Dual-factor coupling effect on electromagnetic susceptibility of airborne cables

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Abstract This paper investigates the eigenfrequency of the induced current in airborne cables to evaluate the coupling effect of dual-factor on electromagnetic susceptibility of airborne cables. The airborne cable is situated in the scaled fuselage which has lower complexity compared with the aircraft model. Based on the single-factor approach, the simulation results indicate that the electromagnetic environment and the fuselage have little effect on the eigenfrequencies. With the variations of cable length and cable height above the ground, the eigenfrequencies will change significantly. Based on the dual-factor of cable length and height, two improved analytical expressions for the eigenfrequency are proposed.

key words: electromagnetic susceptibility, induced current, eigenfrequency, dual-factor approach, analytical expression

Classification: Electromagnetic theory

1. Introduction

Cables on aircrafts are susceptible to the aviation electromagnetic environments, which penetrate inside the aircrafts inducing currents and voltages in the cable bundles. These induced currents and voltages can exceed the equipment immunity limits, thus causing malfunctions and damages to the equipment. To prevent this problem, it’s necessary to investigate the induced current to assess the electromagnetic susceptibility of airborne cables. The numerical simulation tool was used to predict the induced current and validated by experiment [1, 2, 3, 4, 5, 6, 7, 8, 9].

The factors which influence on the electromagnetic susceptibility of airborne cables can be defined four categories: electromagnetic environment, cable length, cable height above the ground, terminated load. Lightning electromagnetic environment and high-intensity radiated fields (HIRF) are two typical categories of electromagnetic threats for the aviation. In previous studies [10, 11, 12, 13], the authors modeled the numerical prediction in the induced currents of airborne cables which was produced by a lightning stroke to an aircraft. The electromagnetic susceptibility of airborne cables in the HIRF was assessed by the transfer function of the induced current [14, 15, 16, 17]. Conventionally, the effect of cable length, height and terminated load were measured on the induced current in the open area [18, 19, 20, 21]. In these papers, the authors obtained analytical expressions of the eigenfrequency in the frequency-domain induced current with the variation of cable length [18,19]. The influence of variation in the electromagnetic environment was measured on the eigenfrequency of induced currents in a reverberation chamber [20]. Besides, the cable height above the ground and the terminated load, which affect the magnitude of the time-domain induced current, have also been investigated [22, 23, 24, 25, 26]. However, these studies investigated the induced current in the open area, and only focused on the effect of single factor on the induced current in the airborne cable, which did not provide an adequate assessment of the electromagnetic susceptibility of airborne cables. Therefore, the study exposes an analytical expression for the eigenfrequency of the induced current in the fuselage based on the dual-factor approach which is beneficial for the assessment on electromagnetic susceptibility of airborne cables.

The overall organization of this article is as follows. In Section II, the airborne cable in the fuselage will be modeled, and the feasibility of the fuselage model is verified. In Section III, we will investigate the effect of the single factor on electromagnetic susceptibility of airborne cables. And according to the conclusion of single-factor approach, two analytical expressions of the eigenfrequency will proposed based on the dual-factor approach. Conclusions are drawn in Section IV.

2. Simulation setup and model validation

2.1 Simulation setup

The paper [27] measured induced currents of a single core cable in a scaled fuselage under the HIRF. Based on the fuselage model in [27], the simulation model is established with the electromagnetic simulation software of finite integral technique (FIT) and transmission line method (TLM), as shown in Fig.1. The fuselage skin is made of aluminum. The window aperture is set to a diameter of 9 cm circle to ap-
proximate the physical reality. The wing and tail structures are ignored and not implemented in the fuselage model. The single core cable is situated inside the fuselage to simulate an actual cable whose position is chosen based on a typical cable bundle location. The cable is characterized by the length $l$, height $h$ above the fuselage and the terminated loads $Z_1$ and $Z_2$ at the near and far end, respectively. Since the terminated load is not the main concern in the study, $Z_1$ and $Z_2$ are set to 50 $\Omega$.

Fig. 1. Fuselage model.

According to the procedure [28], a swept current (SC) technique is used to provide a uniform field and simulate the HIRF with frequency range from 0 to 400 MHz. Thus, sine waves of different frequencies with the same magnitude are set as external field. The current magnitude of the external field is recorded for 50V/m. The electric field direction is parallel to the Z direction, the magnetic field direction is parallel to the Y direction, and the propagation direction of the plane wave is set to X direction, as shown in Fig.2.

