Study on System Design and Variation of Vehicle Antenna Eccentricity test

Guokai Jiang\textsuperscript{1,2,a}, Guotian Ji\textsuperscript{2,b}, Jiaxu Feng\textsuperscript{1,2,e}, Penghui Shen\textsuperscript{3,4,d,*}, Yifu Ding\textsuperscript{1,2,e}

Changyuan Wang\textsuperscript{1,2,f}

\textsuperscript{1}CATARC Automotive Test Center (Tianjin) Co., Ltd, Tianjin, China
\textsuperscript{2}China Automotive Technology and Research Center Co., Ltd, Tianjin, China
\textsuperscript{3}General Test Systems Inc., Shenzhen, China

\textsuperscript{a}email: jiangguokai@catarc.ac.cn, \textsuperscript{b}email: jiguotian@catarc.ac.cn, \textsuperscript{c}email: fengjiaxu@catarc.ac.cn, \textsuperscript{d}email: penghui.shen@generaltest.com, \textsuperscript{e}email: dingyifu@catarc.ac.cn, \textsuperscript{f}email: wangchangyuan@catarc.ac.cn

\textbf{Abstract:} This paper takes the vehicle antenna as the research object, and carries out a comparative study on vehicle antenna testing by improving the NF-FF transformation algorithm and combining the special application scenarios of vehicle testing. Research has shown that when the vehicle is used as the DUT, there is a significant difference in the near-field test data when the vehicle antenna is in the center and the geometric center of the vehicle is in the test center; however, through correct NF-FF transformation processing, both far-field radiation patterns are consistent. It shows that the far-field radiation information of the whole vehicle can be obtained under the processing of spherical near-field measurement and near-far-field transformation. This conclusion provides a basis for the promotion of wireless performance testing of the vehicle.

1. Preface

With the development of intelligent connected vehicles, traffic management, information services, autonomous vehicles and other functions have been applied in the field of automobiles, which has greatly reduced urban traffic congestion, minimized traffic accidents, and improved the driving experience [1-6].

However, the fundamental difference between connected vehicles and traditional vehicles lies in the collaborative information processing ability based on V2X, the wireless communication technology for Internet of vehicles [7]. At present, there are two types of international wireless communication technical standards for Internet of vehicles, that is, DSRC based on IEEE 802.11p standard for wireless LAN and C-V2X based on 3GPP protocol for cellular network. The connected vehicles can be figuratively compared to a super-large smart phone. The whole-vehicle wireless test of intelligent connected vehicles is an essential means to ensure the performance and reliability of its wireless communication [8-12]. However, compared with the terminal test, the vehicle test faces tougher challenges: due to the large size of the vehicle as the tested piece (the length of the passenger car is generally no more than 6m), and limited by the installation position of the vehicle mounted antenna and the multi-antenna technology, the equivalent radiation aperture of the vehicle is difficult to obtain. If the vehicle is used as a radiator for far-field wireless performance evaluation, a distance of several hundred meters or more needs to be tested, which greatly increases the difficulty of implementation of the project. For the passive pattern test of the automobile antenna, currently the research institutions and enterprises at home and abroad
mostly adopt near-field scanning + near-far-field transformation (NF-FF) technology to realize it. Foreign well-known automobile enterprises, such as Daimler, Renault, Peugeot Citroen PSA, General Motors, Toyota, Tesla, have already built vehicle antenna testing laboratories based on NF-FF method. However, the research results based on these laboratories are still in the primary stage. It is an urgent problem at present how to evaluate the uncertainty of the testing system. Based on this, this paper conducts in-depth studies on the automobile antenna testing system based on NF-FF algorithm, and aims at solving the problem of accurate measurement of automobile antenna.

