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A Novel Large Platform Virtualization Method for Antenna Electromagnetic Environment Effects Test

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ABSTRACT: The electromagnetic environment effect test of UAV airborne equipment is commonly completed in anechoic chambers. Due to the influence of platform on antenna radiation characteristics, it is necessary to move the large platform with a antenna to anechoic chambers. However, testing costs even make this case impossible. To evaluate the electromagnetic effect of platform-free antenna ports, this study proposes an antenna platform virtualization technique. The FIT (Finite Integration Technique) is employed to calculate the antenna gain corresponding to different frequencies with and without an antenna platform. Subsequently, the difference in antenna gain under these two cases is obtained. By compensating for this variation at the interference source, the frequency domain response of the interference signal at the antenna port can be predicted, disregarding the platform. To validate the effectiveness of the proposed technique, a UAV's airborne antenna is employed for simulation analysis. The root-mean-square error of the proposed technique is less than 0.5 dB. Moreover, in terms of time domain transient interference, the effect of the platform on the transient interference signal at the antenna port is equivalent to a transfer function. The root-mean-square error for the transient response prediction method is less than 0.1%. The results demonstrate that the proposed antenna platform virtualization technique makes it possible to test the electromagnetic effect of antenna in anechoic chambers without a platform.

1. INTRODUCTION

Powered by the rapid development of technology, Unmanned Aerial Vehicles (UAVs) have attracted extensive attention in various fields, including geographic mapping, ocean monitoring, and post-disaster rescue [1–3]. Owing to increasingly complex electromagnetic environment, particularly complicated data link transmission channel between UAV and ground control station (GCS), these vehicles are susceptible to electromagnetic interference, which potentially disrupts their normal operations. Consequently, the UAVs' adaptability to complex electromagnetic environments has progressively emerged as a focal point of interest. The intense electromagnetic interference generated by high-power microwaves poses a grave threat to UAV communication. Therefore, UAV electromagnetic effect testing is of paramount importance in evaluating the electromagnetic sensitivity of the UAV communication system. To date, there has been ongoing research on UAV electromagnetic effect testing [4–6].

The optimal approach to effectively reducing electromagnetic compatibility testing cost and enhancing test flexibility is to relocate the UAV system into an anechoic chamber. However, it is still challenging due to its large size. Furthermore, it is of great importance to construct a larger anechoic chamber, which incurs exorbitant costs. In order to mitigate expenses and difficulties associated with airborne antenna anti-interference testing, antenna platform needs to be visualized. Currently, electromagnetic effect virtualization technology encompasses three key aspects, namely scene virtualization, source reconstruction, and bulk current injection (BCI).

Scene virtualization plays a crucial role in predicting electromagnetic environment by accounting for modulation effects caused by various scenes. Existing research on equivalent technology for simulating electromagnetic environments mainly aims at analyzing electromagnetic compatibility and effect within an anechoic chamber [7]. A dynamic multi-source heterogeneous construction method is proposed here so that the constructed electromagnetic environment affects the coupling responses of receiving antennas, thereby virtually replicating complex electromagnetic environments within anechoic chambers. Additionally, discrete Laplace transform methodology is employed to extract transfer functions from different scenes. Meanwhile, the transfer functions represent distinct linear time-invariant systems in the propagation processes of electromagnetic waves across varying scenarios. This approach has been successfully applied in target echo prediction echoes [8]. Furthermore, this technique has also been employed for the investigation of electromagnetic wave propagation features in complex obstacle scenarios [9].

Regarding source reconstruction is a crucial technical approach [10–12], which can fully consider the influence of the scene on the electromagnetic environment towards the interference source. A compensation method, proposed in [13], eliminates arbitrary ground effect at the observation point by deducting field quantity at the compensation point. Moreover, based on the correlation between the power of the operation signal received by the UAV antenna and the transmitting power of the ground control station, antenna properties, operating fre-

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quency, UAV attitude, flight radius, UAV speed, and other factors, a novel UAV data link model for different flight conditions was introduced in [14]. This model is then incorporated into a new electromagnetic sensitivity testing method in anechoic chambers, where static testing rather than dynamic flight testing is employed. A virtual emission plane is established to determine the amplitude and direction of these rays in the evaporation conduit in front of the target. In [15], a novel signal-to-background ratio (SBR)-based evaporation pipeline environment model was proposed to create a link between propagation and scattering.

