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# Helical Antenna Characterization Using the Singularity Expansion Method

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**Abstract**—This paper presents the application of the Singularity Expansion Method (SEM) to model the measured field backscattered by a high gain helical antenna. The SEM allows modeling its late time response using poles which are theoretically independent of the incident wave angle. These poles can thus be used for antenna identification. One of the major limitations of the SEM is its complexity to extract the physical poles of the antenna, i.e. those which are independent of the direction. In this paper, we show that it is possible to estimate one physical set of poles by considering only the boresight direction. This poles' set allows modeling the late time measured field backscattered the antenna with a very high accuracy in both time and frequency domains. Then, these poles are compared to those extracted from other directions and we observe a very good stability of the poles regarding the incident wave angle.

## I. INTRODUCTION

The Singularity Expansion Method (SEM) has been first established by C. E. Baum in 1971 [1]. The SEM allows modeling the late time response of an object as a decay exponential sum, using two parameters: poles and residues. The poles are independent of the incident wave angle. Indeed, only the weights of these poles, i.e. the residues, vary from one direction to another. The SEM has been applied on antennas for the first time in 1973 [2-3] and is still currently used to model the antenna effective length in a compact way [4-6]. Since the poles are independent of the incident wave angle, the SEM has also been widely used for object identification like aircraft [7-8] and chipless RFID tag [9]. One critical point of the SEM is the complex split between the early and late time parts. Although the duration of the early time  $T_e$  is theoretically defined as  $T_e = 2D/c + \tau$ , where  $D$  is the largest dimension of the antenna,  $c$  is the speed light and  $\tau$  is the impulse width, this value is very important and impact directly the pole extraction [10-12]. Another point which is usually neglected is the length of the considered windowed response. Indeed, this value also impacts the pole extraction, especially when dealing with noisy data like measurement. [13].

Using the measured field backscattered by a helical antenna, we show that a good definition of the considered window on which the SEM is applied, leads to a very relevant

set of poles. Indeed, these poles allow modeling the antenna backscattering in both the time and frequency domains with a very high accuracy. There are several extraction methods. In this paper, we use the Matrix Pencil Method (MPM) [14-15] using a Total Least Square approach [16]. Indeed, this method has been shown as the most robust to noise to extract the physical poles of an antenna [17].

## II. POLES EXTRACTED FROM THE HELICAL ANTENNA

### A. Presentation of the measurement

We consider the helical antenna presented in Fig. 1 [18]. A 4-turns printed helix antenna wrapped around a cylindrical Rhoacell foam is placed into a truncated cone cavity whose small radius is 58 mm and large radius is 120 mm. The helix is 45 mm high while the cavity is only 32 mm high.

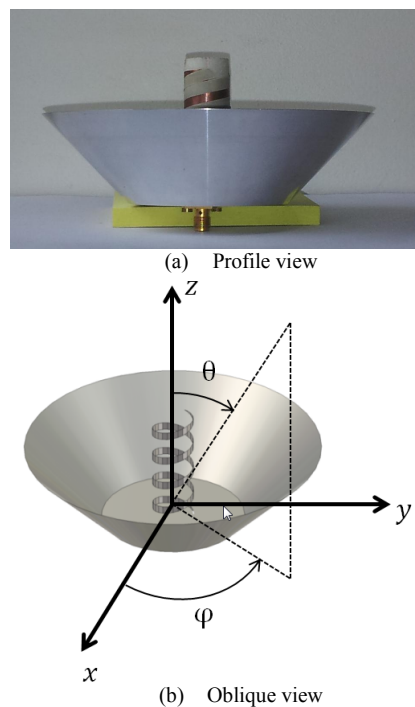


Fig. 1. Presentation of the helical antenna.

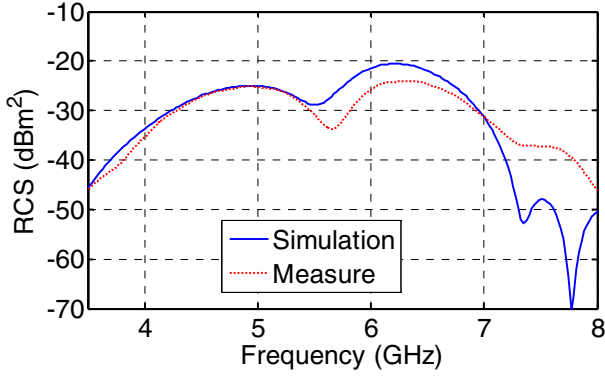


Fig. 2. Simulated and measured monostatic Radar Cross Section of the helical antenna in the boresight direction in the frequency domain.

