Recent Advances in Plane Wave Generators for Low Frequency Antenna and System Level Testing

Lars Jacob Foged[1*]
[1]Microwave Vision Group, Italy
[*]email: lars.foged@mvg-world.com

***Abstract* – The Plane Wave Generator (PWG) concept has been employed for various testing applications for over four decades. Recently, it has gained renewed attention as a promising measurement technique for antennas and devices operating at low frequencies where traditional test methodologies, such as Compact Antenna Test Range (CATR) or direct far-field ranges, are less practical or cost-effective. This paper provides an overview of the historical development of PWG technology, with a focus on recent advancements and emerging applications in antenna and system-level testing.**

***Keywords* — antennas, antenna measurements, device measurements, plane wave generator.**

I. INTRODUCTION

The Plane Wave Generator (PWG), also known as Plane Wave Synthesizer (PWS) is an array comprising radiating elements with optimized complex excitation coefficients designed to approximate a plane wave at close range. The PWG achieves this by discretely sampling the radiating aperture using its array elements, focusing energy in the near field to synthesize a plane wave within a spherical quiet zone at the design distance. This method contrasts with the Compact Antenna Test Range (CATR), which forms a plane wave within a cylindrical quiet zone in front of a reflector, relying instead on continuous sampling of the radiating surface [1].

II. EARLY DEVELOPMENT OF PWG ARRAYS FOR LOW-FREQUENCY TESTING

Two-dimensional antenna arrays for PWG applications were initially developed for electromagnetic susceptibility testing, with the goal of approximating far-field conditions within a confined test volume. These arrays have proven particularly effective at sub-GHz frequencies, specifically in the 50 MHz to 2 GHz range, where other techniques, such as Compact Antenna Test Range (CATR) face significant challenges. Alternative approaches, such as direct far-field testing, were considered suboptimal at these frequencies due to the low fraction of radiated power intercepted by the test volume, placing stringent demands on the size and performance of the anechoic enclosure. Additionally, the far-field distances required at these frequencies are often prohibitively large, making traditional outdoor or indoor ranges impractical for many applications.

The concept of the PWG and an array generating an approximation to a plane wave is widely credited to the work of Martsafey and Bennett & Schoessow [2], [3]. The foundation theory for generating a plane wave in the near field is further detailed in Hansen [4] and IEEE Standard 149-2021 [1].

The first experimental demonstration of a two-dimensional PWG array was reported by Lynggaard [5], who designed and tested a five-element planar array composed of horn antennas. Although the array geometry was planar, the element weightings were derived based on theoretical formulations for large spherical apertures. The resulting plane wave approximation was evaluated within a small spherical test volume positioned at a significant distance from the array. Building on this concept, subsequent work introduced further advancements. Hill [6], for instance, implemented a seven-element Yagi-Uda array operating at 500 MHz for similar purposes.

In another effort [7], a circular array configuration was synthesized to generate a plane wave within the enclosed region of the array, and dynamic beam scanning was successfully demonstrated. The array was designed to operate across a wide frequency range, from 50 MHz to 1000 MHz, thanks to the tunability of its elements. However, experimental validation was carried out specifically at 500 MHz, and the complex excitation coefficients were only defined at discrete frequencies, as will be discussed later. The array employed an inter-element spacing of λ_0, and the quiet zone (QZ) was a cubic region with side lengths of $1.5\lambda_0$. During testing, the QZ was centered at distances of $1.75\lambda_0$ and $2.75\lambda_0$ from the array, with results showing improved plane wave approximation at the greater distance. To preserve the quality of the approximation, the QZ dimensions needed to remain smaller than the maximum inter-element spacing. The array employed a hexagonal layout, which could also be interpreted as a two-ring configuration with a central element. Broader synthesis methodologies and design principles for PWG systems are detailed in [8], [9].

In parallel, significant attention has been given in the literature to the generation of near-field plane waves using linear arrays of line sources [10]. This approach is particularly appealing for specialized measurements, such as testing linear antenna arrays, due to its simplicity and the reduced number of radiating elements required. However, it lacks the capability to generate a sufficiently large two-dimensional QZ suitable for general-purpose antenna testing.

III. MEASURMENTS AND SIMULATIONS OF LOW FREQUENCY PWG ARRAY DEMONSTRATOR

A low frequency PWG array demonstrator, consisting of 19 elements distributed on a hexagonal lattice, has been manufactured and measured to validate the PWG design at VHF/UHF frequencies. The diameter of the array is roughly $2.1\lambda_0$, with an element spacing of $0.4\lambda_0$, where λ_0 is the wavelength at the lowest operating frequency f_0=100MHz. Different QZ syntheses were performed across a frequency range from f_0 to $10f_0$ to optimize specific sub-bands. Various QZ sizes and QZ to PWG distances were also considered. It was observed that increasing the distance between the QZ and the array improved QZ performance during the wideband optimization of the coefficients, and it also enabled the creation of a larger QZ.

