Research on the test method of using injection as an equivalent substitute for electromagnetic radiation

X D Pan*, G H Wei, X F Lu, K Li
Institute of electrostatic and electromagnetic protection, Mechanical Engineering College, heping west road, shijiazhuang, China

E-mail: xiaodong-pan@hotmail.com

Abstract. This paper presents a method to carry out high intensity radiated field (HIRF) effect experiments by using injection as an equivalent substitute for electromagnetic radiation. In allusion to typical interconnected system, the equal response voltage on the equipment cable port is regarded as an equivalent basis of injection and radiation methods. The equivalent relation formula between injected voltage and radiated field is derived theoretically. The conditions needed for extrapolating injected voltage in HIRF are confirmed, and the extrapolation method is proposed. On the basis of the above research, the electromagnetic environment effect test new method combined injection with radiation for interconnected system is summarized. The typical nonlinear interconnected system is selected as equipment under test, and the single frequency continuous wave radiation and injection effect experiments are carried out separately. The test results indicate that the relation between radiated field and injected voltage is linear, and the equivalent injected voltage used to substitute HIRF can be obtained by linear extrapolation.

1. Introduction
With the development of high power radio equipment, electronic warfare system, electromagnetic pulse bomb, high power microwave weapon and so on, the electromagnetic environment in limited space is on the slide [1]. High intensity radiated field (HIRF) has become a new challenge faced by weaponry and civil electronic system [2]. “MIL-STD-464A electromagnetic environmental effects requirements for systems” illuminate external electromagnetic environment (EME) for system. The electric field intensity is higher than 200 V m⁻¹ in vast frequency band. In the frequency band of 2.7~3.6 GHz, the peak external EME for shipboard operations in the main beam of transmitters is 27460 V m⁻¹, and the average value is 2630 V/m. If carrying out electromagnetic interference safety margin test, the much higher electric field intensity should be provided. Yet the needed electric field intensity cannot be simulated under the condition of present laboratory. Thus, it is hard to carry out electromagnetic radiated susceptibility and safety margin test for system with single electromagnetic radiation method [3].

Therefore, it is necessary to explore a new injection method to substitute for radiation test. Under this condition, the theory and method of using coupling module injection as an equivalent substitute for radiation is proposed in this paper.

* To whom any correspondence should be addressed.
2. Theoretical research

2.1. Equivalence analysis between injection and radiation
Strictly speaking, injection cannot be equivalent to radiation completely. Because radiated response is the result of a good many distributed source, but injected response is the result of lumped source. However, as for the system under test with definite coupling channel, such as interconnected system and antenna feeding system, the electromagnetic energy acts on the inner circuit of the system mainly through cable or antenna port with conducted interference mode [4]. Hence, if examining the electromagnetic susceptibility of the equipment connected by the cable, the injection test method can be adopted to substitute for radiation effect test equivalently [5].

The strict equivalent base in theory between injection and radiation method is equal response on the equipment under test, and the equivalent base in engineering is the same effects caused by the two test methods. Based on the above-mentioned viewpoint, if the response voltage or induced current acted on the cable port of the equipment, it could be ensured equal, the equivalence of the two test methods can be guaranteed [6]. So the equivalent base of the two test methods in this paper is identified as the equal response voltage on the cable port of the equipment under test [7].

The purpose of presenting a new injection test method is to substitute for HIRF radiated effect experiments. How to acquire the corresponding relation between injected voltage and HIRF intensity is the crucial problem because HIRF is difficult to simulate under the condition of laboratory presently, the equivalent injected voltage could not be obtained by practical experiment. Therefore, the equivalent injected voltage used to substitute HIRF test can only be obtained by linearly extrapolating with the correspondent relation in lower radiated field.

