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STATISTICAL ANALYSIS OF ELECTROMAGNETIC FIELD INSIDE A JET ENGINE USING THE REVERBERATION CHAMBER APPROACH

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Abstract—In this paper, the electromagnetic field distribution inside a jet engine is studied through full wave analysis. Results are statistically analyzed by comparisons to the models used for the reverberation chamber with a mechanical mode stirrer. The jet engine is simulated as an open cylinder containing one set of rotating blades by using 'Ansys®HFSS'. A simple Hertzian dipole illuminates the interior structure as an incident wave excitation representing a transmitting antenna radiating continuous wave fields. The field distribution inside the engine, which results from a distinct set of rotating positions of the blades, is primarily studied through the simulation program. In our case, the mechanical stirrer is represented by the rotating set of blades. The field values are extracted at different planes along the cylindrical engine, and the average field is statistically analyzed. We show that the squared magnitude of the field component along the engine's main axis has an exponential distribution compared to the theoretical exponential distribution proved in a reverberation chamber. This approach promises to act as a novel effective method to analyze the engine system without dealing with the complex details inside the engine cavity.

1. INTRODUCTION

Analysis and modeling of electromagnetic field distribution inside the jet engine are considered as important problems because they span both civilian and military needs. In particular, with the quest for fly-by-wireless [1] where wireless sensors and actuators are used to replace the costly wired systems in different components of the aircraft

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including inside jet engines, this analysis is even more important. Moreover, jet engine designs and analysis techniques are not only limited to aircraft applications but it spans many areas of research such as industrial gas turbines and electrical power generation by natural gas. Different models and numerical techniques were used to get an approximate approach for calculating the electromagnetic fields inside the engine [2–6]. Exact field calculations inside a real engine seem to be extremely difficult due to the complex nature of the problem. Researchers are facing many challenges analyzing such a complex structure to determine the field distribution inside the engine. Basically, the complexity arises from the large jet dimensions, its complex design geometry, and its natural harsh environment. This paper presents a novel approach for the electromagnetic field analysis inside a jet engine using the concept of statistical electromagnetics.

Statistical electromagnetics address the problem of treating interior responses of complex field enclosures or systems by modeling the problem using a probabilistic approach. As the problem becomes more complex, its nature gets closer to statistical systems and it is better to describe its parameters statistically [7]. Reverberation chambers (RC) are one field of applications for statistical electromagnetics. They are used mainly as an effective and efficient testing facility for electromagnetic compatibility measurements. RCs are electrically large, high Q-cavities that generate statistically uniform fields by either mechanical stirrers or frequency stirring [8]. RCs have been well studied theoretically and experimentally [9, 10]. The concept of statistical electromagnetics and reverberation chamber have been applied to many applications characterized by having large cavities with a complex environment [11, 12]. Experimental studies have been done using this approach to determine the commercial aircrafts electromagnetic vulnerability [13, 14]. Moreover, this method was applied to study both the shielding effectiveness of a cylindrical scaled fuselage model and the high intensity radiated fields (HIRF) penetration into aircraft fuselage [15, 16]. Statistical electromagnetics was also applied in wireless communications problems to address the problem of field propagation inside large buildings [17].

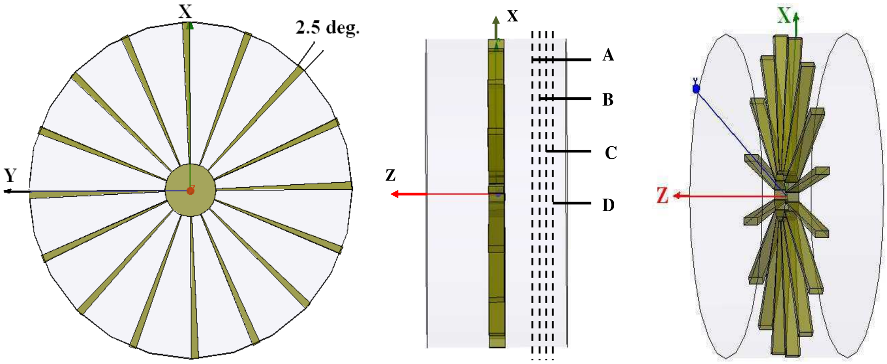
Jet engine environment can be considered as a mechanically stirred RC with the blades acting as a stirrer. The statistical distribution of the field can be evaluated based on the field's cumulative density function (cdf). Analyzing the field nature inside the jet engine can be used in many future studies and applications such as to characterize the communication channel inside the jet engine for the purpose of monitoring its parameters like fuel consumption, pressure and temperature [18, 19].

