Research Article

A Novel Inversion Method of Manufacturing Flaws in the Packaging of Conformal Load-Bearing Antenna Structure

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Composite material is widely used in the conformal load-bearing antenna structure (CLAS), and the manufacturing flaws in the packaging process of the CLAS will lead to the degradation of its wave-transparent property. For this problem, a novel inverse method of the flaw's dimension by antenna-radome system's far field data has been proposed. Two steps are included in the inversion: the first one is the inversion from the far field data to the transmission coefficient of the CLAS's radome; the second one is the inversion from the transmission coefficient to the flaw's dimension. The inversion also has a good potential for the separable multilayer composite material radome. A 12.5 GHz CLAS with microstrip antenna array is used in the simulation, which indicates the effectiveness of the novel inversion method. Finally, the error analysis of the inversion method is presented by numerical simulation; the results is that the inversed error could be less than 10%, if the measurement error of far field data is less than 0.45 dB in amplitude and $\pm 5^\circ$ in phase.

1. Introduction

Conformal load-bearing antenna structure (CLAS) combines load-bearing capability and electrical performance to the one structure [1, 2] and has broad application prospects in aircraft and aerospace. It could reduce weight, volume, drag, and signature, enhance stealth and damage resistance, and increase structural efficiency [3, 4]. Since its good application prospect in aircraft and aerospace, many novel antennas and advanced materials are applied to enhance the electrical and mechanical performance of CLAS.

A conductive carbon nanotube sheet is proposed to realize CLAS, which has good radiation performances (high dielectric constant and low loss tangent) and desirable mechanical properties [5]. Daliri recommends the use of spiral shaped slot waveguide antenna for future CLAS concepts because of its broader bandwidth and better mechanical strength [6, 7] and realizes the slot spiral in carbon-fiber composite laminate successfully [8]. Galehdar et al. design a CLAS that consists of a cavity-backed slot in a carbon-fiber reinforced polymer (CFRP) panel and enhance the

gain of CLAS [9]. Yao and Qiu design a novel CLAS, and the microstrip antennas are integrated in three-dimensional orthogonal woven composites; the application of fibrous materials could enhance the flexibility of CLAS [10]. Hwang et al. investigate the embedding of microstrip antennas in multilayer composite structure from the radiation and mechanical properties, respectively [11, 12], and propose a structure design method of a CLAS for communication and navigation. Dai and Du analyze the influence of honeycomb thickness on the mechanical and electrical performance and obtain some integrated relation curves [13].

To get a planar profile, CLAS with microstrip antennas is in common use (Figure 1). The microstrip antennas are packaged with a composite material radome (glass fiber skin and honeycomb/foam) by hot pressing process. The radome has the capability of load bearing. Meanwhile, it influences the electrical performance [13, 14]. In the process of packaging, some manufacturing flaws are inevitable, such as degumming stratification, thickness nonuniformity of bonding films and composite materials, or air bubbles in the bonding films layer [14, 15]. After packaging, the machining process (cutting,

FIGURE 1: Conformal load-bearing antenna structure (CLAS) with microstrip antennas.

drilling) may also lead to some flaws [16, 17]. In working condition, the environment load may cause some damages [18]. Both the flaws and damages will degrade the mechanical [19] and electrical performance [14]. So the detection of flaws is a necessary step in the manufacture of radome or CLAS. Many sophisticated approaches could be found to detect the flaws for a removable radome, such as ultrasonic, industrial CT, and infrared thermography [15]. But for the CLAS that has an inseparable radome, it will be challenging to find the flaws using these approaches.

This paper investigates the detection of manufacturing flaws in the packaging process of CLAS, especially for the nonuniformity of thickness and air bubbles in the bonding films. The thickness of the radome could be inverted from a measured far field data of CLAS, under the premise of knowing the material parameters of radome and the near field of inside antenna. The material parameters could be tested or gotten from the agent. The near field could be calculated by a full-wave analysis such as FEM or MOM with the known design parameters of the CLAS. In Section 2, the relations between the far field data, near field data, and transmission coefficient are researched by the ray tracing-surface integration method, and two inversion formulas are proposed: one is the inversion from the far field data to the radome's transmission coefficient and the other is from the transmission coefficient to the thickness of the radome. In Section 3, the design and experiment of a CLAS are presented, and the influence of flaw's location and dimension on the far field pattern is also analyzed. In Section 4, two inversion examples of the flaws' location and dimension from ideal and unideal far field data are proposed with good results. In Section 5, the error analysis of the two inversion formulas is implemented via numerical simulation. The conclusion and work plane in the future are in Section 6.