2.2. Equivalent model of using injection as a substitute for radiation
The structure of typical interconnected system is shown in figure 1. Assuming B is the equipment under test, and A is either interconnected equipment or receiving antenna. Under the condition of electromagnetic radiation, the interconnected system can be reduced to a transmission network shown in figure 2. Where \( Z_A \) is the equivalent impedance of equipment A, \( Z_L \) is the equivalent impedance of equipment B, and \( Z_C \) is the characteristic impedance of transmission line. If the transmission line is coaxial cable, the whole system can be regarded as two independent transmission line models. The one is external transmission line model composed of shielding layer and ground, and the other is inside transmission line model composed of shielding layer and inner conductor. When the interconnected system is radiated by electromagnetic field, the inside transmission line is excited by external transmission line through transfer impedance and transfer admittance. Accordingly, the interconnected transmission line is coaxial cable, and the circuit model shown in figure 2 also could be adopted to analyze the radiated response of the terminal load.

![Figure 1. Scheme of typical interconnected system structure.](image1.png)

![Figure 2. Reduced transmission network of interconnected system.](image2.png)

In order to calculate the response voltage on the equivalent impedance \( Z_L \) of equipment B, the interconnected system is divided into two parts at the position of A-A’ in circuit analysis. The left branch of A-A’ can be equivalent to Thevenin equivalent circuit, as shown in figure 3. In this way, the
interference on the external port of equipment B can be equivalent to impedance element $Z_{SR}$ and voltage source $U_{SR}$. Where $Z_{SR}$ is the output impedance of A-A’ left branch, and $U_{SR}$ is the open-circuit voltage. Therefore, the entire radiated response equivalent circuit combined the left branch with equipment B is shown in figure 4.

![Figure 3. Thevenin equivalent circuit of left branch.](image)

Defining the transmission line length between A-A’ port and impedance $Z_A$ is $l$, and the reflection coefficient is $\rho_A$. According to transmission line theory, the internal impedance $Z_{SR}$ of equivalent voltage source is as follows:

$$Z_{SR} = Z_A (1 + \rho_{A-A'}) (1 - \rho_{A-A'})^{-1} = Z_A (1 + \rho_A e^{-j2\gamma l}) (1 - \rho_A e^{-j2\gamma l})^{-1}$$  \hspace{1cm} (1)

Under the condition of electromagnetic radiation, the open-circuit voltage $U_{SR}$ can be calculated with BLT equation. Set A-A’ port is open, i.e., $\rho_A = 1$. The open-circuit voltage at the position $x=l$ is as follows:

$$U_{SR} = 2(1 - \rho_A e^{-j2\gamma l})^{-1} (e^{-j\gamma l} S_1 + \rho_A e^{-j\gamma l} S_2)$$  \hspace{1cm} (2)

where $S_1$, $S_2$ are the source vector in BLT equation. If adopting Agrawal model [8], there is a linear relation between the source vector and incident electric field intensity. In order to simplify the expression, defining the transfer function between source vector $U_{SR}$ and incident electric field $E$ is $f$. Hence, the equation (2) can be simplified as follows:

$$U_{SR} = f(E)$$  \hspace{1cm} (3)

The transfer function $f$ satisfies the equation $f(k \cdot E) = k \cdot f(E)$. By solving the impedance element $Z_{SR}$ and voltage source $U_{SR}$, according to equivalent circuit in figure 4, the radiated response on equivalent impedance $Z_L$ can be derived as follows:

$$u_{LR} = Z_L (Z_{SR} + Z_L)^{-1} U_{SR} = Z_L (Z_{SR} + Z_L)^{-1} f(E)$$  \hspace{1cm} (4)

![Figure 4. Radiated response equivalent circuit of system.](image)

![Figure 5. Injected response equivalent circuit of system.](image)
Consulting the above analysis process, the injected response equivalent circuit can be easily obtained, which is shown in figure 5. Where \( U_{SI} \) is injected voltage source, \( Z_{SI} \) is the inner impedance of injected voltage source, and \( u_{LI} \) is the injected response of equipment B.