2. Overview of Automobile Antenna Test System

Figure 1 is a schematic diagram of the test method for the automobile antenna based on NF-FF. The testing method takes the tested vehicle as the center of the sampling coordinate system, samples the tangential electric field radiated by the vehicle in the upper hemisphere, and then performs near-far field transformation on the sampled data to obtain the far-field radiation situation [8 ~ 9]. Among them, according to the sampling theorem, the sampling density of the theta and phi axes must meet the requirements of $\rho \leq \frac{\lambda}{D}$, in which $\lambda$ is the wavelength, and $D$ is the maximum size of the vehicle.

![Figure 1. The schematic diagram of NF sampling for automobile antenna performance test.](image1)

Figure 2 is an automobile antenna test system, which includes microwave anechoic chamber, mechanical scanner, network analyzer, rotating platform and other accessories. Among them, the microwave anechoic chamber is used to create a microwave test environment without reflection, the mechanical arm scanner is used to carry the measured antenna to realize the electric field acquisition of the hemispherical surface of the tested vehicle, the network analyzer is used to measure the S parameter between the horn antenna and the tested piece, and the rotating platform is used to carry the tested piece to realize the phi rotation. With a scanning radius of 3m, the test system can conduct the test sampling of theta in the field between 0 ° and 95 ° and has a mechanical accuracy of $\pm 0.05 \degree$.

![Figure 2. The system diagram of NF sampling for automobile antenna performance test.](image2)

3. Principle of Near-Field and Far-Field Transformation Algorithm

In this paper, the near-field and far-field algorithm is used to transform the experimental data, and the field source reconstruction algorithm is used to optimize the near-field and far-field transformation algorithm. A source of radiation with finite size can be replaced by an equivalent multipole expansion, which can provide the same radiation pattern as the real source. With proper division, the volume of the radiation source can be divided into several electrically small sizes, which can be represented by dipoles,
with three electric field components along the x axis, y axis, and z axis (expressed as \( Q_x, Q_y, Q_z \)) and three magnetic field components along the x axis, y axis, and z axis (expressed as \( M_x, M_y, M_z \)).

![Diagram](image.png)

Figure 3 shows \( u \) dipole sources inside the sphere and \( s \) observation points outside the sphere. The electric field observed at the point \( s \) generated by the source \( u \) can be described as shown in formula (1), (2) and (3).

\[
E_{x,s,u} = -\frac{j\eta_0 G}{k_0 R^3} \left[ (k_0^2 R^2 - kRj - 1)R^2 Q_{x,u} \right.
\]

\[
+ (3k_0^2 R^2 - 3kRj - 1)(x-x')(x-x') Q_{x,u} \]

\[
+ (3k_0^2 R^2 - 3kRj - 1)(y-y')(y-y') Q_{y,u} \]

\[
+ (3k_0^2 R^2 - 3kRj - 1)(z-z')(z-z') Q_{z,u} \]

\[
- \frac{jG}{R^2} (k_0 Rj + 1)(y-y') M_{y,u} \]

\[
+ \frac{jG}{R^2} (k_0 Rj + 1)(z-z') M_{z,u} \]

\[
(1)
\]

\[
E_{y,s,u} = -\frac{j\eta_0 G}{k_0 R^3} \left[ (k_0^2 R^2 - kRj - 1)R^2 Q_{y,u} \right.
\]

\[
+ (3k_0^2 R^2 - 3kRj - 1)(y-y')^2 Q_{y,u} \]

\[
+ (3k_0^2 R^2 - 3kRj - 1)(x-x')(y-y') Q_{x,u} \]

\[
+ (3k_0^2 R^2 - 3kRj - 1)(y-y')(z-z') Q_{z,u} \]

\[
- \frac{jG}{R^2} (k_0 Rj + 1)(z-z') M_{z,u} \]

\[
+ \frac{jG}{R^2} (k_0 Rj + 1)(z-z') M_{z,u} \]

\[
(2)
\]
\[ E_{z,u} = -j\eta_0 G \left[ \left( k_0^2 R^2 - kR_j - 1 \right) R^2 Q_{z,u} \right] + \left( 3k_0^2 R^2 - 3kR_j - 1 \right) (z - z') Q_{z,u} \]
\[ + \left( 3k_0^2 R^2 - 3kR_j - 1 \right) (x - x')(z - z') Q_{x,u} \]
\[ + \left( 3k_0^2 R^2 - 3kR_j - 1 \right) (y - y')(z - z') Q_{y,u} \]
\[ \frac{-jG}{R^2} (k_0 R_j + 1)(y - y') M_{x,u} \]
\[ + \frac{jG}{R^2} (k_0 R_j + 1)(x - x') M_{y,u} \] (3)