The measurement results related to the following PWG configuration are reported:

- QZ diameter: $1\lambda_0$
- PWG to QZ distance: $3\lambda_0$
- Optimized sub-band: f_0 to $2f_0$
- Lowest frequency f_0: 100MHz

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 [11]. The PWG array was positioned on the ground, radiating upwards into the hemispherical near-field (NF) system as shown in Fig. 1. 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 beamforming network (BFN). Measurements have been conducted on the extended 8:1 bandwidth from $0.5f_0$ to $4f_0$, in order to validate the digital twin predictions.

Fig. 1. Left: measurement scenario of the 19 element PWG array during validation measurement in the Pulsart by AGC spherical near field automotive range. Right: Image of the 19-element array during measurement.

A comparison of the measured and predicted (digital twin) amplitude and phase variation within the QZ down-range at 1.5fo frequency are shown in Fig. 2. Minimal differences between the measurements and predictions are observed, for both downrange and cross range measurements and predictions, indicating that the PWG concept can be easily scaled to other frequency bands.

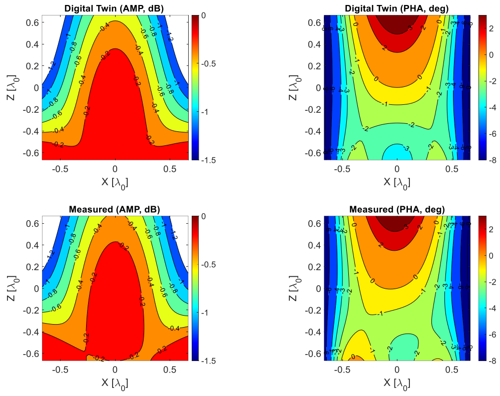

Fig. 2. Measured and simulated (digital-twin) amplitude and phase variations over the QZ down range at the center $1.5f_0$ frequency for the 19-element array.

IV. CONCLUSION

A 19-element PWG demonstrator for VHF/UHF band in dual polarization and 10:1 operating frequency bandwidth has been successfully validated by measurements.

ACKNOWLEDGMENT

The author thanks the Pulsart by AGC team, Yvain Cornet, Arthur Romeijer and Vincent Vandenberghe, for support during the measurement campaign and Francesco Saccardi, MVG, for the measurements post-processing.

REFERENCES

[1] IEEE std 149-2021 "IEEE Recommended Practice for Antenna Measurements," [1] (Revision of IEEE Std 149-1977)

[2] Martsafey, V.V., “Measurement of electrodynamic antenna parameters by the method of synthesized aperture”, Radio Eng. Electron. Phys., vol. 13, n. 12, pp. 1869-1873, 1968.

[3] Bennet, J. C., Schoessow, E.P., "Antenna near-field/far-field transformation using a plane-wave-synthesis technique", Proceedings of the IEEE, vol. 125, n. 3, pp. 179-184, Mar. 1978.

[4] J.E. Hansen, Spherical Near-field Antenna Measurements , Chapter 7, "Plane-wave Synthesis," Peter Peregrinus Ltd., London, England 1988.

[5] Lynggaard, S. K. Plane wave synthesis for antenna measurements. Technical University of Denmark (in Danish), M. S. thesis; 1982.

[6] D.A. Hill, "A Near-field Array of Yagi-Uda Antennas for Electromagnetic-susceptibility Testing," IEEE Transactions on Electromagnetic Compatibility , Vol. 28, No. 4, August 1986.

[7] D.A. Hill, "A Circular Array for Plane-wave Synthesis," IEEE Transactions on Electromagnetic Compatibility, Vol. 30, No. 1, February 1988, pp. 3-8.

[8] O. M. Bucci, M. D. Migliore, G. Panariello and D. Pinchera, "Plane-wave generators: Design guidelines achievable performances and effective synthesis", IEEE Trans. Antennas Propag., vol. 61, no. 4, pp. 2005-2018, Apr. 2013

[9] A. Capozzoli, C. Curcio, G. D'Elia, A. Liseno and P. Vinetti, "A novel approach to the design of generalized plane-wave synthesizers," 2009 3rd European Conference on Antennas and Propagation, Berlin, Germany, 2009, pp. 3375-3379

[10] R.L. Haupt, "Generating Plane Waves from a Linear Array of Line Sources," Antenna Measurement Techniques Association Conference , Denver, CO, October 2001.

[11] F. Saccardi et al., "Uncertainty Analysis of a Multiprobe Antenna Measurement System for Full Vehicle Testing," AMTA symposium, Cincinnati, OH, USA, 2024.