]. Results for both orthogonal polarizations of the PWG are shown. The correlation between measurements and digital twin is encouraging but some discrepancies are noted. These are in part due to the finite measurement accuracy but can also be attributed to errors on the realized excitation of the PWG.

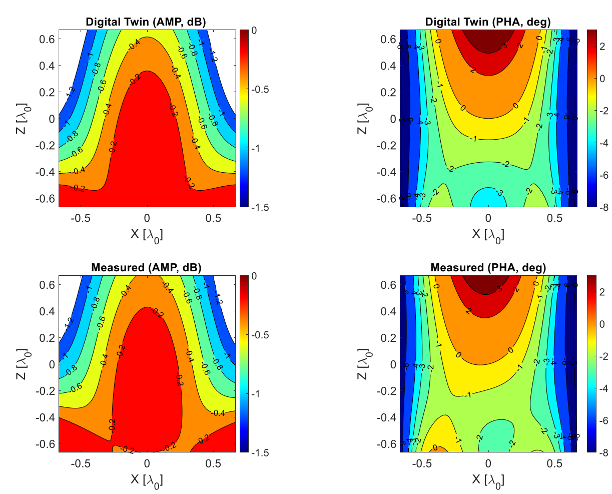

Fig. 3. Measured and simulated (digital-twin) amplitude and phase field maps over the QZ down range at the center $1.5f_0$ frequency for the 19-element array using wide-band coefficients optimized at f_0 to $2f_0$.

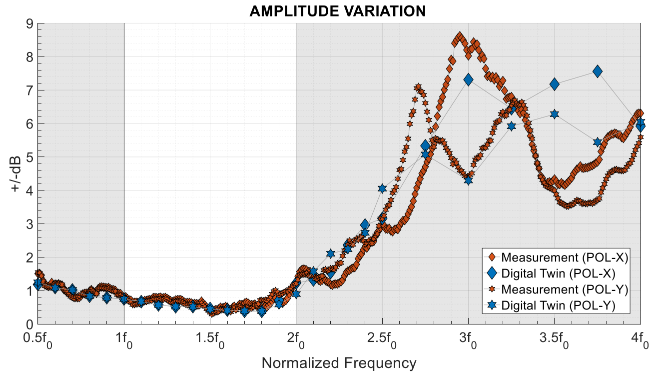

Fig. 4. Measured and simulated (digital-twin) worst case, nominal-to-peak amplitude variations over the QZ volume with dedicated wide-band optimisation in the f_0 to $2f_0$ frequency range for the 19-element array.

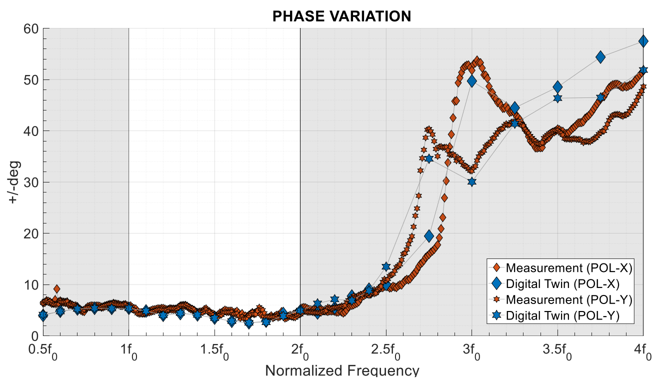

Fig. 5. Measured and simulated (digital-twin) worst case, nominal-to-peak phase variations over the QZ volume with dedicated wide-band optimisation in the f_0 to $2f_0$ frequency range for the 19-element array.

IV. Exitation Error Investigation

The investigation of the error on the realized excitation coefficients of the measured array was performed by different methods and the results compared to the error determined by conducted measurements on the individual programmable amplitude/phase modules. The latter was found to be of minimum influence in the available measurement setup.

A. Holography investigation

A straightforward and easy investigation method is to use the well-known holographical back-propagation to the array aperture [7]-[8]. The hologram at the desired distance is obtained by properly phase-shifting the far-field of the device under test, computing the plane wave spectrum and finally applying the inverse FFT (Fast Fourier Transform). The achievable resolution of this method is well-known to be half-wavelength [8].