Among them, the \( Q_{x,u}, Q_{y,u}, Q_{z,u} \) and \( M_{x,u}, M_{y,u}, M_{z,u} \) are respectively the electric field and magnetic field components of the source \( u \) in the location of \( (x', y', z') \) along the directions of \( x, y, \) and \( z; \) \( E_{x,u}, E_{y,u}, E_{z,u} \) are the observed electric field components generated by the source \( u \) along the directions of \( x, y, \) and \( z \) at the observation point \( s \) (corresponding position is \( (x,y,z) \)); \( k_0 \) and \( \eta_0 \) are wavelength and impedance, respectively. \( G \) and \( R \) are expressed as follows:
\[ G = e^{j\eta_0 \theta} \] (4)
\[ R = \sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2} \] (5)

The relationship between \( M_{x,u}, M_{y,u}, M_{z,u} \) is shown in formula (6):
\[ \begin{bmatrix} E_{x,u} \\ E_{y,u} \\ E_{z,u} \end{bmatrix} = T_{s,u} \cdot QM_u \] (6)

Then the coefficients of \( T_{s,u} \) and \( QM_u \) are shown in formula (7):
\[ T_{s,u} = \begin{bmatrix} x_{x,u} & x_{y,u} & x_{z,u} & 0 & \psi_{x,y} & \psi_{x,z} \\ x_{y,u} & x_{y,u} & x_{y,u} & 0 & \psi_{y,x} & \psi_{y,z} \\ x_{z,u} & x_{z,u} & x_{z,u} & 0 & \psi_{z,x} & \psi_{z,y} \end{bmatrix} \]
\[ QM_u = \begin{bmatrix} Q_{x,u} \\ Q_{y,u} \\ Q_{z,u} \end{bmatrix} \]
\[ M_{x,u} \quad M_{y,u} \quad M_{z,u} \end{bmatrix}^T \] (7)

Therefore, for the observation point \( s \), the total electric field \( \begin{bmatrix} E_{x,s} \\ E_{y,s} \\ E_{z,s} \end{bmatrix} \) generated by \( u \) sources can be deduced as follows:
\[ \begin{bmatrix} E_{x,s} \\ E_{y,s} \\ E_{z,s} \end{bmatrix} = \sum_{u=1}^{U} (T_{s,u} \cdot QM_u) \] (8)

Equation (8) is further expressed as:
\[ \begin{bmatrix} E_{x,s} \\ E_{y,s} \\ E_{z,s} \end{bmatrix} = \begin{bmatrix} T_{s,1} & T_{s,2} & \cdots & T_{s,U} \\ \vdots & \vdots & \ddots & \vdots \\ T_{U,1} & T_{U,2} & \cdots & T_{U,U} \end{bmatrix} \begin{bmatrix} QM_1 \\ QM_2 \\ \vdots \\ QM_U \end{bmatrix} \] (9)

Finally, the observed electric field generated by all sources at all observation points is:
\[ \begin{bmatrix} E_{o,1} \\ E_{o,2} \\ \vdots \\ E_{o,U} \end{bmatrix} = \begin{bmatrix} T_{1,1} & T_{1,2} & \cdots & T_{1,U} \\ T_{2,1} & T_{2,2} & \cdots & T_{2,U} \\ \vdots & \vdots & \ddots & \vdots \\ T_{U,1} & T_{U,2} & \cdots & T_{U,U} \end{bmatrix} \begin{bmatrix} QM_1 \\ QM_2 \\ \vdots \\ QM_U \end{bmatrix} \] (10)

The above equation can be simplified as:
Where $T_{ET}$ is recorded as a generated matrix, which is a coefficient dependent on the observed position and the source position.

