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Analysis of the coupling effects on main feeder in more electrical aircraft

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Abstract: Isolation distance is an important consideration in aircraft wiring for coupling effect. according to electrical wiring interconnect system (EWIS) isolation requirements specified in SAE 50881D and airworthiness regulations CCAR 25.1707, explicit isolation distances are not specified. Aircraft wiring is complex or diverse. In order to evaluate coupling effects between the main feeder and signal wire, the three-phase-seven-wire main feeder with 230 VAC, 250 kVA was chosen as the simulation object. The impedance model of three-phase feeder is given with which the coupling effects can be analysed in theory at first. The coupling voltage amplitude is the main evaluation index. In the simulation process, the following cases are chosen: different distances between signal wire and main feeder; signal wire lies in the different phase of the main feeder; isolation distance analysis with types of loads; there exits arc faults on main feeder. Based on the analysis of the simulation results, proposed methods to reduce the coupling effects between wires are given. Through the work in this study, it has some guiding significance for wire or cable laying.

1 Introduction

With the development of more electrical aircraft (MEA), the numbers and types of airborne electrical equipment are rapidly increasing. The power rate of the generators needs to be increased which can insure the safety level of aircraft power supply system. For the Boeing 787, the generator power is 1.46 MW, which includes four main generators (230 VAC, 250 kVA), two auxiliary power unit (APU) (230 VAC, 225 kVA) and one ram air turbin (RAT) (230 VAC, 10 kVA). The rated current of the main generator is 627.57 A. Assuming the flight altitude is from 35,000 to 45,000 inch, according to the height reduction curve in SAE 50881D, the reduction factor 0.833 should be considered in the copper wire gauge selection process. According to the relationship between wire gauge and ampacity, the wire with 2/0 gauge can carry 361 A current. So two parallel wires with 2/0 gauge can be used as the main feeder. Similarly, the APU and RAT generator feeders can be selected.

For the main feeder in MEA carries more heavy current, the electromagnetic environment nearby the main feeder is even worse than before. Some signal wires with low voltage are more vulnerable to main feeder confined to the limited on-board space. If electric arc occurs, the signal wires even could be burned. In order to ensure the safety of all kinds of wire, EWIS isolation requirements are specified in EWIS specification files such as SAE 50881 and airworthiness regulations CCAR 25.1707. While some qualitative provisions are made in the isolation requirements, quantitative provisions are not illustrated. As to a specified routing environment, there would be some conflicts caused by too many wire types in a channel which can affect the wire laying. In fact, 90% of the reasons for the equipment or system performance descending result from electromagnetic coupling between wires [1]. In order to solve the conflict in wiring, the coupling effects among various types of wires should be analysed.

In this paper, the EWIS isolation requirements specified in SAE 50881D and airworthiness regulations CCAR 25.1707 are collated and analysed at first. Then, the impedance model of three-phase feeder is given with which the coupling effects can be analysed in theory. In order to evaluate coupling effects between the main feeder and signal wire with the three-phase-seven-wire main feeder with 230 VAC, 250 kVA was chosen as the simulation object. The coupling voltage is the main evaluation index. In the simulation process, the following cases are chosen: different distances between signal wire and main feeder; signal wire lies in the different phase of the main feeder; isolation distance analysis with types of loads; there exits arc faults on main feeder. Based on the analysis of the simulation results, proposed methods to reduce the coupling effects between wires are given. Through the work in this paper, it has some guiding significance for wire or cable laying.

2 Aircraft EWIS isolation requirements

2.1 FAR&CCAR isolation requirements

General requirements about EWIS isolation in CCAR 25.1707 (a) can be described as follows: each EWIS must be designed and installed with adequate physical separation from other EWIS and airplane systems so that an EWIS component failure will not create a hazardous condition. Unless otherwise stated, for the purposes of this section, the adequate physical separation must be achieved by separation distance or by a barrier that provides protection equivalent to that separation distance [2, 3].

As described in 25.1707, each EWIS must be designed and installed so that any electrical interference likely to be present in the airplane will not result in hazardous effects upon the airplane or its systems especially for wires and cables carrying heavy current.

