Fast Prediction of Coupling Coefficient between Monopole Antennas on Electrically Large Cylindrical Platforms Using a Linear Parametric Model

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Abstract **─** Antenna placement on electrically large cylindrical platforms requires a number of time consuming computer simulations that involve analysis of big electromagnetic data. In order to save simulation time, a linear parametric model is proposed to predict the coupling coefficient between monopole antennas on electrically large cylindrical platforms. The two parameters of the model are determined by the values of coupling coefficients at two different distances. The parametric model is then used to predict the coupling coefficient between monopole antennas at various distances. The proposed parametric model avoids repeated time consuming analysis of big electromagnetic data for predicting the coupling coefficients at various distances, and it thus significantly reduces simulation time. Given the desired level of isolation, the proposed parametric model can be used to find the required distance without a trial-and-error process, which further saves the time required by the analysis of big electromagnetic data.

Index Terms **─** Antenna placement, electromagnetic interference, parametric model.

I. INTRODUCTION

Electrically large cylindrical platforms represent an important class of platforms (e.g., commercial aircraft, rocket, etc.). A number of antennas may be installed on a platform for various onboard wireless systems. These antennas may result in interference between different electronic systems. In order to reduce the level of interference, a suitable position should be chosen for every antenna, which is called antenna placement.

An important step in antenna placement is to predict the level of coupling between antennas. Due to the large size of a platform, full wave simulation of antennas on a platform involves the analysis of big electromagnetic data, and it is very time consuming. Besides, the multi-scale feature of antennas on a platform results in ill-conditioned matrix, which further increases the simulation time. Moreover, if an antenna is provided by an external supplier, its detailed design information is usually unavailable to the system engineer, which prohibits the direct modeling of antennas on a platform. Last but not least, a trial-and-error process is usually performed in order to find suitable positions of antennas, which further increases the size of electromagnetic data.

In order to deal with the aforementioned challenges, various new methods were proposed. Recent advances include hybrid methods [1, 2], domain decomposition methods [3-5] and equivalent model methods [6, 7]. These methods have significantly reduced the CPU time and memory cost required by the simulation of antennas on large platforms. However, the trial-and-error process is still needed for antenna placement. Hence, it is highly desirable to develop new models that can avoid the trial-and-error process.

This paper presents a parametric model for the fast prediction of coupling coefficient between monopole antennas on electrically large cylindrical platforms. Ray analysis is performed to derive an analytical formula of the radiated electromagnetic fields by a transmitting monopole antenna. The Poynting vector is then obtained, and a linear parametric model of the coupling coefficient is proposed based on the expression of the Poynting vector. There are two parameters in the proposed parametric model, and they can be determined by performing two electromagnetic simulations. Once the two parameters are found, the parametric model can be

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used to predict the coupling coefficients at various distances between monopole antennas.

Once determined, the proposed parametric model no longer requires electromagnetic simulations to predict the coupling coefficients at various distances. It can also be used to calculate the required distance to achieve the desired isolation. Therefore, the trial-and-error process is avoided and the time required by antenna placement can be significantly reduced.

The rest of this paper is organized as follows. Section II presents derivation of the proposed parametric model. Section III shows numerical results and Section IV concludes this paper.

II. THE PROPOSED PARAMETRIC MODEL

Consider the electrically large cylindrical platform shown in Fig. 1. Assume a transmitting monopole antenna and a receiving monopole antenna are located at the source point Q' and the observation point Q, respectively. According to [8], the electromagnetic filed radiated by a uniform short monopole current I at point Q' can be expressed by Equation (1) at the bottom of this page. In Equation (1), k is the wavenumber, η_0 is the free space wave impedance, and U and V denote the Fock functions whose definition can be found in the Appendix of [9]. As show in Fig. 1, $\hat{n}$ is the unit vector normal to the cylindrical surface at point Q, $\hat{t}$ is the unit vector tangential to the geodesic between Q and Q', and $\hat{b}=\hat{t}\times\hat{n}$. The other symbols in Equation (1) are defined as follows $\xi = t\left(k/2\right)^{\mathbf{1/3}} a^{-\mathbf{2/3}}\left(\sin\delta\right)^{\mathbf{4/3}}$, $T_0=\cot\delta$, and $G_0\left(kt\right)=e^{-jkt}/t$, where t is the length of the geodesic between Q and Q', a is the radius of the cylindrical surface, and δ is the angle between the axial direction and the geodesic at Q. For antenna placement, the worst case of electromagnetic interference is the most interesting. For two monopole antennas on a cylindrical surface, the worst case occurs when Q and Q' have the same φ coordinate. In this case, $\delta=0$ and $\xi=0$. We further assume that $\left(kt\right)^{-2}<<1$, Equation (1) is then simplified and the radiated electromagnetic field is rewritten as:

$$\vec{E}\left(Q|Q'\right)\big|_{\delta=0}=\eta_0 IF\left(t\right)G_0\left(kt\right)\hat{n}, \tag{2.1}$$

$$\vec{H}\left(Q|Q'\right)\big|_{\delta=0}=IF\left(t\right)G_0\left(kt\right)\hat{b}, \tag{2.2}$$

where

$$F\left(t\right)=\frac{-jk}{2\pi}\left\{1-j\left(\frac{\sqrt{\pi}e^{j\pi/4}}{4\sqrt{2}}\frac{\left(kt\right)^{\frac{1}{2}}}{ka}+\frac{1}{kt}\right)\right\}. \tag{3}$$

The Poynting vector $\vec{P}$ is then calculated as follows:

$$\vec{P}\left(Q|Q'\right)=\frac{k^2\eta_0 I^2}{8\pi^2 t^2}\left[1+X\left(t\right)\right]\hat{t}, \tag{4}$$

where

$$X\left(t\right)=\frac{\pi}{32\left(ka\right)^2}kt+\frac{\sqrt{\pi}}{4ka}\sqrt{kt}+\frac{\sqrt{\pi}}{4ka}\frac{1}{\sqrt{kt}}. \tag{5}$$

It can be shown that the first and third terms of $X\left(t\right)$ are negligible as long as the following two conditions are satisfied:

$$\frac{312.5}{\left(ka\right)^2}<\frac{t}{\lambda}<\frac{0.16\left(ka\right)^2}{\pi^2}, \tag{6}$$

where λ is the wavelength. For electrically large cylindrical platforms, it can be assumed that $ka>20\pi$. When deriving Equation (2), it is assumed that $\left(kt\right)^{-2}<<1$. Combining that assumption with the condition in (6), the following range of t is derived:

$$1.6<\frac{t}{\lambda}<64. \tag{7}$$

Equation (7) defines the range of t that allows us to neglect the first and third terms in (5). For electrically large cylindrical platforms, the wavelength is small and the lower bound of t is usually satisfied. Beyond the upper bound of t, the electromagnetic interference is negligible. Therefore, the condition in (7) is assumed to be satisfied in this work. The Poynting vector $\vec{P}$ is then simplified as:

$$\vec{P}\left(Q|Q'\right)=\frac{k^2\eta_0 I^2}{8\pi^2}\left[t^{-2}+\frac{\sqrt{k\pi}}{4ka}t^{-1.5}\right]\hat{t}. \tag{8}$$

Equation (8) indicates that the decaying rate of radiated power is between -2 and -1.5. Therefore, the power received by a receiving monopole antenna at Q

$$\vec{E}\left(Q|Q'\right)=\frac{-jk}{2\pi}I\left[\eta_0\hat{n}\left\{\left(1-\frac{j}{kt}\right)V\left(\xi\right)+\left(\frac{j}{kt}\right)^2U\left(\xi\right)+T_0^2\frac{j}{kt}\left[U\left(\xi\right)-V\left(\xi\right)\right]\right\}\right]G_0\left(kt\right), \tag{1.1}$$

$$\vec{H}\left(Q|Q'\right)=\frac{-jk}{2\pi}I\left[\hat{b}\left\{\left(1-\frac{j}{kt}\right)V\left(\xi\right)+T_0^2\frac{j}{kt}\left[U\left(\xi\right)-V\left(\xi\right)\right]\right\}+\hat{t}\left\{T_0\frac{j}{kt}\left[U\left(\xi\right)-V\left(\xi\right)\right]\right\}\right]G_0\left(kt\right), \tag{1.2}$$

is proportional to t^{β}, where $-2<\beta<-1.5$, and the magnitude of coupling coefficient between transmitting and receiving antennas can be described by the following parametric model:

$$|S_{21}| = Ct^{\beta}. \tag{9}$$

By expressing the coupling coefficient in dB scale, we have:

$$|S_{21}|_{dB} = \beta 10\log t + \alpha, \tag{10}$$

where $\alpha = 10\log C$. In Equation (10), α and β are two unknown parameters. With two groups of data $\left(\log t_1, |S_{21}|_{dB,1}\right)$ and $\left(\log t_2, |S_{21}|_{dB,2}\right)$, α and β can be calculated as follows:

$$\begin{cases} \alpha = \dfrac{\log t_1 |S_{21}|_{dB,2} - \log t_2 |S_{21}|_{dB,1}}{\log t_1 - \log\log t_2} \\ \beta = \dfrac{|S_{21}|_{dB,1} - |S_{21}|_{dB,2}}{10\left(\log t_1 - \log\log t_2\right)} \end{cases}. \tag{11}$$

Therefore, the two parameters in (10) can be determined by two groups of simulation or measurement data. Once α and β are solved, the coupling coefficient can be computed from (8) without running the electromagnetic simulation. The simulation cost is then saved.