An alternative approach is bulk current injection method [16–18], which serves as a crucial and effective technical means to mitigating radio frequency (RF) radiation interference within anechoic chambers. Using this method, the current of radiation interference coupled to antennas, cables, and other components can be obtained through testing or simulation. The resulting current is then injected into the port to simulate the same effect as radiation interference. The substitution effect of bulk current injection cables for irradiation interference was analyzed in [19]. Based on antenna gain, propagation distance, wavelength, and other parameters, the output power of the antenna under irradiation interference was calculated, and the injection method was employed to replace the irradiation method, resulting in a simplified experimental device [20]. The relationship between injected excitation source voltage and radiation field intensity was established by means of experiment and equivalent circuits, among other methods. The study demonstrated that BCI could accurately replace high-field electromagnetic radiation effect tests, with a maximum test error of 2.7 dB [21].

Currently, for antenna platform virtual technology, an equivalent source model was employed in [22]. The radiation characteristics of an integrated antenna composed of an antenna and a vehicle were analyzed by an equivalent source model. Transient interference plays a vital role in the construction of complex electromagnetic environments. However, the equivalent model is only suitable for addressing narrow-band radiation issues.

The aforementioned approach primarily compensates for the dynamic variations of the scene and equipment to the interference source via simulations and mathematical models and mimics the alterations in the scene by regulating the emission properties of the interference source. The primary objective of the equivalent method is to minimize the space and cost required for testing electromagnetic effect within an anechoic chamber while ensuring its effectiveness. In the context of electromagnetic effect tests for systems, particularly in the case of broadband interference, there is limited research on the virtualization of large-scale platforms. In reality, platform virtualization method holds significant potential for reducing the cost of electromagnetic effect tests and enhancing test flexibility.

The antenna port serves as the main coupling channel between the receiver and external electromagnetic environment. External interference mainly includes single-frequency continuous wave and pulse two forms. To predict the coupling characteristics of single-frequency continuous wave interference and realize carrier virtualization, only the amplitude and frequency can be considered. However, for pulse interference, it has the characteristics of wide frequency range. At the same time, considering that the receiving characteristics of the receiving antenna at different frequencies are different, if the frequency domain interference characteristics are still obtained by Fourier transform, the antenna gain of different frequencies needs to be simulated, which will increase the difficulty and workload of prediction.

The remainder of this article is organized as follows. In Section 2, we elaborately outline the UAV virtualization prediction methods. Specifically, we propose a frequency domain response prediction method for narrow band interference, as well as a time domain response method for transient interference. In Sections 3 and 4, taking the monopole antenna mounted on the top of UAV as a representative scene, we simulate and verify the accuracy of the proposed time and frequency domain response prediction methods. In addition, the time domain prediction method is applied to the evaluation of electromagnetic environmental effects of satellite navigation receivers. The results reveal that the antenna platform virtualization method is very precise. Finally, we present a summary in Section 5.

2. ANTENNA PLATFORM VIRTUALIZATION METHOD

The platform virtualization method can be categorized into frequency-domain and time-domain response prediction methods. The frequency-domain response method is suitable for platform virtualization in the presence of narrow-band interference and continuous wave interference, while the time-domain response method is more appropriate for platform virtualization in the context of transient interference.

2.1. Frequency Domain Response Prediction Method

In accordance with the principle of antenna reciprocity, the prediction of antenna port response is determined by the impact of an electrically large platform on antenna gain. Therefore, a crucial parameter for forecasting the voltage response of antenna port is the variation in antenna gain with or without a platform. If the interference source compensates for this variation in antenna gain, it enables transfer of the influence of the antenna platform on interference coupling characteristics to the interference source.

We obtained the single antenna gain $G(f,\theta,\varphi)$ through measurement. The FIT method is employed to calculate the integrated antenna gain $G'(f,\theta,\varphi)$, where φ represents the azimuth angle, and θ denotes the elevation angle.

The flowchart of the frequency domain response prediction method is illustrated in Fig. 1.

It is assumed that the incident wave source power is denoted as S when considering only an antenna, while it is represented as S' when both an antenna and a platform coexist. Moreover, the corresponding voltage at the antenna port is denoted as V and V' respectively.

$$V = S + G + 107 \tag{1}$$

$$V' = S' + G' + 107 \tag{2}$$

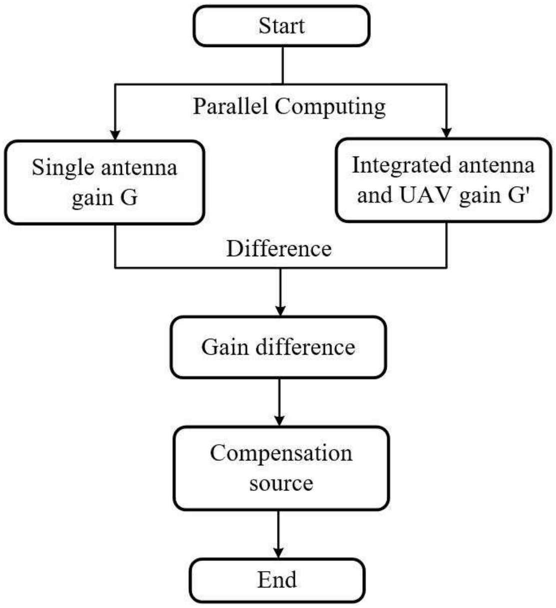

FIGURE 1. Flowchart of the frequency domain response prediction method.