According to the equivalent circuit in figure 5, the injected response on equivalent impedance \( Z_L \) can be expressed as:

\[
u_{LI} = Z_L (Z_{SI} + Z_L)^{-1} U_{SI}
\]

(5)

The equivalent basis for injection and radiation test methods presented in section 2.1 is the equal response on equipment under test, i.e., \( u_{LR} = u_{LI} \). The injected voltage source can be derived as follows:

\[
U_{SI} = (Z_{SI} + Z_L) Z_L^{-1} u_{LR}
\]

(6)

\[
U_{SI} = (Z_{SI} + Z_L) (Z_{SR} + Z_L)^{-1} U_{SR} = (Z_{SI} + Z_L) (Z_{SR} + Z_L)^{-1} f(E)
\]

(7)

Here, \( Z_{SR} \) and \( Z_{SI} \) can be analyzed according to equation (1), and \( Z_L \) can be obtained by practical testing using radio frequency impedance analyzer. The lumped voltage source \( U_{SR} \) can be calculated according to equation (2). Finally, according to equation (7), the correspondent relation between theoretical equivalent injected voltage \( U_{SI} \) and radiated field \( E \) is confirmed, which ensures the equivalence between injection and radiation.

2.3. Extrapolation model for injected voltage source in high intensity field

The test method using injection as a substitute for radiation mainly solves electromagnetic radiation effect test for interconnected system in HIRF. According to the above equivalent principle, the low power equivalent injected voltage \( U_{SI} \) obtained through pretest need to be extrapolated in high intensity field, and the high power equivalent injected voltage \( V_{SI} \) can be obtained in this way. So the high intensity radiated effect experiment which is difficult to accomplish in present laboratory condition can be substituted by high power injection experiment.

The majority of systems under test are nonlinear response system. It means the relation between voltage response and the input signal is not linear because of the working state, material performance and parasitic parameter change. As to nonlinear system, how to extrapolate the injected voltage source is the crucial problem. Therefore, on the basis of theoretical analysis and experiment research to the typical nonlinear system, the interference (degradation, failure and damage) caused by electromagnetic radiation is divided into two process. The one is field coupling process to the cable, and the other is the response process on the module and device. As can be known from electromagnetic field theory, the field coupling process is linear, and the device response process is nonlinear. As long as the exciting effect on the device input port excited by injected voltage source and the radiated equivalent voltage source can ensure equal, the response voltage in injection experiment will be the same as it in radiation experiment, and the equivalent injected voltage source used to substitute high intensity field radiation test can be extrapolate with linear relation. In order to ensure the exciting effect on the input port is the same under the condition of high intensity field, two conditions must be satisfied. The first one is the same open circuit voltage of injected voltage source and radiated equivalent lumped voltage source in high intensity field, viz. \( U_{SI} = U_{SR} \), the other is the same voltage dividing rate for device input port response in the radiation and injection equivalent circuit, viz. \( Z_L / (Z_{SI} + Z_L) = Z_L / (Z_{SR} + Z_L) \).

The equation (2) gives the theoretical calculation method for radiated equivalent lumped voltage source. However, for practical engineering test, it is inconvenient to obtain \( U_{SR} \) through complicated calculation process and carry out equivalent substitute injection test. Moreover, because of the effect of surrounding environment and the existence of error, it may result in a certain gap between theoretical calculation result and practical situation. Therefore, it is very important to get injected voltage source \( U_{SI} \) by using practical test method. In order to solve the above problem, the forward voltage \( u^+ (0) \) on the interconnected transmission line is regarded as equivalent parameter in low intensity field pretest. The equivalent injected voltage \( U_{SI} \) in low intensity field pretest can be obtained
when the forward voltage \( u^+ (0) \) in injection pretest is equal to the one in radiation pretest. Finally, the equivalent injected voltage \( V_{SI} \) in high intensity field can be obtained by linear extrapolate from \( U_{SI} \) \( (V_{SI} = kU_{SI}) \), and then the equivalent injection test substituting for high intensity field radiation test can be accomplished in this way. It has more universal meaning and engineering application value for interconnected system to carry out radiated effects test.