2. Inversion Method

2.1. The Conventional Analysis Process of the CLAS. The microstrip antennas of the CLAS are covered with a composite radome, which plays the dual roles of wave transparency and load bearing. There are three typical methods to analysis the electromagnetic property of the radome: one is high frequency method [20–22] (e.g., PO, GO), another one is full-wave method [23–25] (e.g., FEM, FDTD, MOM), and the last one is hybrid method [26, 27] (e.g., PO-MOM). The ray tracing-surface integration (RT-SI) approach [20] is a high

FIGURE 2: Analysis process of far field pattern of CLAS.

frequency method and is adopted in this work. Compared to accurate full-wave method or efficient hybrid method, the RT-SI approach has the acceptable accuracy, and, more important, it has clear physical principle and the possibility to reveal the relation of far field data, radome, and near field data [28]. The basic analysis process of CLAS with RT-SI approach is indicated in Figure 2.

First, the electric fields $\mathbf{E}^{\text{in}}$ and magnetic fields $\mathbf{H}^{\text{in}}$ of the inner surface of the radome could be obtained according to some known parameters of the microstrip antenna based on full-wave method (in this work, FEM has been used):

$$\mathbf{E}^{\text{in}} = i\mathbf{E}_x^{\text{in}} + j\mathbf{E}_y^{\text{in}} + k\mathbf{E}_z^{\text{in}} \quad \mathbf{H}^{\text{in}} = i\mathbf{H}_x^{\text{in}} + j\mathbf{H}_y^{\text{in}} + k\mathbf{H}_z^{\text{in}}. \quad (1)$$

For the nonplanar radome, the tangent plane of the radome is necessary. E_b, E_t and H_b, H_t are the two components of the electric and magnetic fields in the tangent plane of radome's inner surface:

$$\begin{aligned} E_b &= E_x^{\text{in}} n_{bx} + E_y^{\text{in}} n_{by} + E_z^{\text{in}} n_{bz}, \\ E_t &= E_x^{\text{in}} t_{bx} + E_y^{\text{in}} t_{by} + E_z^{\text{in}} t_{bz}, \\ H_b &= H_x^{\text{in}} n_{bx} + H_y^{\text{in}} n_{by} + H_z^{\text{in}} n_{bz}, \\ H_t &= H_x^{\text{in}} t_{bx} + H_y^{\text{in}} t_{by} + H_z^{\text{in}} t_{bz}, \end{aligned} \quad (2)$$

where $\mathbf{n}_b$ and $\mathbf{t}_b$ are the two unit vectors in the tangent plane, which were perpendicular to each other.

Second, the transmitted electric and magnetic fields, $\mathbf{E}^{\text{out}}$ and $\mathbf{H}^{\text{out}}$, in the outer surface of the radome could be obtained:

$$\begin{aligned}\mathbf{E}^{\text{out}} &= \mathbf{i}E_x^{\text{out}} + \mathbf{j}E_y^{\text{out}} + \mathbf{k}E_z^{\text{out}} \\ &= \mathbf{i}(E_b n_{bx} T_V + E_t t_{bx} T_H) + \mathbf{j}(E_b n_{by} T_V + E_t t_{by} T_H) \\ &\quad + \mathbf{k}(E_b n_{bz} T_V + E_t t_{bz} T_H), \\ \mathbf{H}^{\text{out}} &= \mathbf{i}H_x^{\text{out}} + \mathbf{j}H_y^{\text{out}} + \mathbf{k}H_z^{\text{out}} \\ &= \mathbf{i}(H_b n_{bx} T_H + H_t t_{bx} T_V) + \mathbf{j}(H_b n_{by} T_H + H_t t_{by} T_V) \\ &\quad + \mathbf{k}(H_b n_{bz} T_H + H_t t_{bz} T_V),\end{aligned}\quad (3)$$

where T_H and T_V are the transmission coefficients of the radome for horizontal and vertical polarization electromagnetic wave and could be obtained according to the parameters of the radome based on ray tracing approach [29, 30].