Moreover, from Equation (10), the required distance between transmitting and receiving antennas can be calculated directly from the desired isolation by the following formula:

$$t_{\min} = 10^{-\frac{IS_{dB}+\alpha}{10\beta}}, \tag{12}$$

where IS_{dB} is the desired isolation and $t_{\min}$ is the minimum distance between transmitting and receiving antennas to satisfy the isolation requirement. Equation (12) avoids the tedious trial-and-error process in the conventional antenna placement method, and provides a fast way to determine the distance between transmitting and receiving antennas.

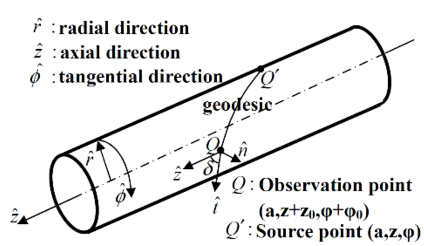

Fig. 1. Placement of monopole antennas on an electrically large cylindrical structure.

III. SIMULATION RESULTS

This section presents simulation results to show the advantages of the proposed method. Three examples are considered. The first example is a monopole antenna on a large planar ground plane, for which $ka \to \infty$. The second example is two monopole antennas on a half-cylinder. The third example is two monopole antennas on a commercial aircraft.

A. A monopole antenna on a large planar platform

In order to verify the theoretical analysis in Section II, a planar platform is first considered. In this case, $ka \to \infty$ and the second term in Equation (8) becomes zero. Consider a quarter-wavelength monopole antenna and assume the current distribution along the monopole antenna is $I(z) = I_0 \cos(kz)$. By taking integral of the current along the monopole antenna, it is found that the Poynting vector of the monopole antenna on a large planar platform is:

$$\vec{P}_m\left(Q|Q'\right) = \frac{15 I_0^2 \lambda^2}{\pi} t^{-2}\hat{t}. \tag{13}$$

Equation (13) is used to calculate the magnitude of Poynting vector of a quarter-wavelength monopole antenna on a rectangular ground plane. As shown in the inset of Fig. 2, the size of the ground plane is $15\lambda \times 20\lambda$. The monopole is 4λ away from the left edge of the ground plane. The magnitude of Poynting vector is calculated at a series of points on the right of the monopole antenna, and the results are shown in Fig. 2. It is seen that the proposed model agrees well with FEKO simulation. Note that discrepancies occur when $t > 11\lambda$, because the observation point is no longer on the platform.

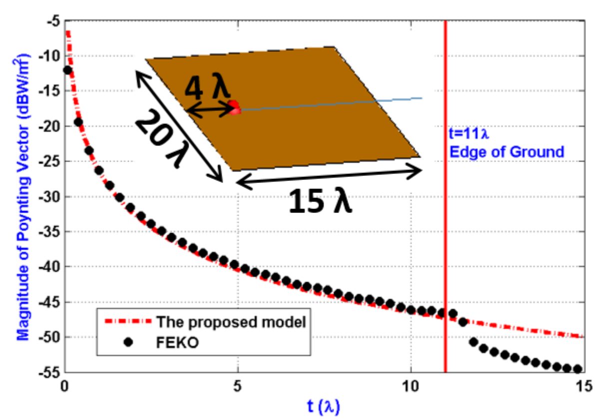

Fig. 2. The magnitude of Poynting vector of the quarter-wavelength monopole antenna on a large planar platform.

B. Two monopole antennas on a half-cylinder

The second example is two monopole antennas on a half-cylinder. The half-cylinder is a one tenth scaled model of the curved surface of a commercial aircraft fuselage. As shown in Fig. 3, the radius of the half-cylinder is 18.8 cm, and its length is 150 cm. Eleven holes of equidistance are drilled on the half-cylinder to mount monopole antennas. Ten measurements of coupling coefficient between transmitting and receiving antennas are performed. In these measurements, the transmitter is fixed at the first hole H1, and the receiver moves from the second hole H2 to the eleventh hole H11. To make the surface smooth, unused holes are covered by aluminum foils in every measurement.

Using the measurement data at H2 and H11, α and β are calculated by Equation (11). The coupling coefficient for different values of t is then calculated by Equation (10). The calculation results by the proposed model are shown in Fig. 4. Also shown in Fig. 4 are the measurement results. It is seen that the proposed model agrees well with measurement. In this example, the proposed model only requires two measurements to predict the coupling coefficients for different distances between transmitting and receiving antennas, which significantly saves measurement cost. If the desired isolation between transmitting and receiving antennas is given, the required distance can be calculated directly by Equation (12).