As to the grounding connection, airplane independent electrical power sources must not share a common ground terminating location. In this way, an EWIS component failure will not create a hazardous condition.

As described in 25.1709, each EWIS must be designed and installed so there is an adequate physical separation between it and other aircraft components and aircraft structure, and so that the EWIS is protected from sharp edges and corners, to minimise the potential for abrasion/chafing, vibration damage and other types of mechanical damage.

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2.2 SAE 50881 guidelines for aircraft wiring

(i) 3.10.12 sensitive circuits: Sensitive circuits such as low-power level signal circuits shall be kept separate from other circuits at junctions. This shall be accomplished by using separate connectors for the sensitive circuits and by having at least one grounded terminal stud between sensitive circuits and other circuits on a common terminal board [4].

(ii) 3.10.13 power systems: Electrically unprotected wiring of the primary electrical power system shall not be bundled or grouped with distribution circuit wiring. Wiring from two or more sources shall not be in the same bundle or group to prevent a single damage from affecting more than one power source.

(iii) 3.10.14 essential equipment: Wiring to each system which must operate to maintain flight control of the vehicle under normal or emergency conditions shall be separately routed from other wiring. Essential engine circuits shall have their wiring so routed as to prevent damage to any circuit for one engine from affecting circuits of any other engine. Propeller circuits shall be routed separately from all other circuits.

(iv) 3.10.15 parallel circuits: The procuring activity may specify parallel circuits for specific equipment circuits and feeders to load centres. Wiring to equipment performing duplicate functions shall be run in separate bundles to prevent damage to one system affecting the other. On airborne vehicles that employ dual or multiple redundant MIL-STD-1553 multiplex data bus systems, the redundant data bus cables shall be run in separate bundles and routed to prevent damage to one data bus cable affecting the operation of the redundant data bus or buses.

3 EWIS coupling effects simulation

3.1 EWIS coupling effects in theory

If a signal wire was selected as the signal interference source, another signal wire as the disturbed source, the ground was assumed to be the ideal power ground; the multi-conductor transmission wire system is shown in Fig. 1 [5, 6].

As shown in Fig. 2, ground height of the interference wire is h_G, the radius of copper core is r_G, unit length inductance and capacitance are, respectively, l_G and c_G. Ground height of the disturbed wire is h_R, the radius of copper core is r_R, unit length inductance and capacitance are, respectively, l_R and c_R. The distance between interference source wire and disturbed wire is d. Unit length mutual sense and mutual capacity of the two wires are, respectively, l_m and c_{m}. l_G, l_R and l_m can be deduced as follows:

$$\begin{cases} l_G = \dfrac{\mu}{2\pi}\ln\left(\dfrac{2h_G}{r_G}\right) \\ l_R = \dfrac{\mu}{2\pi}\ln\left(\dfrac{2h_R}{r_R}\right) \\ l_m = \dfrac{\mu}{4\pi}\ln\left(1+\dfrac{4h_Gh_R}{d^2}\right) \end{cases} \tag{1}$$

Unit length inductance and capacitance matrix for multi-conductor transmission wire are shown in the following equations:

$$\boldsymbol{L} = \begin{bmatrix} l_G & l_m \\ l_m & l_R \end{bmatrix} \tag{2}$$

$$\boldsymbol{C} = \begin{bmatrix} c_G + c_m & -c_m \\ -c_m & c_R + c_m \end{bmatrix} \tag{3}$$