An example of such investigation for the considered array at $1f_0$ and $3f_0$ is reported in Fig. 6. As the element spacing is only $0.4\lambda_0$, this technique, as expected, does not allow to distinguish the excitations of the individual array elements at low frequencies like $1f_0$. On the other hand, at $3f_0$, elements are electrically more separated, and they can be easily identified. This allowed us to positively verify the realized excitation coefficients at higher frequencies.

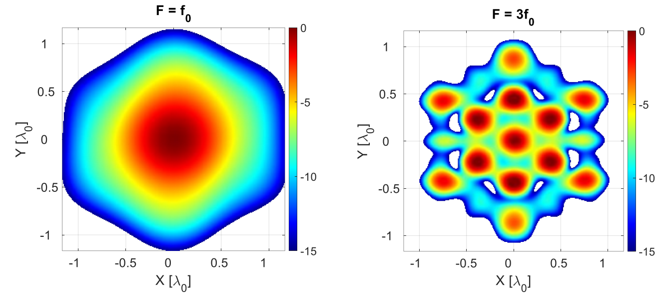

Fig. 6. Holography back-propagation from measured far field data on the array aperture (amplitude in dB).

B. Field Expansion Method

The field expansion method is a simplified form of the expansion discussed in 0. Using the measured spherical NF (SNF) pattern of each individual sub-array ($SNF_{subarray,i}$), the measured complex pattern of the array (SNF_{pwg}) can be expanded into best fit complex exitation coefficinets C_i as shown in the equation below:

$$SNF_{pwg}(r,\theta,\varphi) = \sum_i C_i SNF_{subarray,i}(r,\theta,\varphi)$$

The advantage of this approach is that, as the sub-arrays are measured, we get a good approximation to the excitation errors from BFN and thus a comparison basis with the errors determined from the conducted measurements of each individual programmable amplitude/phase module. The determined amplitude and phase variations on the BFN from these measurements on a $1f_0$ and $4f_0$ bandwidth are reported in Fig. 7. Excellent agreement between the conducted measured deviations (dashed traces) and the errors determiend by the expansion technique (solid traces) can be observed across the whole frequency range.

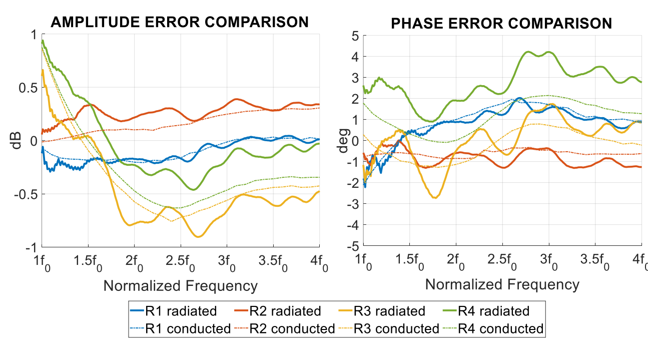

Fig. 7. Comparison between amplitude and phase error for each PWG ring: radiated field expansion method (solid); conducted measurements of individual programmable modules (dashed).

V. Discussion of the Results

The comparison highlights significant differences in performance between holography and the field expansion method, particularly at low frequencies. A bit as expected, the holography demonstrates limited effectiveness in this range, whereas the field expansion method provides significantly better results, making it more suitable in these cases of LF applications and where individual measurements of the sub-array patterns are available and feasible to do.

As general comment on the array performance it can be noticed that the determined excitation errors are well within reasonable limits for PWG applications. This indicates that the programmable amplitude and phase shifters are delivering reliable performance as well as the remaining BFN components and cables. The achieved excitation is accurate, with no adverse effects observed from factors such as coupling, active impedance variations, or leakage in the elements of the BFN. This indicates robust system integrity and minimal degradation in array performance.

Future work on this topic would be to investigate the full array pattern with more accurate diagnostics techniques such as equivalent current techniques [10].

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