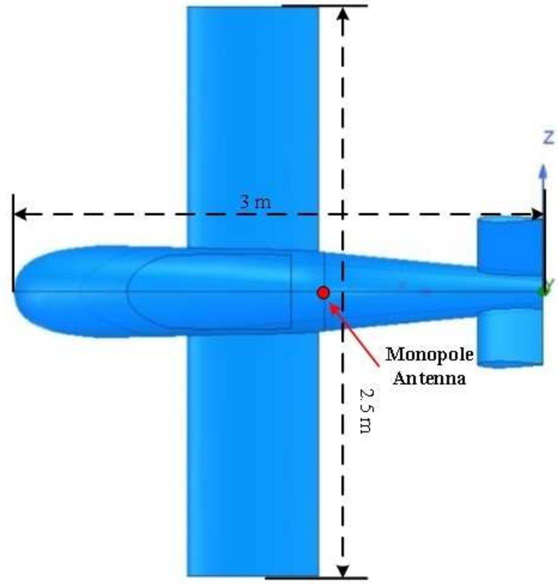

FIGURE 2. UAV model.

The logarithmic units are assigned to the above variable, and let S' represent 0 dBm. In addition, in order to achieve the same interference effect without a platform, the port voltage should be $V = V'$. Consequently, the compensation power of the interference source can be determined as follows:

$$\Delta S = G - G' = \Delta G \tag{3}$$

The corresponding compensated interference source intensity is denoted as $\Delta S(\theta, \varphi)$. The specific procedure for applying the frequency domain response prediction method is as follows:

1) Utilize platform virtualization method to rapidly acquire the compensation power ΔS of the interfering emitter.

2) Subsequently, increase the output power at the initial signal generator to compensate for $S + \Delta S$.

3) Adjust the transmitting antenna's direction to corresponding position.

4) Reconfigure the signal generator and apply signals from the transmitting antenna to irradiate the equipment under test.

5) Finally, analyze and study electromagnetic effects on the tested device by examining voltage responses from receiving antennas.

The accuracy evaluation method for antenna platform virtualization is as follows: we define interference source as the plane wave, utilizing a plane wave irradiation airborne antenna and a composite model of UAV. The voltage V of the antenna port is obtained and used as a reference value. After determining the incidence direction, the gain difference in the corresponding direction is compensated to obtain the plane wave amplitude. Then, considering only the single pole antenna scenario, we obtain the voltage V' of the single pole antenna port. Finally, the root mean square error is employed to evaluate the accuracy of platform virtual technology.

2.2. Time Domain Response Prediction Method

The transient interference signals are enable to encompass the received signal frequency of the antenna, leading to interference. If we just utilize frequency domain response method, simulating this process becomes intricate due to its wide frequency band. Hence, a method is required to virtualize the coupling process between the interference signal and antenna port. We assume that this coupling process resembles a linear system. Hence, that we use the transfer function to characterize the transient interference through the antenna coupling process is effective.

We define the transfer function of the coexisting antenna and platform system as $T(z)$, while referring to the transfer function of the single antenna system as $T'(z)$. The interference excitation signal and antenna coupling voltage are presented by $s(t)$ and $v(t)$ when the platform is included, respectively. Meanwhile, when the platform is not included, the interference excitation signal and antenna coupling voltage are presented by $s'(t)$ and $v'(t)$. The discrete Laplace transforms of the aforementioned variables are denoted as $S(z)$, $V(z)$, $S'(z)$, and $V'(z)$.

$$S(z) \cdot T(z) = V(z) \tag{4}$$

$$S'(z) \cdot T'(z) = V'(z) \tag{5}$$

The platform-antenna coupling effect is virtualized by assuming $V(z) = V'(z)$, then

$$S(z) = V'(z)/T(z) \tag{6}$$

The specific procedure for implementing the time-domain response prediction method is outlined as follows:

1) Determine the frequency range of broadband interference, Δf_r.