Fig. 2. 3D electromagnetic model of the fuselage.

The eigenfrequency is used to describe the frequency-domain characteristics of the induced current, which concerns the multiple influence factors on the electromagnetic susceptibility of cables, including the resonances caused by the cable length.

2.2 Model validation
Since the fuselage is a scaled model, a real-size aircraft model is built to compare the differences between the fuselage model and the aircraft model. Fig.3 shows the aircraft model used in the simulation, with the cable parameters and field excitation set in keeping with the fuselage model. The aircraft is B737-800, which is one of the most typical aircraft in civil aviation with the length of 39.5 m, the wingspan of 35.8 m and the height of 12.5 m. The skin is made of 1.5 mm thick aluminum.

Fig. 3. 3D electromagnetic model of the aircraft.

Fig.4 shows the induced currents of the aircraft model and the fuselage model. The trends of the two frequency-domain waveforms show a good match. Eigenfrequencies of both induced currents are in good agreement with error of 6.7%, 2.3%, 1.1%, respectively. The cables under the two models have same physical parameters and are located on the central axis of the models. Thus, the results demonstrate that the variation of the model physical size has little influence on the eigenfrequency. The induced current average magnitude of the fuselage is greater than 20 dB due to the larger physical size of the aircraft model and less energy from the electromagnetic environment coupled to the aircraft cable. Since the main interest of the study is the electromagnetic susceptibility of airborne cables, we only focus on the eigenfrequency of the induced current, the effect of the model simplification on the magnitude can be neglected. Moreover, it is worth noting that the numerical simulation of the aircraft model takes more than 10 hours whereas the computation time for the fuselage model is about 10 minutes.

Fig. 4. Induced currents under two models ($l=1$ m, $h=0.1$ m, $Z_1=Z_2=50$ $\Omega$).

3. Results and discussion
3.1 Variation of Single factor
In this study, the single-factor approach will be used to investigate the influence of external electromagnetic environments and cable parameters. Based on the conclusions of single-factor approach, the coupling effect between these factors will be studied.

In order to describe the variation of the electromagnetic environment and the coupling effect of the fuselage on induced currents, four types of electromagnetic environments can be defined: the cable is directly exposed to the HIRF, the cable is directly exposed to the lightning electromagnetic environment, the cable in the fuselage is exposed to the HIRF; and the cable in the fuselage is exposed to the lightning electromagnetic environment.

Fig. 5 illustrates induced currents for different electromagnetic environments. With changes in electromagnetic environment, eigenfrequencies of different electromagnetic environments have a good agreement, as shown in Table I. In [18] the authors investigated that the frequency characteristics of the induced currents in a reverberation chamber. Although the loading layout changed the characteristics of the electromagnetic environment in the reverberation chamber, the magnitude of induced currents was also influenced, however, it didn’t have influence on the frequency-domain characteristics of the current. Hence, this demonstrated when the electromagnetic environment changed, the induced current magnitude was also affected, but the eigenfrequency variation is quite low.

Fig. 6 shows the eigenfrequency for variations in the cable length $l$. It can be concluded that the eigenfrequencies decrease as the length increases. In [18, 19], according to the experimental and simulation results, in the open area the analytical expression of the eigenfrequency is expressed as:

$$f = \frac{nc}{2l}$$

Where $f$ is the eigenfrequency; $c$ is the speed of light; $l$ is length of the cable; $n=1, 2, \ldots$

Based on the Eq. (1), the first eigenfrequency of the induced current approximately satisfies $f_1 = 0.5c/l$, the second eigenfrequency satisfies $f_2 = c/l$, the third eigenfrequency satisfies $f_3 = 1.5c/l$. Table II shows the comparison of these simulation results with the calculated results, which indicate that the errors of eigenfrequencies are 13.4%, 17.4%, 15.5%, respectively. The reason for the large error in these results is that this analytical expression was obtained by single factor approach, which only considered the effect of cable length on eigenfrequency.