The backscattering of this antenna has been measured between 3.5 and 8 GHz in the anechoic chamber CHEOPS of the DGA, Bruz, France. This chamber measures 25\*25\*12 m and its Radar Cross Section (RCS) sensitivity is  $-60 \text{ dBm}^2$ . The measured RCS in the boresight direction ( $\theta = 0^\circ$ ) is compared to the simulated one in Fig. 2. Between 3.5 and 5.5 GHz, the two curves are very close. Then, there is up to 5 dB difference between 5.5 and 7 GHz. Beyond 7 GHz, the difference is much higher (up to 30 dB). This is due to the imperfections of realization and mainly to the quality of the helix shape.

### B. Antenna physical poles extraction

In order to apply the MPM, an Inverse Fast Fourier Transform (IFFT) is applied to the measured backscattered field and the result is presented in Fig. 3. Considering the size of the antenna, the theoretical beginning of the late time occurs at 1.2 ns in Fig. 3. To define the optimal length of the window, we use the Window Increasing Technique (WIT) [14]. Results are presented in terms of resonant frequencies and damping coefficients in Fig. 4. Until 2.8 ns, the poles are not stable, especially regarding their damping coefficients. Then, until 3.5 ns, they become stable for both real and imaginary parts. After 3.5 ns, they look very stable but if we consider the very low level of the new samples for these windows (after 3.5 ns in Fig. 3), there is no reason that the poles change that much. Moreover, we can see that the magnitude of the damping coefficients decrease a lot. One explanation of this

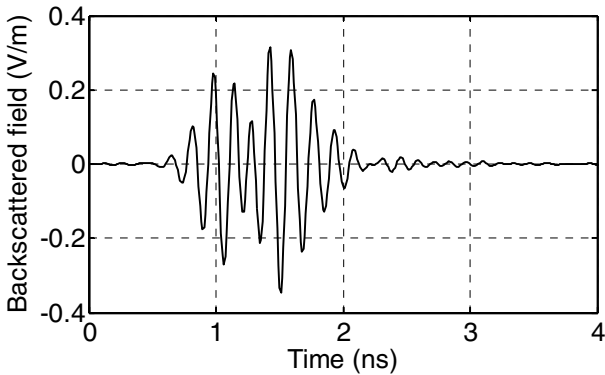
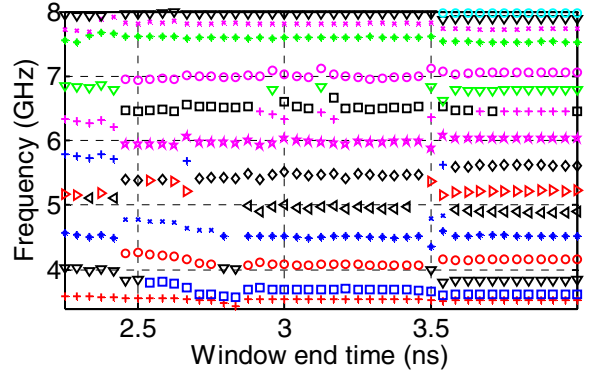
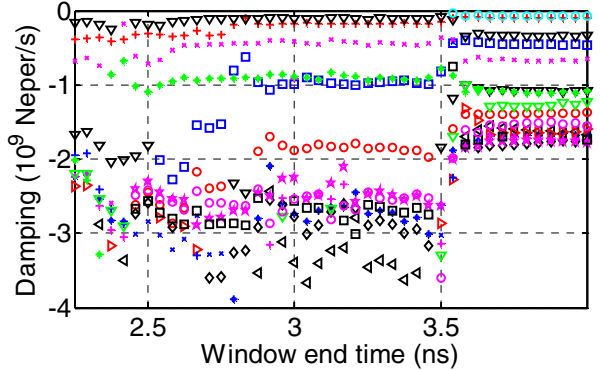


Fig. 3. Measured electric far field backscattered by the helical antenna in the time domain.