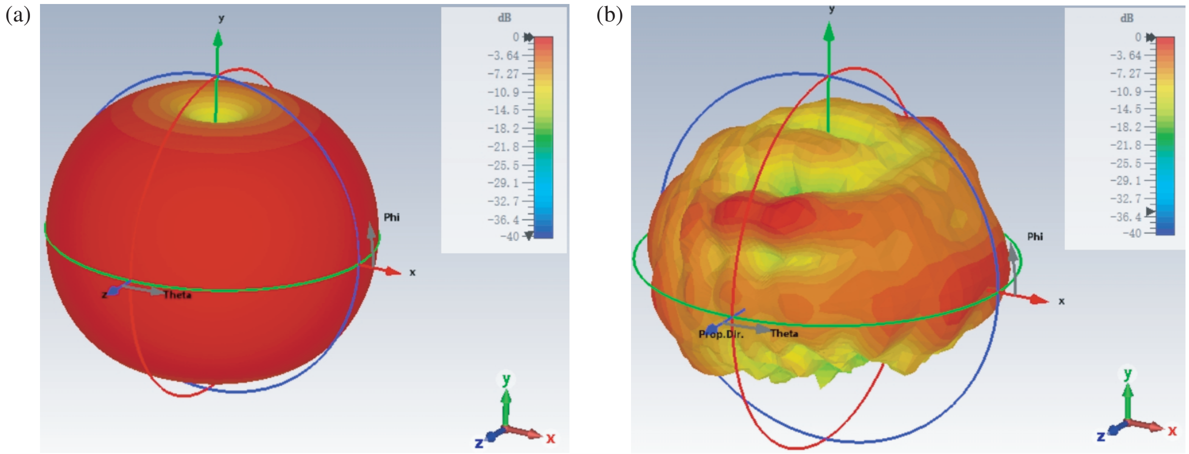

FIGURE 3. (a) monopole antenna gain and (b) monopole — UAV integrated gain.

2) Adjust the parameters of the sinusoidal modulated pulse signal $s(t)$ to ensure that its frequency range satisfies $\Delta f_s \geq \Delta f_r$.

3) Use FIT method to calculate the time-domain response $v(t)$ and $v'(t)$ respectively under irradiation by the interference signal $s(t)$.

4) By employing system identification module, the transfer function $T(z)$ for the coexistence of antenna and platform, as well as the transfer function $T'(z)$ for a single antenna, are determined using $s(t)$ as the input signal and $v(t)$ and $v'(t)$ as the output signals.

5) Utilize the transfer function $T(z)$ for predicting the temporal response of other waveform interference signals within the frequency range of Δf_s.

6) The inverse transformation of the transfer function $T(z)$ is employed for predicting the interference source $s'(t)$ in scenarios involving a single antenna.

3. VERIFICATION OF FREQUENCY DOMAIN RESPONSE PREDICTION METHOD

The accuracy of the proposed prediction model is evaluated through simulation in this section. It is assumed that the monopole antenna is positioned at the top of the UAV, as depicted in Fig. 2. The drone has a body length of 3 m and a wing length of 2.5 m.

By utilizing the FIT method, we obtained the gain of the three-dimensional monopole antenna and its integration with the platform. The results depicted in Fig. 3 demonstrate a significant impact of the UAV on antenna gain. The structure of wing and fuselage is the main factor that causes the variation of antenna radiation characteristics.

Significant variations in gain across different angles are evident, particularly observed in the $Z0Y$ cross section where gains decrease and increase at specific angles. These findings have implications for accurately predicting antenna response to external interference sources, especially when considering changes in UAV attitude.

The frequency domain response prediction method was compared with FIT method results in two cases, where the incident angle of the interference source was $\phi = 0°$, $\theta = 0°$ and $\phi = 0°$, $\theta = 90°$, respectively (Fig. 4).

In order to further validate the virtualization capability of the frequency domain response prediction method for the UAV, we established a verification model using Antenna Tool, as illustrated in Fig. 5. The upper model represents the simulation results of the antenna output power under UAV conditions, while the lower model depicts the output power of the antenna port after compensation through the corresponding frequency domain prediction method. The disparity between these two models can be utilized to quantify the virtualization error of the UAV.

The results demonstrate a prediction error of less than 0.35 dB, indicating high accuracy of the proposed method.

4. VERIFICATION OF TIME DOMAIN RESPONSE PREDICTION METHOD

Taking the scene depicted in Fig. 2 as an illustrative example, the excitation source for plane waves consists of a sinusoidal modulated Gaussian pulse signal with specific parameters: a central frequency of 500 MHz, a rise time of 0.9 ns, and a pulse width of 15 ns. The mathematical expression representing this sinusoidal modulation Gaussian pulse can be described as follows:

$$g(t) = \mathrm{e}^{-\left(\frac{t-t_0}{T}\right)} \sin(2\pi f_0 (t - t_0)) \tag{7}$$

Subsequently, the coupling voltage at the antenna port in the presence of both the antenna and platform is calculated using FIT method. The input signal is a sinusoidal modulated Gaussian pulse, while the output signal is taken as the coupling voltage. The transfer function can be obtained through system identification module. To further investigate its predictive performance, two new interference excitation signals are defined as sinusoidal modulated pulse signals with center frequencies of 400 MHz and 500 MHz, respectively. The pulse signal's rise time is 3 ns, and pulse width is 15 ns. The transfer function coefficients of $T(z)$ are illustrated in Fig. 6.