Finally, the far field data $\mathbf{F}$ of CLAS could be calculated by surface integration method [29, 30]:

$$\begin{aligned}\mathbf{F}(\theta, \phi) &= \mathbf{i}F_x + \mathbf{j}F_y + \mathbf{k}F_z \\ &= \mathbf{i} \iint_{S_r} f_x e^{jk_0(x \sin \theta \cos \phi + y \sin \theta \sin \phi + z \cos \theta)} dS_r \\ &\quad + \mathbf{j} \iint_{S_r} f_y e^{jk_0(x \sin \theta \cos \phi + y \sin \theta \sin \phi + z \cos \theta)} dS_r \\ &\quad + \mathbf{k} \iint_{S_r} f_z e^{jk_0(x \sin \theta \cos \phi + y \sin \theta \sin \phi + z \cos \theta)} dS_r,\end{aligned}\quad (4)$$

where $f_x = \sin \theta \sin \phi D_z - \cos \theta D_y$, $f_y = \cos \theta D_x - \sin \theta \cos \phi D_z$, and $f_z = \sin \theta \cos \phi D_y - \sin \theta \sin \phi D_x$:

$$\begin{aligned}D_x &= n_{ry} E_z^{\text{out}} - n_{rz} E_y^{\text{out}} \\ &\quad - \sqrt{\frac{\mu_0}{\epsilon_0}} \left[\sin \theta \sin \phi (n_{rx} H_y^{\text{out}} - n_{ry} H_x^{\text{out}}) \right. \\ &\quad \left. - \cos \theta (n_{rz} H_x^{\text{out}} - n_{rx} H_z^{\text{out}}) \right], \\ D_y &= n_{rz} E_x^{\text{out}} - n_{rx} E_z^{\text{out}} \\ &\quad - \sqrt{\frac{\mu_0}{\epsilon_0}} \left[\cos \theta (n_{ry} H_z^{\text{out}} - n_{rz} H_y^{\text{out}}) \right. \\ &\quad \left. - \sin \theta \cos \phi (n_{rx} H_y^{\text{out}} - n_{rz} H_x^{\text{out}}) \right], \\ D_z &= n_{rx} E_y^{\text{out}} - n_{ry} E_x^{\text{out}} \\ &\quad - \sqrt{\frac{\mu_0}{\epsilon_0}} \left[\sin \theta \cos \phi (n_{rz} H_x^{\text{out}} - n_{rx} H_z^{\text{out}}) \right. \\ &\quad \left. - \sin \theta \sin \phi (n_{ry} H_z^{\text{out}} - n_{rz} H_y^{\text{out}}) \right].\end{aligned}\quad (5)$$

2.2. The Inversed Process of the Far Field Data. In order to get an explicit expression of transmission coefficients and far field data, the derivation is presented here, and the component F_x is used as an example.

Inserting D_y and D_z into the expression of f_x of formula (4), we get

$$\begin{aligned}f_x &= (A_{ex}^x E_t t_{bx} + A_{ey}^x E_t t_{by} + A_{ez}^x E_t t_{bz} + A_{hx}^x H_b n_{bx} \\ &\quad + A_{hy}^x H_b n_{by} + A_{hz}^x H_b n_{bz}) T_H \\ &\quad + (A_{ex}^x E_b n_{bx} + A_{ey}^x E_b n_{by} + A_{ez}^x E_b n_{bz} + A_{hx}^x H_t t_{bx} \\ &\quad + A_{hy}^x H_t t_{by} + A_{hz}^x H_t t_{bz}) T_V,\end{aligned}\quad (6)$$