Based on the electric field observed in (11), the source can be constructed as

$$[QM_1 \; QM_2 \; \vdots \; QM_J] = (T_{ET}^*T_{ET})^{-1}T_{ET}^* [E_{o,1} \; E_{o,2} \; \vdots \; E_{o,S}]$$

(12)

Among them, $(\cdot)^*$ is the conjugate transpose.

Finally, the far-field electric field at the position $k$ is expressed as $G_{o,k}$:

$$G_{o,k} = T_{ER,k} [QM_1 \; QM_2 \; \vdots \; QM_J]$$

(13)

Where the $T_{ER,k}$ is the line $k$ of $T_{ER}$, $[QM_1 \; QM_2 \; \vdots \; QM_J]$ is the equivalent source, $G_{o,k}$ contains the three components along the axis directions of $x$, $y$, and $z$, $G_{o,k} = [G_{x,k} \; G_{y,k} \; G_{z,k}]^T$.

4. Field Test and Verification

Figure 4 shows the microwave anechoic chamber for performance test of automobile antenna in CATARC Automotive Test Center (Tianjin) Co., Ltd. In this laboratory, two experiments were carried out respectively. One experiment is for the near-field data acquisition and far-field verification of single antenna pattern. The other experiment is for the near-field data acquisition and far-field verification of automobile antenna pattern.

In order to verify the correctness of the algorithm, the most ideal way is to get the direct far-field test results of the car antenna, and then compare the results with the far-field reduction results of the system. However, due to the problem that the vehicle’s far-field distance is uncertain and cannot be directly obtained, this paper designs a new near-field and far-field verification method for eccentric correction: A. The geometry center of the vehicle is placed in the test center for testing and near-field and far-field reduction. B. Move the vehicle and place the geometric center of the vehicle mounted antenna in the test center for testing and near-field and far-field reduction. If the NF-FF theory is correct, the far-field
results of A and B shall be consistent, which is also the verification method of the NF-FF algorithm considering eccentric correction.

4.1. System Calibration
The first step of system execution is to calibrate the system path loss and the difference in the dual polarization of the antenna. As shown in Figure 5, the standard calibrated antenna is placed in the test center of the darkroom to perform the calibration of the dual-polarization antenna loss and polarization difference.

After the loudspeaker is calibrated, a comparative test is performed and the results are described below.

4.2. Eccentric + Non-eccentric Test for Single Antenna
The single antenna verification is to compare the results of near-field sampling when the antenna is at the center of the measurement circle and 2m off-center, and the results after the far-field reduction. Test settings are shown in Figure 6. The same antenna is tested in two different positions.

The near-field sampling results are shown in Figure 7, in which the left side of Figure 7 is the sampling result of the single antenna at the center, and the right side of Figure 7 is the sampling result of the single antenna at 2m off-center. It can be seen that the near-field pattern changes greatly for the same antenna due to eccentricity.

The results of NF-FF far-field reduction are shown in Figure 8, in which the left side of Figure 8 is the far-field reduction result of the single antenna in the center, and the right side of Figure 8 is the far-field reduction result of the single antenna with 2m off-center. It can be seen that for the same antenna, eccentricity and non-eccentricity are consistent in the far-field radiation pattern.
Figure 7. Near-field Data Comparison of Eccentric + Non-eccentric Single Antenna

Figure 8. Far-field Data Comparison of Eccentric + Non-eccentric Single Antenna

Taking one of the phi plane data of the two remote fields for comparison, as shown in Figure 9, it can be seen that the data difference between the two is less than 1dB.