This paper reports results of a numerical study of the statistical nature of the field inside a simplified jet engine. The numerical study was done using Ansys HFSS which is a powerful full wave simulation environment utilizing the finite element method (FEM) and incorporates the automatic adaptive meshing technique leading to accurate solutions. To analyze the structure numerically, the problem has been approached by considering a set of blades assumed to be extended to the jet engine cylinder with normal position. The statistical properties of the electromagnetic field as a function of the stirrer position were determined and compared to those of the mechanically mode stirred RC. We concluded that the jet engine resembles the interior of a RC; it generates a statistically uniform fields. As a result, we can use all the statistical models that have been derived for the RC to figure out the electromagnetic field inside a jet engine [20, 21]. The statistical analysis of the extracted field values was studied in two cases. The first case is along the jet engine to prove that its average field medium supports the statistical field distribution as in electrically large cavities. The second case is at certain defined plane where the receiving antenna can be placed and analyzed easily depending on the obtained results from the statistical data. The presented analysis in this paper will help us in a future work to characterize the communication channel for wireless sensors inside the engine. These sensors can measure parameters such as strain and temperature.

The paper is organized as follows: Section 2 presents the simplified jet engine model with its dimensions. In Section 3, the average field along the cylindrical engine and in a particular plane was studied. Finally, conclusions are given in Section 4.

2. SIMPLIFIED JET ENGINE MODEL

The engine model is represented by an open cylinder with a single stage of coplanar rotating blades mounted on the central shaft. The length of the blades have been extended to the wall of the cylinder. This model simplifies the problem but in the same time it gives a deep insight into the propagation mechanism. This is done by providing sufficient details of the system and the basic elements for the analogy with the reverberation chamber models. Using HFSS as a full wave simulation environment, the excitation was realized by deploying a hertzian-dipole radially polarized. The outer cylinder radius is 19 cm, the central shaft radius is 3 cm. The dipole is placed at a distance equal to one wavelength from the center of the jet engine along $+Z$ axis according to the geometrical view. There are 16 blades uniformly distributed



(a) (b) (c)

Figure 1. Simplified jet engine model. (a) Front view. (b) Side view. (c) 3-D engine view.

around the shaft as shown in Figure 1(a). The blades were simulated for 90 distinct positions with 0.25 degrees angular increase each time to ensure the randomness of the medium. The blades represent the mode stirrer for the reverberation chamber approach. Figure 1(a) represents the front view for the simplified model, Figure 1(b) represents the side view for the used model with the positions of the used planes for the analysis, and Figure 1(c) represents the 3-D view for the engine. It is important to mention that the dimensions are scaled down by a factor of 10 in order to simplify the geometrical design. The scaled frequency used in the simulations is 5 GHz. The used computer is Intel(R) Core(TM) i7 CPU@1.73 GHz, and 3.18 GB of RAM. The simulation for one position takes about 20 minutes.

3. STATISTICAL ANALYSIS

The hertzian-dipole represents a simple transmitting antenna that radiates continuous wave fields. The hertzian-dipole is characterized by the current multiplied by the dipole length which is equal to 0.012 Am in our simulation. The statistical characterization of the propagating field was generated and studied. More precisely, we discuss the statistical analysis of the field at many different sectional planes along the cylindrical jet engine; in addition to the statistical analysis of the field at a certain defined plane. This discussion will give an idea about the criteria of determining the best place of the receiving antenna in future analysis for a real jet engine. Comparisons between empirical and theoretical probability density functions are performed by curve matching tools. In the next two subsections we discussed the statistical results for the propagating field along the engine and along one of the predefined planes.

3.1. Probability Density Function of $|E_z|^2$ along the Cylindrical Jet Engine

The field values were extracted at different planes defined as shown in Figure 1(b). These planes were set at distances from the center 54 mm (A), 60 mm (B), 66 mm (C), and 72 mm (D) along the $-Z$ axis. These planes are circular planes, and for the purpose of our study all the field values were extracted upon points distributed over a circle which has a 15 cm radius. Such radius was chosen to be approximately in the middle between the outer cylinder and the central shaft. We selected 6 points around each plane. At each point, we calculate the field at the different 90 blade positions. Then we average the field values to compare with the statistical concepts. It was proven that the squared magnitude of any of the electric field components propagating inside a large complex cavity as a reverberation chamber with mechanical mode stirrer, has an exponential distribution [20, 22, 23]. Both the radial and the longitudinal components of the field were extracted from the simulation at different planes. Their squared magnitude were calculated and studied. It is found that $|E_z|^2$ has an exponential distribution. Figure 2 represents the relative frequency histograms and its comparison with the theoretical pdf and cdf exponential models according to (1) which represents the mathematical formulas

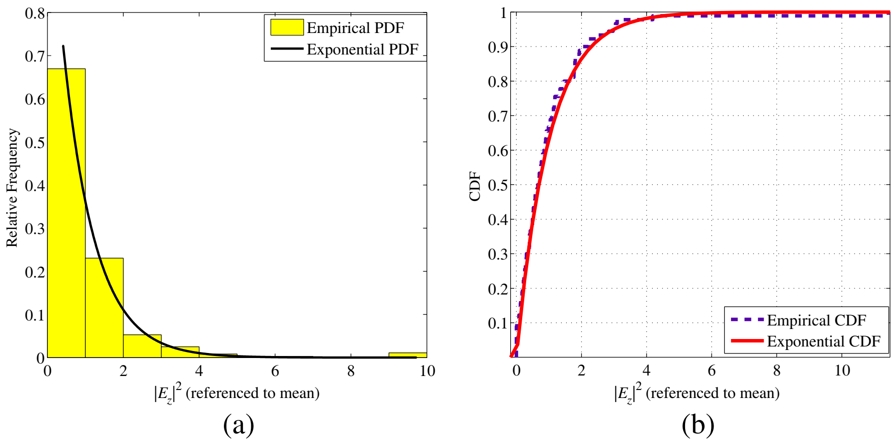


Figure 2. Data relative frequency histograms for the field along the cylindrical jet engine. (a) Empirical pdf versus theoretical pdf model. (b) Empirical cdf versus theoretical cdf models.