where

$$A_{ex}^x = -\cos \theta n_{rz} - \sin \theta \sin \phi n_{ry},$$

$$A_{ey}^x = \sin \theta \sin \phi n_{rx},$$

$$A_{ez}^x = \cos \theta n_{rx},$$

$$A_{hx}^x = \sqrt{\frac{\mu_0}{\epsilon_0}} (\sin \theta \cos \theta \cos \phi n_{ry} - \sin^2 \theta \sin \phi \cos \phi n_{rz}),$$

$$\begin{aligned}A_{hy}^x &= \sqrt{\frac{\mu_0}{\epsilon_0}} (-\sin^2 \theta \sin^2 \phi n_{rz} - \cos^2 \theta n_{rz} \\ &\quad - \sin \theta \cos \theta \cos \phi n_{rx}), \\ A_{hz}^x &= \sqrt{\frac{\mu_0}{\epsilon_0}} (\sin^2 \theta \sin \phi \cos \phi n_{rx} + \sin^2 \theta \sin^2 \phi n_{ry} \\ &\quad + \cos^2 \theta n_{ry}).\end{aligned}\quad (7)$$

Given that

$$\begin{aligned}B_x &= (A_{ex}^x E_t t_{bx} + A_{ey}^x E_t t_{by} + A_{ez}^x E_t t_{bz} + A_{hx}^x H_b n_{bx} \\ &\quad + A_{hy}^x H_b n_{by} + A_{hz}^x H_b n_{bz}) \\ &\quad \cdot e^{jk_0(x \sin \theta \cos \phi + y \sin \theta \sin \phi + z \cos \theta)}, \\ C_x &= (A_{ex}^x E_b n_{bx} + A_{ey}^x E_b n_{by} + A_{ez}^x E_b n_{bz} + A_{hx}^x H_t t_{bx} \\ &\quad + A_{hy}^x H_t t_{by} + A_{hz}^x H_t t_{bz}) \\ &\quad \cdot e^{jk_0(x \sin \theta \cos \phi + y \sin \theta \sin \phi + z \cos \theta)},\end{aligned}\quad (8)$$

we get $f_x = B_x T_H + C_x T_V$.

Inserting all the corresponding terms into formula (1):

$$F_x = \iint_{S_r} (B'_x T_H + C'_x T_V) dS_r, \quad (9)$$

where $B'_x = B_x e^{jk_0(x \sin \theta \cos \phi + y \sin \theta \sin \phi + z \cos \theta)}$, $C'_x = C_x e^{jk_0(x \sin \theta \cos \phi + y \sin \theta \sin \phi + z \cos \theta)}$. So the explicit expression

about transmission coefficients T_H , T_V and far fields data F_x is obtained. The expressions about F_y and F_z can be derived in an even similar way (omitted here).

Assume that n and m are the corresponding discrete points of antenna's near fields and far fields. Formula (9) could be written as

$$\sum_{i=1}^n (B'_{xij} \Delta S_{ri} T_{Hi} + C'_{xij} \Delta S_{ri} T_{Vi}) = F_x(\theta_j, \phi_j), \quad (10)$$

$$j = 1, 2, \dots, m.$$

Let coefficients b_{ij} , c_{ij} be $b_{ij} = B'_{xij} \Delta S_{ri}$, $c_{ij} = C'_{xij} \Delta S_{ri}$, and the matrix form of formula (10) can be expressed as

$$\begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} & c_{11} & c_{12} & \cdots & c_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} & c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ b_{m1} & b_{m2} & \cdots & b_{mn} & c_{m1} & c_{m2} & \cdots & c_{mn} \end{bmatrix} \cdot \begin{bmatrix} T_{H1} \\ T_{H2} \\ \vdots \\ T_{Hn} \\ T_{V1} \\ T_{V2} \\ \vdots \\ T_{Vn} \end{bmatrix} = \begin{bmatrix} F_x(\theta_1, \phi_1) \\ F_x(\theta_2, \phi_2) \\ \vdots \\ F_x(\theta_m, \phi_m) \end{bmatrix}. \quad (11)$$