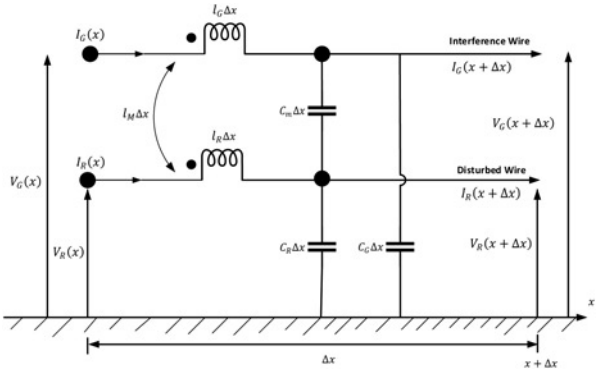


Fig. 1 *Multi-conductor transmission wire system*

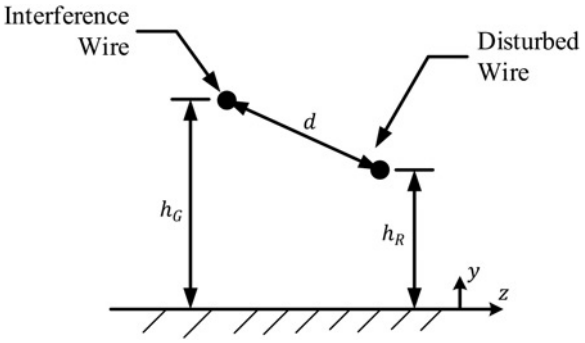


Fig. 2 *Space distribution of double wire transmission line*

Ideally, the relationship between unit length inductance matrix and the capacitance matrix can be expressed in the following equation:

$$\boldsymbol{L}\cdot\boldsymbol{C} = \frac{1}{v^2}\mathbf{1}_2 \tag{4}$$

where v is the transmission rate of waves in the conductor, and $\mathbf{1}_2$ is a two-order unit matrix.

Then, the chain parameter matrix $\boldsymbol{\Phi}_2$ is

$$\boldsymbol{\Phi}_2 = \begin{bmatrix} \cos(\beta L)\mathbf{1}_2 & -jv\sin(\beta L)\boldsymbol{L} \\ -jv\sin(\beta L)\boldsymbol{C} & \cos(\beta \mathrm{L})\mathbf{1}_2 \end{bmatrix} \tag{5}$$

where L is the length of the entire wire.

So the port voltage and current relationship is

$$\begin{bmatrix} \boldsymbol{V}(L) \\ \boldsymbol{I}(L) \end{bmatrix} = \boldsymbol{\Phi}_2 \begin{bmatrix} \boldsymbol{V}(0) \\ \boldsymbol{I}(0) \end{bmatrix}$$
$$\text{where } \boldsymbol{V}(x) = \begin{bmatrix} V_G(x) \\ V_R(x) \end{bmatrix} \quad \boldsymbol{I}(x) = \begin{bmatrix} I_G(x) \\ I_R(x) \end{bmatrix}. \tag{6}$$

Combined with the Thevenin equivalence theorem, the near and far voltage currents of the conductor transmission wire model can be obtained with the following equation [7]:

$$\begin{cases} \boldsymbol{V}(0) = \boldsymbol{V} - \mathrm{Z}_{\mathbf{0}}\boldsymbol{I}(0) \\ \boldsymbol{V}(L) = \mathrm{Z}_{\boldsymbol{L}}\boldsymbol{I}(L) \end{cases} \tag{7}$$

where

$$\boldsymbol{Z_0} = \begin{bmatrix} Z_{0G} & 0 \\ 0 & Z_{0R} \end{bmatrix} \quad \boldsymbol{Z_L} = \begin{bmatrix} Z_{LG} & 0 \\ 0 & Z_{LR} \end{bmatrix} \quad \boldsymbol{V} = \begin{bmatrix} V_S \\ 0 \end{bmatrix}$$

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Define the coupling effect of one wire to the another wire is S_1

$$S_1 = 20\log_{10}(V_L(x)) \tag{8}$$

During the calculation process, different types of coupling wires need different parameters. Similarly, the coupling effect of single cable to double parallel line, shielded wire and so on can be calculated. As to the shielded wire, shield transfer impedance should be considered. In general, the EWIS coupling effects mainly depend on current, voltage, isolation distance, shielding, laying and other factors.

3.2 EWIS coupling effects simulate process

In this paper, CST CABLE STUDIO is used to simulate and find out the coupling effect of main feeders caused by several factors [8].

The modelling and simulation process of CST CABLE STUDIO is as follows. First, the wire physical model is established, and the wire material, structure, length and other parameters are defined. Then, the wire laying design is carried out based on defining the laying configuration, the laying distance between wires and the laying ground height of wires and so on. Then, the two-dimensional electromagnetic solver is used to solve the wire parameters and import it into the circuit simulation environment with the configuration of the signal source and the grounding. Finally, a built-in solver is used to analyse the coupling effects between wires.