for the exponential pdf and cdf. The parameter (a) was estimated by calculating its maximum likelihood estimator (MLE) [23], and it was shown that (a) equals to the mean average [23]:

$$f_x(x) = \frac{1}{a}e^{-\frac{x}{a}}, \quad x > 0 \tag{1}$$

$$F_x(x) = 1 - e^{-\frac{x}{a}}, \quad x > 0 \tag{2}$$

It is clear that there is a great agreement between the two curves for this particular field component, and our main idea is successfully applied.

3.2. Probability Density Function of $|E_z|^2$ at Plane C

One of the purposes of this study is to investigate the propagation model inside the jet engine such that we can measure some useful parameters and control the whole system. One of the basic parameters under study is the location of the receiving antenna. The field values were extracted at plane C, which is a circular plane. The values were extracted at different points located at a circle of radius 15 cm. The empirical and theoretical values for the pdf and cdf of $|E_z|^2$ were compared and illustrated in Figure 3.

The statistical approach is supposed to simplify the analysis of the propagation inside the jet engine and consequently the polarization intended for the receiving antenna. The field at plane C is proved to be

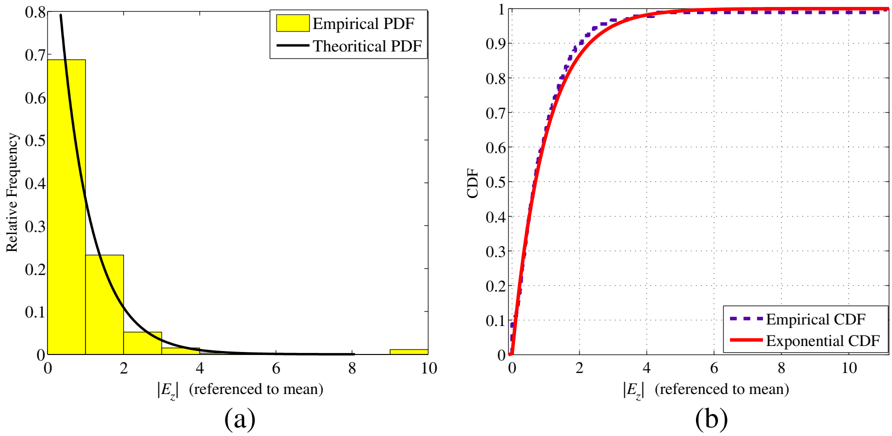


Figure 3. Data relative frequency histograms for the field at plane C. (a) Empirical pdf versus theoretical pdf model. (b) Empirical cdf versus theoretical cdf models.

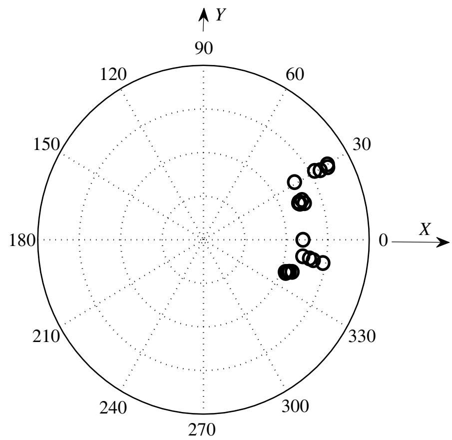


Figure 4. Field strength at different points on plane C.

completely subjected to the proposed statistical analysis and hence this plane presents a good choice for the location of the receiving antenna.

Figure 4 shows the average field values of $|E_z|^2$ at different points on this circular plane such that we can choose the point with the strongest field to put the antenna. This plane was shown as the best location as it is relatively far from the blades and completely satisfies the statistical theory.

4. CONCLUSIONS

A simplified jet engine model has been analyzed using HFSS by dividing the position of the rotating blades in 90 different angles. The field inside the jet engine has been analyzed using a statistical approach derived by the reverberation chamber models. The average field values have been extracted at different planes. Its squared magnitude and its probability density function have been calculated and compared to a theoretical exponential distribution. Moreover, the field values have been extracted at certain plane and compared to the statistical approach, to choose the best location for the receiving antenna. The statistical nature of the field was verified.

The results obtained through this preliminary application of the method are promising. Consequently, this approach suggests a further exploitation of the method to be applied to a real, complete, and complex jet engine with real measurements. Currently, we are building a setup for the jet engine measurements to compare with the simulation. The results will be published in another paper.

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