With the derivation, the transmission coefficients T_H , T_V can be separated from other variables. Multiplying formula (11) by inverse matrix of the coefficients b_{ij} , c_{ij} , the inversion from the far field data to the transmission coefficients could be obtained as follows:

$$\begin{bmatrix} T_{H1} \\ T_{H2} \\ \vdots \\ T_{Hn} \\ T_{V1} \\ T_{V2} \\ \vdots \\ T_{Vn} \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} & c_{11} & c_{12} & \cdots & c_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} & c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ b_{m1} & b_{m2} & \cdots & b_{mn} & c_{m1} & c_{m2} & \cdots & c_{mn} \end{bmatrix}^{-1} \cdot \begin{bmatrix} F_x(\theta_1, \phi_1) \\ F_x(\theta_2, \phi_2) \\ \vdots \\ F_x(\theta_m, \phi_m) \end{bmatrix}. \quad (12)$$

The corresponding derivation for F_y and F_z could also be obtained following the same ways. In practice, the antenna's polarization decides the choice of F_x , F_y , or F_z . Note that only when $m \geq 2n$, the coefficients matrix may be of full rank. In the numerical simulation of this work, two MATLAB functions *PINV* and ** were used to get T_H , T_V of formula (12).

2.3. The Thickness Detection of the Radome. Radome's thickness corresponding to every near field point could indicate manufacturing flaws, such as the nonuniformity of radome's thickness, the air bubble in the radome, or bonding films layer. So the inversion from transmission coefficients to radome's thickness is necessary.

The transmission coefficients T_H and T_V can be expressed as [29, 30]

$$T = \frac{2}{(A + B/Z_\infty + CZ_\infty + D)} = |T| \exp(-j\bar{\omega}_T), \quad (13)$$

where $Z_\infty = \cos \theta$ corresponds to the horizontal polarization and $Z_\infty = 1/\cos \theta$ corresponds to the vertical polarization.

The matrix $\begin{bmatrix} A & B \\ C & D \end{bmatrix}$ is defined as transition matrix:

$$\begin{aligned} A &= \cosh(jVd_b), & B &= Z_1 \sinh(jVd_b), \\ C &= \frac{\sinh(jVd_b)}{Z_1}, & D &= \cosh(jVd_b), \end{aligned} \quad (14)$$

where

$$\begin{aligned} V &= \frac{2\pi(\epsilon_b - \sin^2 \alpha)^{1/2}}{\lambda}, \\ Z_1 &= \begin{cases} \left(\epsilon_b - \sin^2 \frac{\alpha}{\epsilon_b} \right)^{1/2}, & \text{vertical polarization} \\ \frac{1}{(\epsilon_b - \sin^2 \alpha)^{1/2}}, & \text{horizontal polarization,} \end{cases} \end{aligned} \quad (15)$$

$\epsilon_b = \epsilon'_b(1 - j \tan \delta_b)$, α is the incident angle, λ is the wavelength, and ϵ'_b , $\tan \delta_b$, and d_b are the relative permittivity, loss tangent, and thickness of the radome, respectively.

T_V is used for an example to show the derivation of inversion from transmission coefficients to the radome's thickness. Inserting formula (14) into (13), we get

$$\begin{aligned} &\cosh(jVd_b) + Z_1 \sinh(jVd_b) \cos \theta + \frac{\sinh(jVd_b)}{Z_1 \cos \theta} \\ &+ \cosh(jVd_b) = \frac{2}{T_V}. \end{aligned} \quad (16)$$

The relations between trigonometric and hyperbolic functions are known as $\cosh(jVd_b) = \cos(Vd_b)$, $\sinh(jVd_b) = -j \sin(Vd_b)$. Therefore, formula (16) can be rewritten as

$$2 \cos(Vd_b) + j \sin(Vd_b) \left(Z_1 \cos \theta + \frac{1}{Z_1 \cos \theta} \right) = \frac{2}{T_V}. \quad (17)$$

For most materials used in the radome, $\tan \delta_b \rightarrow 0$ and is much less than ϵ'_b , and so $\epsilon_b = \epsilon'_b(1 - j \tan \delta_b) \approx \epsilon'_b$ and ϵ_b became a real number. In this case, V, Z_1 will also become real numbers. Since $2/T_V$ is a complex number, according to the principle of complex number's equation, the following formula can be obtained:

$$d_b = \frac{1}{V} \arcsin \left[\frac{\text{imag}(2/T_V)}{(Z_1 \cos \theta + 1/Z_1 \cos \theta)} \right], \quad (18)$$

where $\text{imag}(2/T_V)$ is the imaginary part of $2/T_V$.