Figure 9. Far-field Data Comparison of Eccentric + Non-eccentric Single Antenna (a Phi plane)

4.3. Eccentric + Non-eccentric Test of Vehicle Antenna
The whole vehicle antenna verification is the comparison between the results of near-field sampling and the comparison between the results of far-field reduction when the whole vehicle is at the center of the measuring circle and when the whole vehicle antenna is at the center. The test settings are shown in Figure 10, where the antenna is fixed at the rear of the vehicle.
The near-field sampling results are shown in Figure 11. The left side of Figure 11 is the sampling result of the vehicle in the center, and the right side of Figure 11 is the sampling result of the vehicle antenna in the center. It can be seen that for the same antenna, the near-field pattern changes greatly due to eccentricity.

The results of NF-FF far-field reduction are shown in Figure 12. The left side of Figure 12 is the far-field reduction result of the vehicle in the center, and the right side of Figure 12 is the far-field reduction result of the vehicle antenna in the center. It can be seen that for the same antenna, eccentricity and non-eccentricity are consistent in the far-field radiation pattern.

Taking one of the phi plane data of the two remote fields for comparison, as shown in Figure 13, it can be seen that the difference between the two data in the main lobe is less than 1dB.
5. Conclusions and Prospects

In this paper, the whole vehicle antenna is taken as the research object. By improving the NF-FF transformation algorithm and combining with the special application scenarios of whole vehicle testing, the comparative study of whole vehicle antenna testing is carried out, and the following conclusions are drawn:

(1) When the whole vehicle is taken as the tested piece, the near-field test data is related to the position of the vehicle relative to the test system. When the position of the vehicle is moved to ensure that the vehicle antenna is in the center and the geometric center of the vehicle itself is in the test center, the near-field test data is significantly different.

(2) In this paper, the traditional NF-FF algorithm is improved for the whole vehicle test, and based on this algorithm, spherical near-field sampling and near-field and far-field transformation of the whole vehicle measurement are realized, and the information of radiation pattern under the whole vehicle condition is obtained. Experimental data shows that with the right NF-FF transformation processing, whether it is for an eccentric + non-eccentric single antenna or for an eccentric + non-eccentric vehicle antenna, the far-field radiation pattern is consistent. It also conforms to the theoretical basis, and illustrates that the radiation information of the vehicle can be obtained under the treatment of spherical near-field measurement and near-field and far-field transformation. The conclusion provides a foundation for promoting the wireless performance test of the whole vehicle.

References

[1] China Institute of Communications. Report on the Frontiers of Internet of Vehicles Technology, Standards and Industrial Development Trend, December 2018.
[2] Boston Consulting Group (BCG), Where Will Corporate Profits Go When Technology Disrupts Human Mobility, October 25, 2018.
[3] U.S. Department of Transportation, Preparing for the Future of Transportation: Automated Vehicles 3.0, October 2018.
[4] European Commission, Road to Automated Travel: The EU’s Future Travel Strategy, May 2018.
[5] Japan National Police Agency, Road Test Permit Processing Benchmark for Remote Automatic Driving System, June 2017.
[6] 3GPP, “Study on enhancement of 3GPP Support for 5G V2X Services (Release 16),” Tech. Report TR 22.886, Revision 16.2.0, Dec. 2018.
[7] 5G Automotive Association, “V2X Technology Benchmark Testing: DSRC and C-V2X”, Sept. 27, 2018.
[8] 3GPP, “User Equipment (UE) Over The Air (OTA) performance; Conformance testing,” Tech. Specif. TS 37.544 v14.5.0, 2018.
[9] CTIA, Washington, DC, USA, “Test plan for 2 × 2 downlink MIMO and transmit diversity over-the- air performance,” Revision 1.1, Aug. 2016.
[10] YEGIN. K, "On-Vehicle GPS Antenna Measurements," in IEEE Antennas and Wireless Propagation Letters, vol. 6, pp. 488-491, 2007, doi: 10.1109/LAWP.2007.907056.

[11] DIJK. J, JEUKEN. M, and MAANDERS. E. J, “Antenna noise temperature,” Proc. IET, vol. 115, no. 10, pp. 1403–1410, Oct. 1968.

[12] HANSEN. J. E, Ed., (1988)Spherical near-field antenna measurements. London, U.K.: Peter Peregrinus.