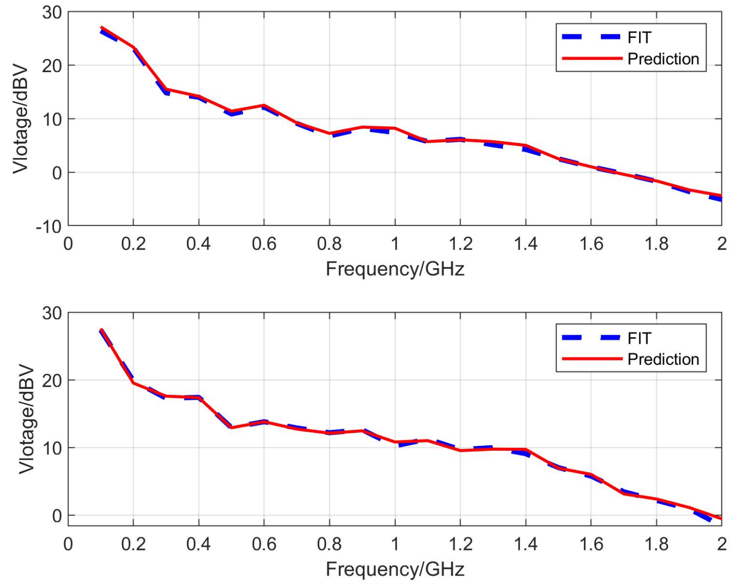

FIGURE 4. Comparison of antenna port voltage response prediction in frequency domain with simulation results when the interference source incident angle are $\phi = 0^{\circ}$, $\theta = 0^{\circ}$ and $\phi = 0^{\circ}$, $\theta = 90^{\circ}$.

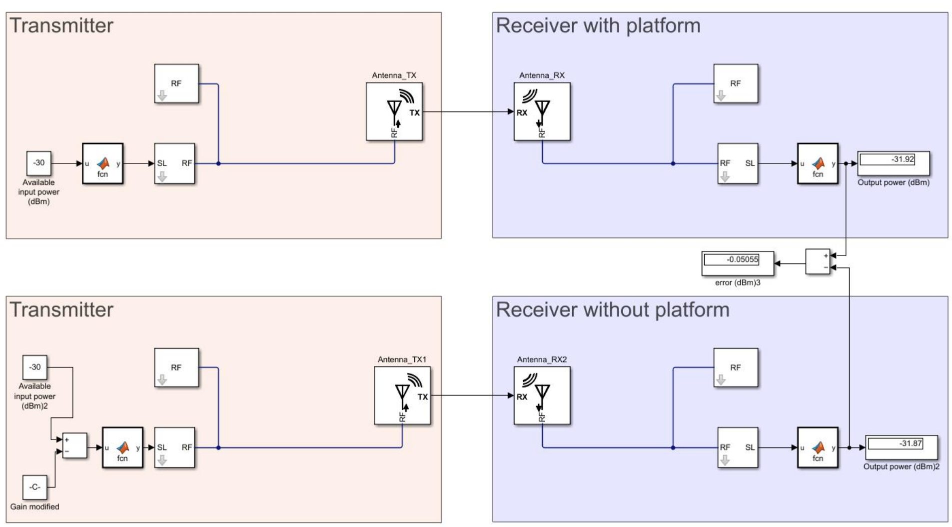

FIGURE 5. Evaluation model for predicting frequency domain responses.

Afterwards, sinusoidal modulated Gaussian pulse signals with center frequencies of 400 MHz and 500 MHz were utilized as the input signals. The coupling voltage at the antenna port was predicted using the previously obtained transfer function and also calculated through FIT method. A comparison between the two methods is presented in Fig. 7. These results demonstrate that the transfer function accurately predicts the coupling voltage of the new signal at the antenna port. Meanwhile, The prediction results of the proposed method are basically consistent with those of FIT method. The root mean square error (RMSE) values are determined to be 0.0607% and 0.0924%, respectively. These findings indicate that the pulse signals with different central frequencies can be effectively predicted utilizing this transfer function.

As illustrated in Fig. 8, the maximum absolute error between the predicted outcome and FIT method result is below 0.00376, which indicates that the proposed method has a high level of accuracy in prediction.