(a) Resonant frequencies



(b) Damping coefficients

Fig. 4. The MPM applied on an increasing window with a fixed start time equal to 1.2 ns.

phenomenon is that since the measured signal in the far late time becomes very weak (low), it is more influenced by the noise and the estimation of poles becomes inaccurate. Thus, the optimal window we define starts from 1.2 ns and includes time until 3.2 ns. Another critical point of the SEM is the order of the model, i.e. the number of poles  $N$  that the MPM try to extract. Poles extracted with the MPM for several  $N$  values from the well-windowed backscattered field are presented in the complex plane in Fig. 5. We can see a very good stability of the poles regarding  $N$ . It means that, once the antenna response is well windowed, the  $N$  value doesn't impact the extracted poles, if  $N$  is chosen large enough. These poles are

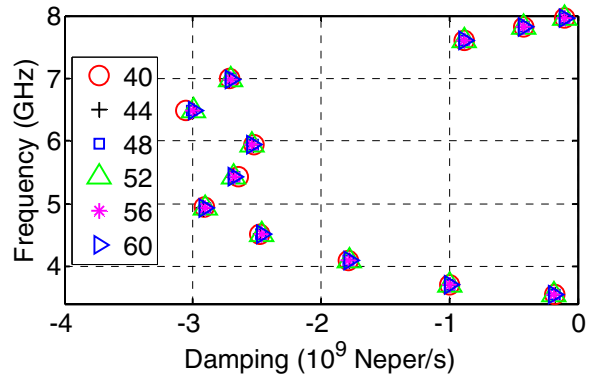


Fig. 5. Poles extracted from the windowed electric far field backscattered by the helical antenna for several  $N$  values.

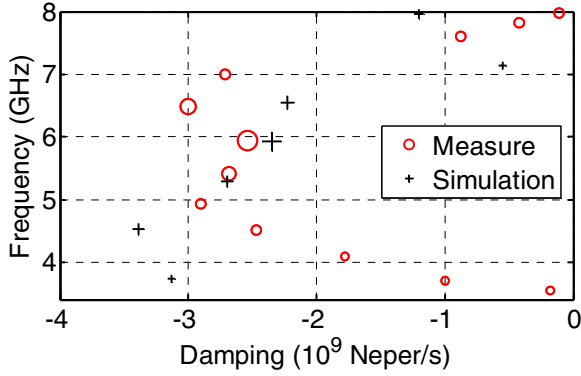


Fig. 6. Poles extracted from the simulated and measured fields backscattered by the helical antenna, represented in the complex plane.

presented using a  $|R|/|\sigma|$  weighting in Fig. 6. The same extraction process has been applied on the field backscattered by the helical antenna in simulation. The defined poles' set is also presented in Fig. 6. The three main poles (around 5.5, 6 and 6.5 GHz) are very close, especially regarding their resonant frequencies.

The physical poles' set extracted from measurement are now used to reconstruct the late time backscattered field. The results are presented in both time and frequency domains in Fig. 7 and Fig. 8, respectively. In the time domain, the measured field and the reconstructed one are perfectly overlapped. Indeed, the Normalized Mean Square Error (NMSE) between the two responses is lower than 0.001 %. In the frequency domain, the two curves are also very close and the NMSE is about 0.05 %.

### C. Poles from other directions

Theoretically, the poles are independent of the incident wave angle. It means that the poles we extract from the boresight direction should be able to model the late time fields backscattered in any other directions. This has been verified in the  $\varphi = 0^\circ$  plane. The NMSE of the reconstructed late time backscattered field as a function of the angle  $\theta$  is presented in Fig. 9. We observe that the NMSE is lower than 0.08 % whatever the angle  $\theta$ . It means that the 24-poles' set extracted

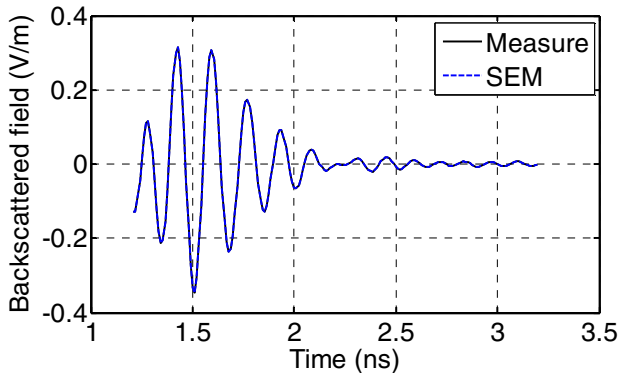


Fig. 7. Late time field backscattered by the helical antenna in the time domain: measured (solid) and reconstructed using SEM (dashed).