3.2.1 Main feeder model: For Boeing 787, the generator power is 1.46 MW, which includes four main generators (230 VAC, 250 kVA), two APU (230 VAC, 225 kVA) and one RAT (230 VAC, 10 kVA). The rated current of the main generator is 627.57 A. Assuming the flight altitude is from 35,000 to 45,000 inch, according to the height reduction curve in SAE 50881D, the reduction factor 0.833 should be considered in the copper wire gauge selection process. According to the relationship between wire gauge and ampacity, the wire with 2/0 gauge can carry 361 A current. So two parallel wires with 2/0 gauge can be used as the main feeder. The gauge of the MIL-W-22759/87-02 is as follows. The conductor diameter varies from 0.440 to 0.475 inch. The finished wire diameter varies from 0.474 to 0.505 inch. The insulating layer is fluoropolymer.

There are mainly two types of main feeder configuration: with independent central wire and with skin as central wire. According to the impendence analysis in [9], the main feeder with phase distribution in Fig. 3 has better impedance characteristics.

So the main feeder with phase distribution in Fig. 3 is selected as the research object. The model of the main feeder built in CST is shown in Fig. 4.

A sensitive signal wire is set nearby the main feeder. The circuit simulation model can be built as shown in Fig. 5, where SW-3 is the sensitive signal wire. Both ends of the wire are connected with 50 Ω resistance. A probe is set in SW-3. As to the main feeder, one end is connected with a 230 VAC, 400 Hz sine wave which can simulate the output voltage of the generator, the other side is connected with a 50 Ω resistance. Then, CST CS co-simulation can be used to simulate the coupling effects between the main feeder and the signal wire.

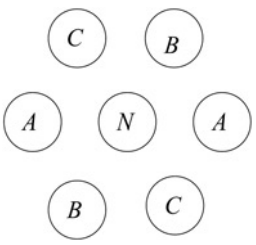


Fig. 3 *Phase distribution of main feeder*

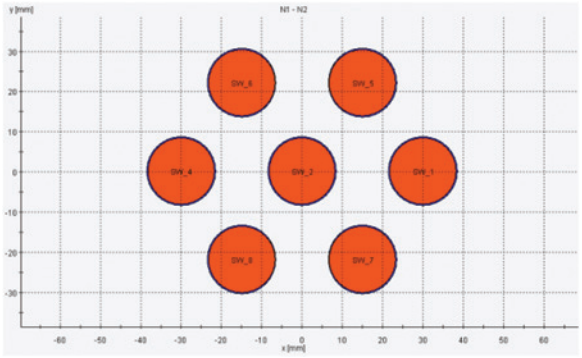


Fig. 4 *Model of the main feeder*

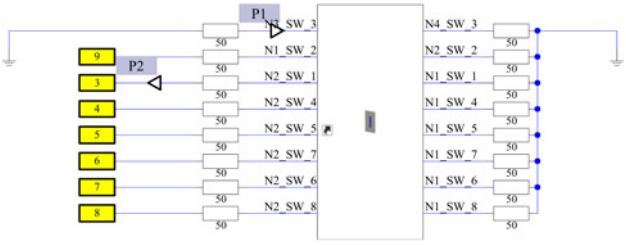


Fig. 5 *Circuit simulation model*

3.2.2 Isolation distance analysis

Assume the distance between main feeder and sensitive signal wire varies from 50 to 400 mm, the sketch map is shown in Fig. 6. Then, the coupling voltage can be got with CS co-simulation. The coupling voltage waveform is shown in Fig. 7.