The transfer function is employed to predict the coupled signal at the antenna port. In order to further evaluate the adaptability of time-domain response prediction methods, Gaussian pulse signal and double exponential pulse signal are chosen as interference sources. Equations (8) and (9) represent the mathematical formulation of Gaussian pulse and double exponential pulse, respectively.

$$f(t) = A \cdot e^{-\left(\frac{t-t_c^2}{2\sigma^2}\right)} \tag{8}$$

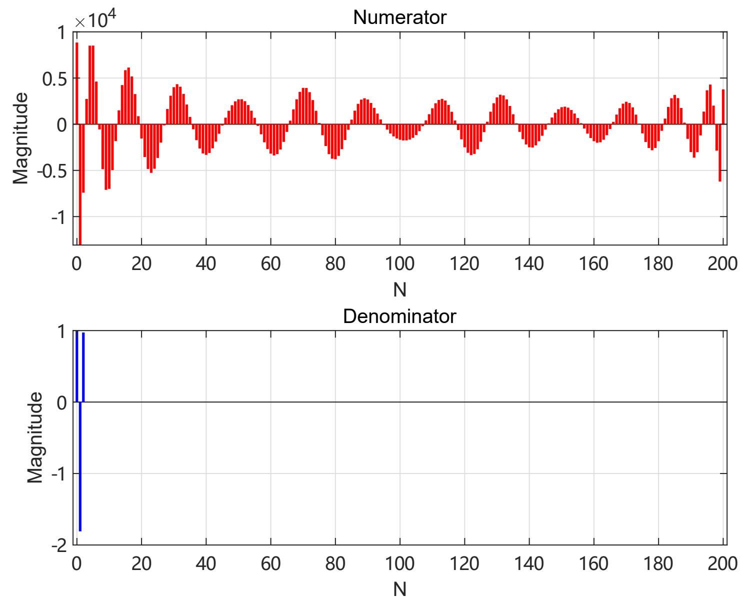

FIGURE 6. Coefficients of the transfer function.

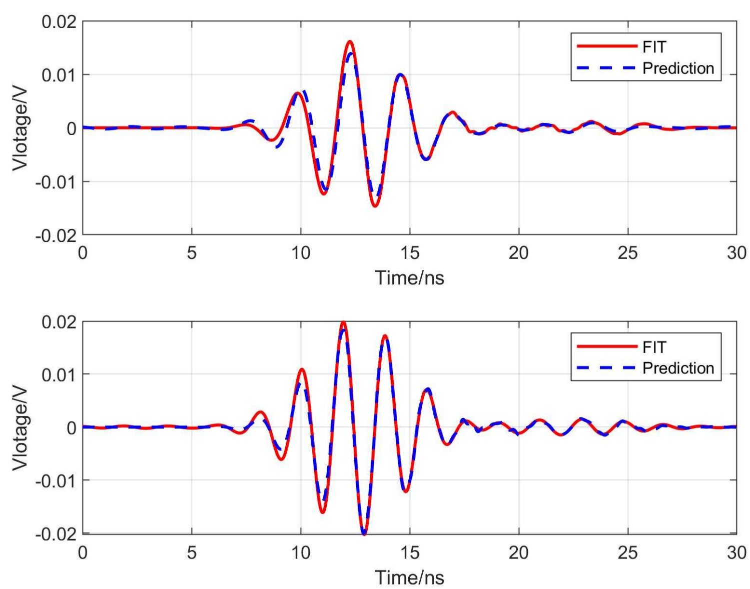

FIGURE 7. When the center frequency are 400 MHz and 500 MHz, the transfer function is used to predict and compare the simulation results.

where A represents the amplitude. The time constant t_c is the pulse delay, and σ is half of the pulse width.

$$u(t) = \begin{cases} 0 & \text{for} \quad t \leq t_0 \\ u_0 \left(\mathrm{e}^{-\frac{t-t_0}{\tau_1}} - \mathrm{e}^{-\frac{t-t_0}{\tau_2}} \right) & \text{for} \quad t > t_0 \end{cases} \tag{9}$$

where u_0 represents the amplitude. Time t_0 is the pulse delay, and τ_1 and the τ_2 are time constants.

The waveforms of these two interference signals are illustrated in Fig. 9.

As illustrated in Fig. 10 and Fig. 11, the time domain response of Gaussian pulse and double exponential pulse at the antenna port is predicted using the aforementioned transfer function.

As shown in Figs. 10 and 11, the transient response of the antenna port can be accurately calculated by the time domain response prediction method, which is consistent with the FIT method results. The root mean square errors of the antenna port prediction results and the FIT method results under the interference of Gaussian pulse and double exponential pulse are 0.000157% and 0.000952%, respectively.