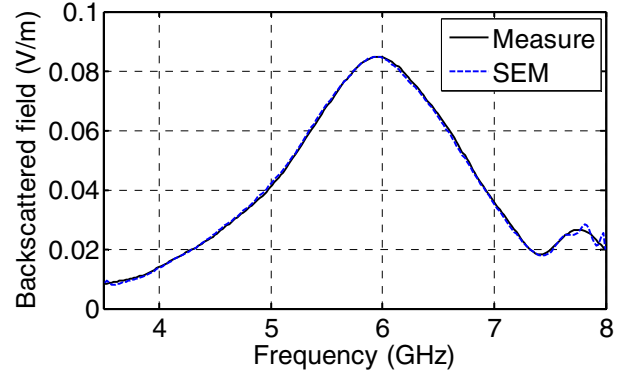


Fig. 8. Late time field backscattered by the helical antenna in the frequency domain: measured (solid) and reconstructed using SEM (dashed).

from the boresight direction is very relevant to model the late time backscattered field from any directions. It has to be noticed that the residues have been computed for each direction using the poles and the backscattered field in the considered direction.

In order to use these poles in an identification process, one needs to be able to extract them directly from all directions. The Fig. 10 presents the poles extracted directly from all the directions of the  $\varphi = 0^\circ$  plane in terms of resonant frequencies and damping coefficients as a function of the angle  $\theta$ . Even if there are some slight variations, the resonant frequencies are stable as a function of  $\theta$ . The damping coefficients vary more significantly but the order of magnitude is quite similar: those linked to the main poles are included between -2 and -3  $10^9$  Neper/s.

### III. CONCLUSION

In this paper, we show that if the considered backscattered field is well windowed, it is possible to extract some poles from the only boresight direction which are relevant for any direction. Moreover, these poles can be directly extracted from these other directions. Indeed, the results obtained with the measurement of the helical antenna show a good stability of the poles regarding the incident wave angle.

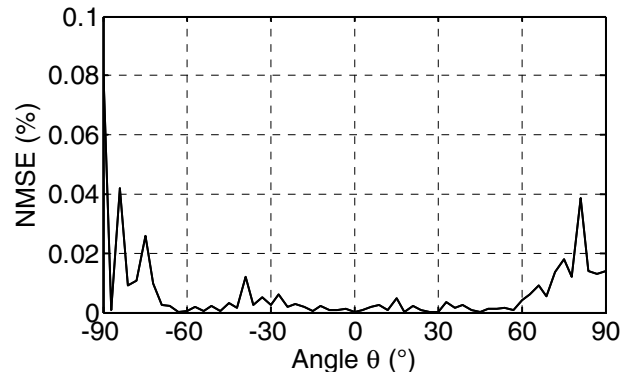
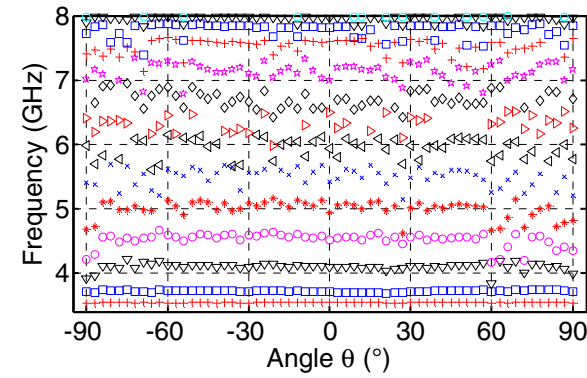
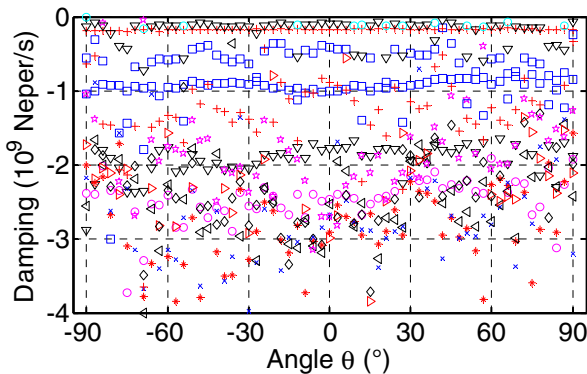


Fig. 9. The Normalized Mean Square Error of the reconstructed response of the helical antenna using the same set of poles as a function of the angle of incidence  $\theta$ .



(c) Resonant frequencies



(d) Damping coefficients

Fig. 10. Poles extracted from the measured electric far field backscattered by the helical antenna as a function of  $\theta$ .

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