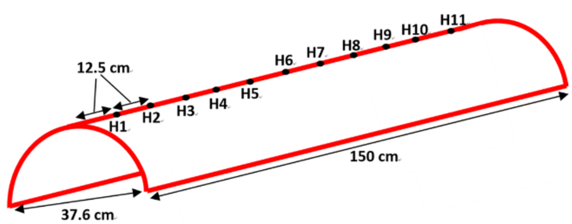

Fig. 3. Geometry of a half-cylinder with eleven holes.

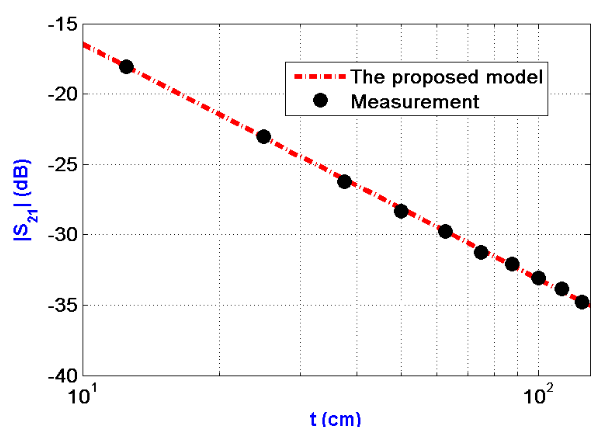

Fig. 4. Coupling coefficient between two monopole antennas on a half-cylinder.

C. Two monopole antennas on a commercial aircraft

In the third example, two monopole antennas mounted on a commercial aircraft are considered. Figure 5 illustrates the geometry of the aircraft. It is assumed that two monopole antennas are mounted on the fuselage of the aircraft. FEKO simulation is performed to calculate the coupling coefficient between the two antennas. Two simulated values of the coupling coefficient are used to compute the two parameters the proposed model. Equation (10) is then used to predict the coupling coefficient versus the distance between the two antennas, which is plotted in Fig. 6. Also shown in Fig. 6 are the FEKO simulation results. It is observed that the proposed model agrees well with simulation by FEKO.

Regarding computational efficiency, the proposed model only requires two electromagnetic simulations, while FEKO requires repeated simulation for every distance of interest. Furthermore, to find the minimum distance that satisfies the isolation requirement, a trial-and-error process is needed by FEKO simulation. However, the proposed model can find the minimum distance directly by using Equation (12), which will significantly save simulation time.

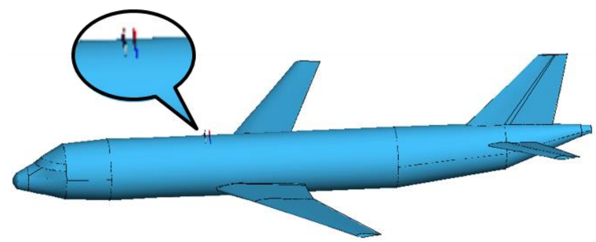

Fig. 5. Two monopole antennas on a commercial aircraft.

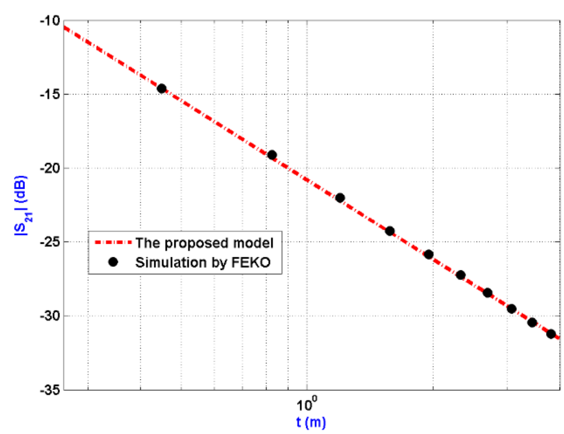

Fig. 6. Coupling coefficient between two monopole antennas on a commercial aircraft.

IV. CONCLUSION

This paper has presented a parametric model for fast prediction of coupling coefficient between monopole antennas on electrically large cylindrical platforms. Theoretical analysis has been performed to find the Poynting vector of a monopole antenna on electrically large cylindrical platforms. It has been found that the decaying rate of the magnitude of Poynting vector against distance is between -2 and -1.5, based on which a parametric model with two parameters has been proposed. The proposed model has been validated by three examples. It has been shown that prediction by the proposed model agrees well with both measurement and simulation results. The proposed model allows us to find the decaying rate of the coupling coefficient against distance from two group of simulation data, which significantly saves the time required by the analysis of big electromagnetic data.

In the present work, only monopole antennas are considered. It is interesting to extend the proposed model to other antennas, which is under investigation and will be reported in the future.

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