In addition to accurately predicting the response of various interference waveforms at the antenna terminal, the time domain response prediction method offers notable advantages in

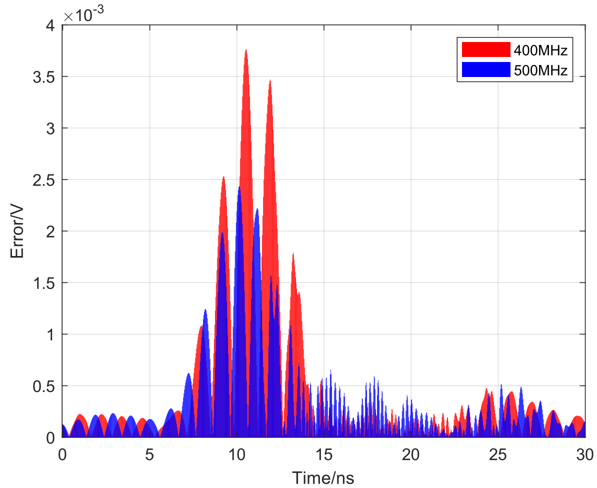

FIGURE 8. Prediction error.

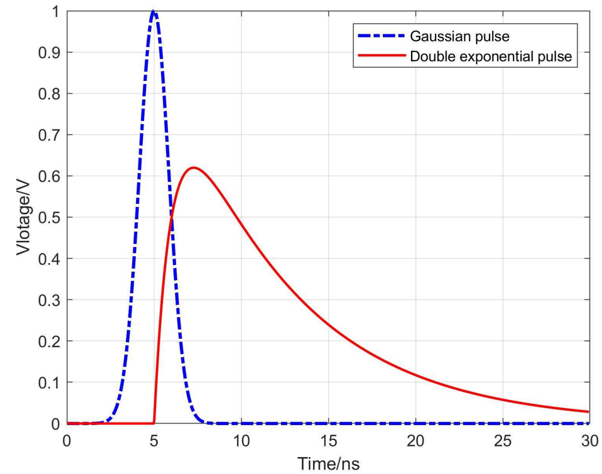

FIGURE 9. Waveforms of Gaussian pulse and double exponential pulse.

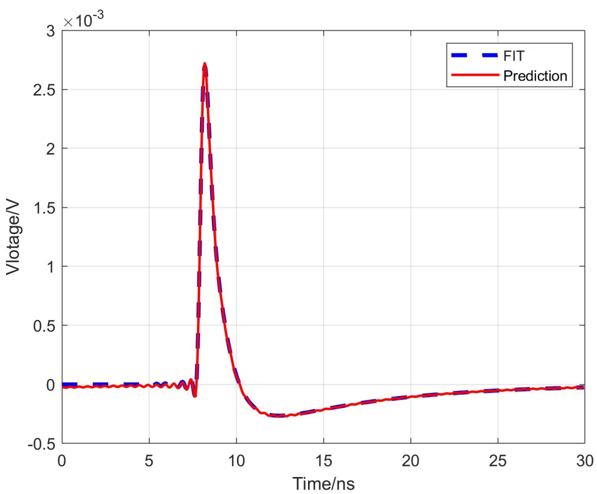

FIGURE 10. Transient response of Gaussian pulse interference at the antenna port.

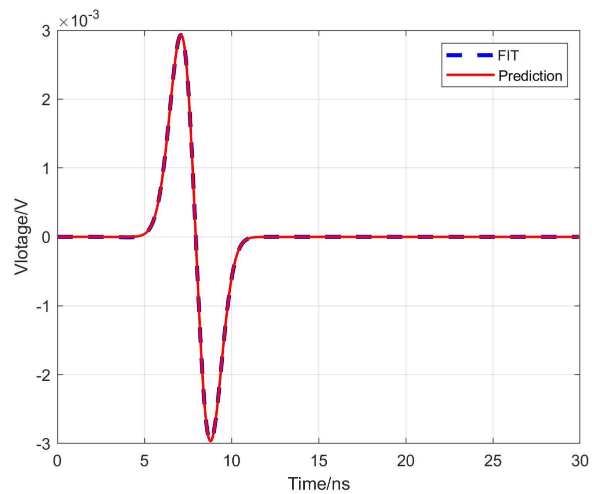

FIGURE 11. Transient response of double exponential interference at the antenna port.