Fig. 7 shows the induced currents for variations in the height. With increasing of $h$, the induced current waveform shifts toward lower frequency. Based on the mirror principle,
The eigenfrequencies are 4.4 MHz. Thus, we introduced the low frequency element of the frequency-domain current waveform to increase, which leading to an increase in the waveform to be shifted to the right and the rise time of the reflected field. This can be defined as:

\[ T_h = 2h/c \]  

The increase in height results in the time-domain current waveform to be shifted to the right and the rise time of the waveform to increase, which leading to an increase in the low frequency element of the frequency-domain current waveform. Thus, we introduced the \( h \) to the Eq. (1), the analytic expression for different heights is expressed as:

\[ f = nc/(1 + 2h) \]  

Table III shows the results of Eq. (3), whose errors of eigenfrequencies are 4.4\%, 2.8\%, 0.7\%, respectively. It’s shown that the height above the fuselage is an important factor for the eigenfrequency of the induced current.

### 3.2 Variation of dual-factor

The results in the previous section indicate that the electromagnetic environment has low impact on electromagnetic susceptibility of airborne cables. Thus, the effect of the electromagnetic environment will be ignored. The coupling effect of length and height will be investigated based on the dual-factor approach.

Eq. (3) is the analytical expression of eigenfrequency with \( l=1 \) m. We extend \( l=1 \) m to the cable length \( l \), and obtain:

\[ f = nc/(l + 2h) \]  

Table IV shows the results of Eq. (4), whose errors of eigenfrequencies are 7.4\%, 2.6\%, 2.0\%, respectively. The errors of eigenfrequencies are significantly reduced compared to the results of Eq. (1) where only length was taken into account. It proves that the coupling effect of cable length and height should be in consideration on electromagnetic susceptibility of airborne cables.

Since the change in terminated load has influence on the induced current, the simulation is supplemented with a case of \( Z_1=50 \Omega, Z_2=1000 \Omega \). Fig. 8 illustrates the induced currents with matched+open-circuit load at different heights. The previous analytical expression Eq. (1) does not apply in the eigenfrequency distribution due to the change of loads. In [29, 30], the change in load from very low (short-circuit) to
very high (open-circuit) cause a shift of the eigenfrequency positions of $\lambda/4$, which means $\Delta f = c/4(l + 2h)$. Therefore, based on simulation results and Eq. (4), the eigenfrequency distribution meets:

$$f = \frac{(2n - 1)c}{4(l + 2h)}$$  \hspace{1cm} (5)

The simulation results and calculation results are compared in Table V. The errors of eigenfrequencies are 7.7%, 5.8%, 2.8%, respectively. It indicates that the variation of load can’t be ignored when investigating the coupling effect of length and height on electromagnetic susceptibility of airborne cables.

### 3.3 Applicability of analytical equations

The induced currents are obtained from different simulation frequency ranges in Fig.9. When the simulation frequency is lower than 400MHz, their eigenfrequencies have a great agreement. However, when the simulation frequency is greater than 400MHz, there are many spikes on the induced current beyond the eigenfrequency frequency distribution. Thus, analytical equations are applicable on the frequency 0 to 400 MHz.

4. **Conclusion**

This paper shows the numerical simulation for investigating the dual-factor coupling effect which influenced on electromagnetic susceptibility of airborne cables, and proposes two analytical expressions of eigenfrequency for the airborne cables.

The scaled fuselage model has the feasibility and lower complexity with respect to the aircraft model. Based on the single-factor approach, the effect of external environments and cable parameters are investigated. The variation of the electromagnetic environment has no influence on the eigenfrequency. When the cable is situated in some cavities, such as fuselage, aircraft, the eigenfrequency of the induced current will has a few variations compared to the open area due to the coupling effect of the cavity. The analytical expression of eigenfrequency in [6-7] doesn’t apply to the airborne cables which are situated in the fuselage, where the cable height is neglected.

Based on the dual-factor of cable length and height, we obtain an improved analytical expression of the induced current for the airborne cables with frequency range 0 to 400 MHz, which express as $f = nc/(l + 2h)$ with matched load. When the terminated loads are matched and open-circuit, the position of eigenfrequency would be shifted to $\lambda/4$ and satisfied $f = (2n - 1)c/4(l + 2h)$. It’s necessary to focus on the coupling effect of dual-factor the electromagnetic susceptibility of airborne cables.

Cable length and height above the fuselage are the most important factors which affect the electromagnetic susceptibility of airborne cables. The influence of electromagnetic environment and fuselage can be neglected, however, when the terminated loads of the cable changes, the electromagnetic sensitivity will also change. It is believed that the study should be useful for EMC (Electromagnetic Compatibility) design of complex airborne cable systems under the aviation electromagnetic environment.
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