3. Experiment verification

By carrying out radiation and injection effect test to antenna receiving system, the linear relation between radiated electric field and equivalent injected voltage source is verified. So the injected voltage source substituting for high intensity field can be obtained by linear extrapolation from the corresponding relation in low intensity field.

3.1. Interconnected system under test

The interconnected system under test is typical nonlinear system. It is composed of receiving antenna, coaxial cable and RF front end assembly. The connected mode is shown in figure 6. The RF front end assembly is integrated in one box including clipping filter module, directional coupler, low-noise amplifier (LNA), sensitivity control module, clipping amplifier and so on.

3.2. Verification experiment method

The interconnected system under test is carried out radiation and injection effect experiments separately. The equipment B in figure 6 appears nonlinear response in radiation and injection test. The corresponding relation between radiated field, injected voltage and the response on equipment B is recorded. Because the response voltage value on equipment B can be monitored, the response voltage on equipment B is regarded as equivalent principle directly. The corresponding relation between radiated field and equivalent injected voltage can be obtained when the equipment B appears linear and nonlinear response. If the corresponding relation keeps linear, the injected voltage source substituting for high intensity field can be obtained by linear extrapolation from the corresponding relation in low intensity field.

3.3. Experiment results and analysis

Three frequency points (3.3 GHz, 4.6 GHz and 7.2 GHz) in interconnected system working frequency band are selected to carry out verification experiments.

According to the radiation test method talked above, the relation curve between equipment B output response and radiated electric field intensity is obtained with different frequency points. It is shown in figure 7.

![Figure 6. Scheme of connection mode for antenna receiving system.](image)

![Figure 7. Relation curve between output response and radiated electric field intensity.](image)
The injection effect test is carried out according to the above test method. The relation curve between equipment B output response and injected voltage value is obtained with different frequency points. It is shown in figure 8.

![Figure 8. Relation curve between output response and injected voltage value.](image)

![Figure 9. Relation curve between injected voltage and radiated field intensity.](image)

In order to quantitatively analyze the equivalent correspondent relation between injected voltage and radiated field intensity, on the premise of equal equipment B output response, the correspondent relation between injected voltage and radiated field intensity is obtained with different frequency points. It is shown in figure 9.

It can be seen from the variation trend of the measured data in figure 8. The correlation between radiated field intensity and equivalent injected voltage value is linear. The measured data is processed by straight-line fitting ($y = mx$). The gradient m and correlation coefficient R under different frequency test condition is shown in table 1.

| system B | $f$ / GHz | straight-line fitting gradient | correlation coefficient |
|----------|-----------|-------------------------------|-------------------------|
| B1       | 3.3       | 12.8281                       | 0.99886                 |
| B1       | 4.6       | 9.7117                        | 0.99972                 |
| B1       | 7.2       | 5.08199                       | 0.99985                 |

In sum, even the response of the equipment under test is nonlinear, on the premise of equal equipment output response, the correspondent relation between equivalent injected voltage and radiated field intensity is linear. Therefore, the equivalent injection voltage used to substitute HIRF test can be obtained by linearly extrapolating the correspondent relation in lower radiated field condition.

4. Conclusions
The equal response voltage on the equipment cable port is regarded as equivalent principle. The equivalent substitute model and injection source extrapolation model in HIRF condition are established. The equivalent correspondent relation between injection voltage and radiated field is put forward theoretically. The couple conditions of using injection as a substitute for radiation are determined. One is the same equivalent source, and the other is the same output impedance.
The forward voltage on interconnected transmission line is regarded as indirect equivalent parameter, and then the equivalent injected voltage source $U_{SI}$ in low intensity field is obtained. The equivalent injected voltage source $V_{SI}$ in high intensity field can be obtained by extrapolating $U_{SI}$ linearly ($V_{SI}=kU_{SI}$).

The typical nonlinear interconnected system is selected as equipment under test, and the single frequency continuous wave radiation and injection effect experiments are carried out separately. The test results indicate that the relation between radiated field and injected voltage is linear, and the equivalent injected voltage used to substitute HIRF can be obtained by linear extrapolation.

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