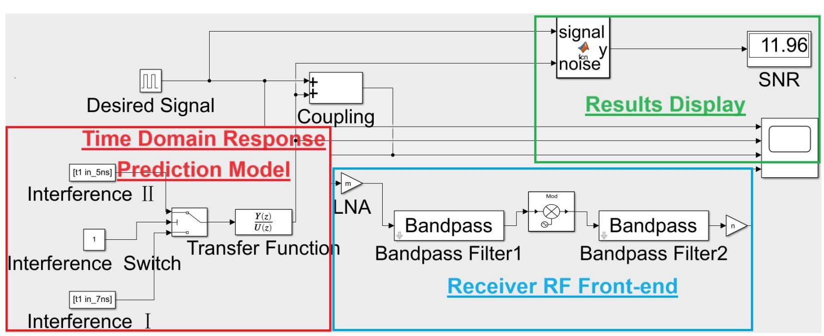

FIGURE 12. Interference analysis platform.

terms of CPU time and memory consumption. As illustrated in Table 1, the FIT method requires 1.56 h and consumes 5.6 GB of memory for computation. Conversely, employing the proposed method necessitates only 2.56 s and 3.5 MB of memory.

In order to further investigate the impact of antenna end response on the secondary circuit, we developed an interference analysis platform using Simulink in Fig. 12. The time domain response prediction method is equivalently represented by the

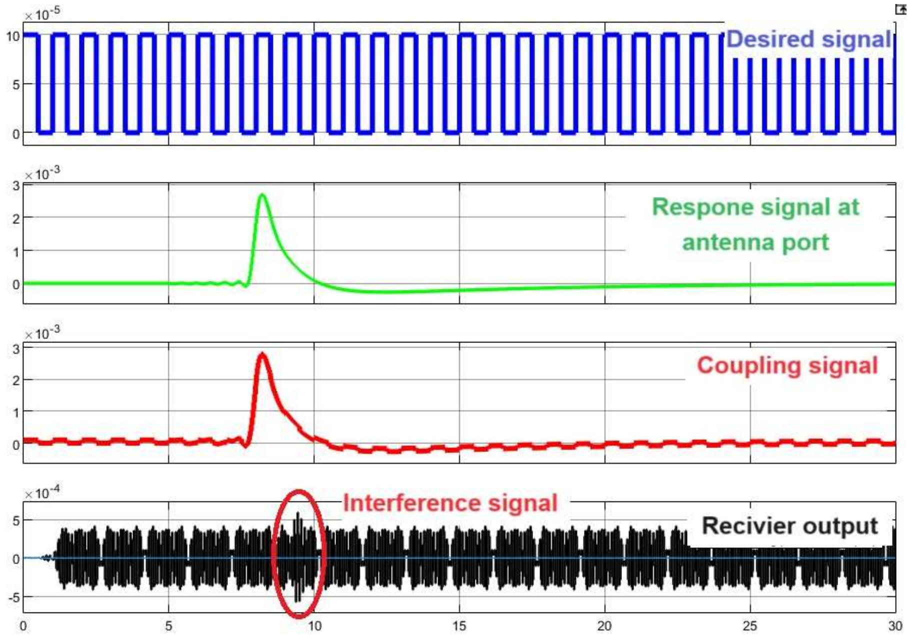

FIGURE 13. Results of transient interference analysis.

TABLE 1. Comparison of CPU time and memory consumption between FIT method and the proposed prediction method.

Method	CPU time	Memory consumption
FIT method	1.56 h	5.6 GB
The proposed method	2.56 s	3.5 MB

transfer function module, followed by selection of the interference signal through an interference waveform selector.

Additionally, as shown in Fig. 12, a receiver circuit model is constructed and integrated with both signal-to-noise ratio (SNR) results and transient response of the receiver.

In this paper, as shown in Fig. 13, the proposed prediction method and the corresponding analysis model enable the rapid analysis of the antenna port response and coupling results for the receiver, ultimately achieving virtualization of the UAV.

5. CONCLUSIONS

We propose an antenna platform virtualization technique for testing the electromagnetic effect of UAVs without relocating antenna platform to anechoic chamber. Specifically, the influence of the antenna platform on the antenna gain is determined, and the gain alteration is compensated to the interference source, thereby virtualizing the platform. Taking UAVs as an example, the accuracy of the platform virtualization technology is validated by simulations. By employing platform virtualization method to reconstruct the interference source, the frequency domain response of the antenna port can be closely aligned with that of the antenna platform. The precision of the proposed technique is also analyzed, with the RMSE being less than 0.5 dB. The presented prediction method is suitable for testing electromagnetic effect under narrow band or continuous wave interference. In addition, we define the coupling process of the transient pulse signal at the antenna port as a transfer function, that is, the platform effect is virtualized through a transfer function. The prediction method had a RMSE below 0.1%, according to analysis results, which is capable to predict the response of temporal transient pulse interference at the antenna port. The proposed prediction method is employed to construct an interference analysis model in Simulink. This model can be applied to the evaluation and analysis of receivers' electromagnetic susceptibility. Hence, it can be concluded that the antenna platform virtualization method has high precision and can be applied to the electromagnetic effect measurement without an antenna platform in anechoic chambers.

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