For the source voltage in main feeder is 230 VAC, 400 Hz, the coupling voltage frequency is also 400 Hz. The coupling voltage amplitude depended on the isolation distance. The relationship

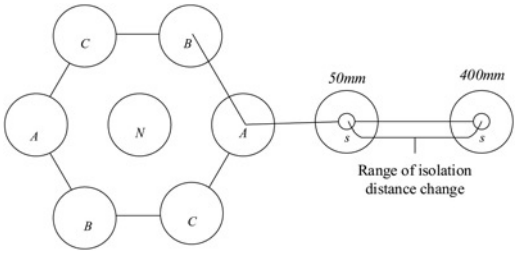


Fig. 6 *Sketch map of isolation distance analysis*

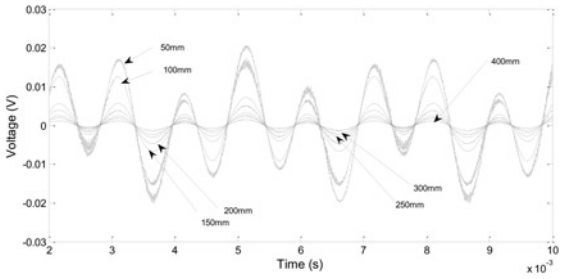


Fig. 7 *Coupling voltage waveform of isolation distance analysis*

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Table 1 Relationship between isolation distance and max coupling voltage amplitude

Isolation distance	Max coupling voltage amplitude
50	0.1184
100	0.0681
150	0.0213
200	0.0132
250	0.0098
300	0.0075
400	0.0065

between isolation distance and max coupling voltage amplitude is shown in Table 1. The coupling voltage can be fitted a smooth curve as shown in Fig. 8. The inflection point lies at 150 mm. So the isolation distance can be defined more than 150 mm.

At the same time, we can see from the waveform that the voltage amplitude is not all the same in different period. As to the main feeder configuration used in the simulation, there are different phase in the two adjacent wires. So the isolation position relative to different phase of the main feeder can affect the isolation effects.

3.2.3 Isolation position analysis: In order to find out the relationship between isolation position relative to different phase of the main feeder and the isolation effect, the simulation is done as sketch map in Fig. 9. Then, the coupling voltage can be got with CS co-simulation. The coupling voltage waveform is shown in Fig. 10.

For the sensitive signal wire lies between two phase lines, the coupling voltage is mainly composed of the two voltage sources. So the coupling voltage is not a perfect sine wave. The coupling voltage varies from 0.0219 to 0.0296 V. According to the relationship between isolation position and max coupling voltage amplitude, if the sensitive signal wire lies between two phase lines, the coupling voltage is the lowest. The highest coupling voltage

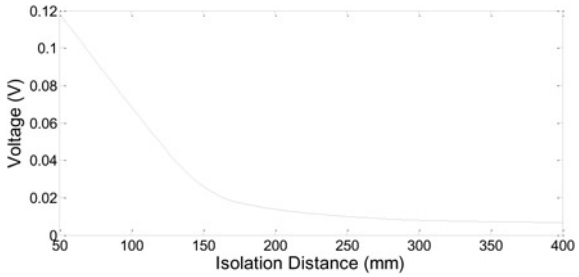


Fig. 8 *Fitted curve with isolation distance and max coupling voltage amplitude*

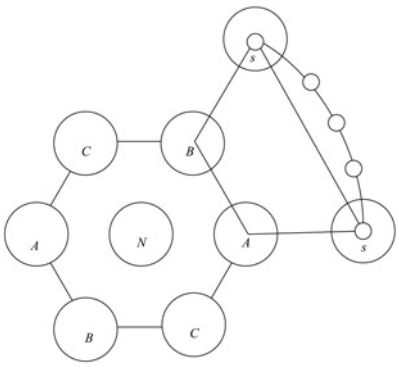


Fig. 9 *Sketch map of isolation position analysis*

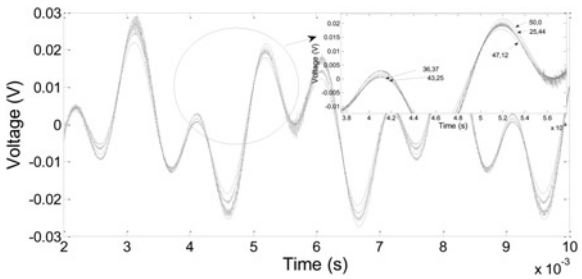


Fig. 10 *Coupling voltage waveform of isolation position analysis*

Table 2 Relationship between isolation position and max coupling voltage amplitude

Isolation position	Max coupling voltage amplitude
50,0	0.0296
47,12	0.0219
43,25	0.0246
36,37	0.0269
25,44	0.0289

appears near a phase. So the sensitive signal wire can be laid between two phase wires (Table 2).

According to the analysis above, all the coupling voltage is very low. So it may affect the quality of signal transmission, but will not cause signal transmission error. However, all the analysis above is under normal condition, and the loads are all ideal resistance. So the other types of loads should be considered.

3.2.4 Isolation distance analysis with types of loads: Considering replacing the ideal resistance load with inductance, all the other conditions are the same with Section 3.2.2. The coupling voltage can be got with CS co-simulation, and the coupling voltage waveform is shown in Fig. 11.

As shown in Fig. 11, the coupling voltage amplitude with ideal resistance loads and 50 mm isolation distance is 0.0296, while with inductance loads and 50 mm isolation distance is 3.2195. If the distance is 300 mm, the corresponding coupling voltage amplitude are separately 0.0075 and 0.3725. So if there were inductance loads in the main feeder circuit, the isolation distance should be set greater. Usually, there are all kinds of loads in the electrical system circuit, so the isolation effects between wires must consider the load characteristic.

3.2.5 Analysis of influence of arc fault on signal line: If there were arc fault in main feeder, the coupling infection to the sensitive signal wire would be more serious than the normal condition. So the fault condition must be considered when laying wires. In this

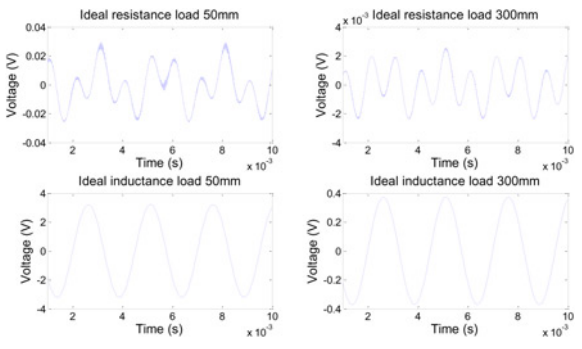


Fig. 11 *Coupling voltage waveform of isolation distance analysis with types of loads*

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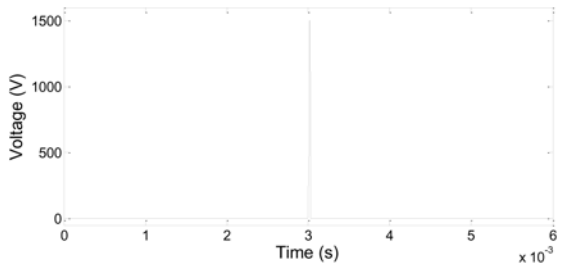


Fig. 12 *Arc waveform*

paper, a typical pulsed arc with 1500 V amplitude, 0.0000185 s rise time, 0.00001 s fall time and 0.000005 s duration is designed as the simulation object. Assume the distance between the fault main feeder and sensitive signal wire varies from 50 to 400 mm [10]. There is arc fault between phase A and phase B of the main feeder. Then, the coupling voltage can be obtained with CS co-simulation. The arc waveform is shown in Fig. 12.

Assume the distance between main feeder with arc fault and sensitive signal wire varies from 50 to 400 mm, the coupling voltage waveform is shown in Figs. 13–15, and the relationship between isolation distance and max coupling voltage amplitude is shown in Table 3.

As shown in Fig. 11, if there were arc fault on the main feeder, and the distance between main feeder and sensitive signal wire is 50 mm, max coupling voltage amplitude is 27.0850 V. So it will seriously affect the quality of transmission signal. If the isolation distance is 400 mm, the coupling voltage is 0.626 V. The arc effects will last for 0.0005 s. As to signal wire with high transmission speed, it may increase the transmission bit error rate. So the arc fault should be considered when laying wires.

4 Proposed methods to reduce the coupling effects between wires

Based on the theoretical analysis and simulation of coupling effects on main feeder, this paper summarises the following measures to reduce the coupling effect between wires.

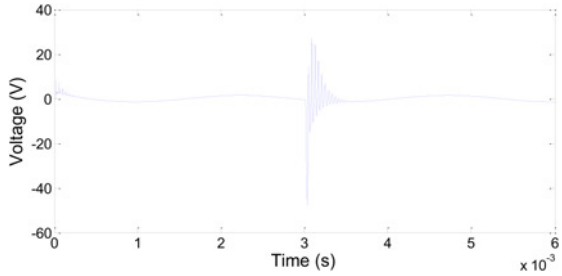


Fig. 13 *Arc waveform 50 mm*

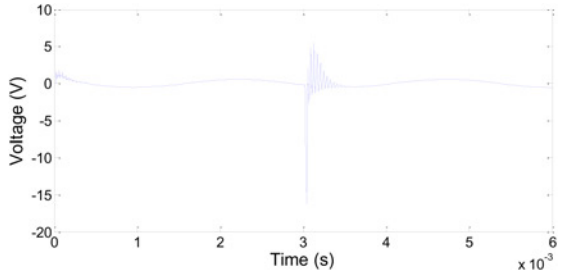


Fig. 14 *Arc waveform 150 mm*

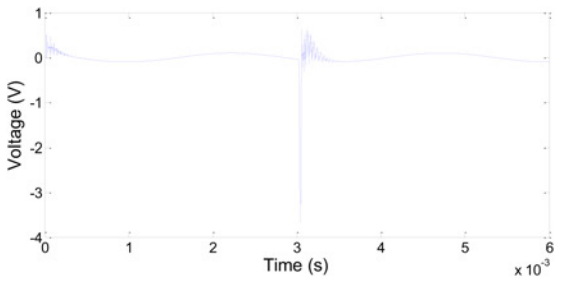


Fig. 15 *Arc waveform 400 mm*

Table 3 Relationship between isolation distance and max coupling voltage amplitude

Isolation distance	Max coupling voltage amplitude
50	27.0850
100	17.3235
150	5.4138
200	2.5414
250	1.5433
300	1.1365
400	0.6260

(i) The mutual inductance and mutual capacitance could be reduced by increasing distance between wires, and then the coupling effects reduced as well. When the distance increases to a certain extent, there is no meaning in decreasing the coupling interference by enlarging the wire isolation distance. For the aircraft wire routing space is limited, the shielded wire, twisted wire or filter should be used to reduce coupling effects for meeting electromagnetic compatibility standards.

(ii) According to the relationship between isolation position and max coupling voltage amplitude, if the sensitive signal wire lies between two phase lines, the coupling voltage is the lowest. The highest coupling voltage appears near a phase. So the sensitive signal wire can be laid between two phase wires.

(iii) If there were inductance loads in the main feeder circuit, the isolation distance should be set greater. Usually, there are all kinds of loads in the electrical system circuit, so the isolation effects between wires must consider the load characteristic.

(iv) If there were arc fault on the main feeder, and the distance between main feeder and sensitive signal wire is 50 mm, max coupling voltage amplitude is 27.0850 V. So it will seriously affect the quality of transmission signal. If the isolation distance is 400 mm, the coupling voltage is 0.626 V. The arc effects will last for 0.0005 s. As to signal wire with high transmission speed, it may increase the transmission bit error rate. So the arc fault should be considered when laying wires.

(v) Overall, the coupling effects between wires have a direct relationship with wire length, wires space, loads and the type of signal. The coupled interference voltage at frequency point is observably different. In order to avoid a larger coupling current at the work frequency, it is necessary to select appropriate type and length of cable or wire, and especially to keep the useful signal work frequency away from the coupling interference resonance frequency.

5 Conclusion

As to the complicated EWIS environment, the coupling effects would be more serious. This paper gives some useful conclusions

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based on the theoretical analysis of wire electromagnetic coupling and the simulation of coupling interference caused by wire space, height to the reference ground, kinds of load and arc fault. Although main feeder is the research object, all kinds of EWIS can be dealt with the simulation steps. So in the process of making design decisions, the isolation distance can be set with simulation at first.

These proposed methods to reduce the coupling effects between wires can be as the reference of EWIS wiring to avoid the blindness and provide a means to reduce cable electromagnetic coupling interference for ensuring the whole system meeting the airworthiness requirements, such as DO-160 and so on. It would be a complement of SAE 50881 and airworthiness regulations CCAR 25.1707.

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