The radome in Figure 1 usually equated to a single layer, because the paper honeycombs, $\epsilon'_b \approx 1$ and $\tan \delta_b \approx 0$, are very close to the air. The bonding films are very thin and ignored. Only the skin is regarded as a dielectric layer. But in fact, the bonding films should not be ignored, especially in high frequency, since its ϵ'_b and $\tan \delta_b$ far outweigh that air's, and the thickness is in the same order of magnitude of skins (more than 0.1 mm). So the inversion of single unknown in a multilayer radome is necessary.

The transition matrix of the multilayer radome could be expressed as the multiplication of single layer's transition matrix [29, 30]:

$$\begin{aligned} \begin{bmatrix} A_N & B_N \\ C_N & D_N \end{bmatrix} &= \prod_{i=1}^n \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} \\ &= \begin{bmatrix} A_{i-} & B_{i-} \\ C_{i-} & D_{i-} \end{bmatrix} \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} \begin{bmatrix} A_{i+} & B_{i+} \\ C_{i+} & D_{i+} \end{bmatrix}, \end{aligned} \quad (19)$$

where the radome contained n layers. If only one layer is unknown, the n -layer radome can be equated with a 3-layer radome. If the i th layer is unknown, from the direction of wave propagation, the 1st to $(i-1)$ th layers could be equated with one layer denoted by the transition matrix $\begin{bmatrix} A_{i-} & B_{i-} \\ C_{i-} & D_{i-} \end{bmatrix}$, and the $(i+1)$ th to n th layers could also be equated with one layer denoted by the transition matrix $\begin{bmatrix} A_{i+} & B_{i+} \\ C_{i+} & D_{i+} \end{bmatrix}$. The i th layer can be denoted by transition matrix $\begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix}$. The parameters of every layer are known except the i th layer; and the transition matrices $\begin{bmatrix} A_{i-} & B_{i-} \\ C_{i-} & D_{i-} \end{bmatrix}$ and $\begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix}$ could be calculated. Then, the inversion formula of the thickness of the i th layer could be derived as follows:

$$\begin{aligned} \begin{bmatrix} A_N & B_N \\ C_N & D_N \end{bmatrix} &= \begin{bmatrix} A_{i-}A_iA_{i+} + B_{i-}C_iA_{i+} + A_{i-}B_iC_{i+} + B_{i-}D_iC_{i+} & A_{i-}A_iB_{i+} + B_{i-}C_iB_{i+} + A_{i-}B_iD_{i+} + B_{i-}D_iD_{i+} \\ C_{i-}A_iA_{i+} + D_{i-}C_iA_{i+} + C_{i-}B_iC_{i+} + D_{i-}D_iC_{i+} & C_{i-}A_iB_{i+} + D_{i-}C_iB_{i+} + C_{i-}B_iD_{i+} + D_{i-}D_iD_{i+} \end{bmatrix}. \end{aligned} \quad (20)$$

Inserting formula (20) into (13) and using T_{iV} as an example, we get

$$\begin{aligned} (A_f^r + jA_f^i)A_i + (B_f^r + jB_f^i)B_i + (C_f^r + jC_f^i)C_i \\ + (D_f^r + jD_f^i)A_i = \frac{2}{T_{iV}}, \end{aligned} \quad (21)$$

where

$$\begin{aligned} A_f^r + jA_f^i &= A_{i-}A_{i+} + \cos \theta A_{i-}B_{i+} + \cos^{-1} \theta C_{i-}A_{i+} \\ &\quad + C_{i-}B_{i+}, \\ B_f^r + jB_f^i &= A_{i-}C_{i+} + \cos \theta A_{i-}D_{i+} + \cos^{-1} \theta C_{i-}C_{i+} \\ &\quad + C_{i-}D_{i+}, \\ C_f^r + jC_f^i &= B_{i-}A_{i+} + \cos \theta B_{i-}B_{i+} + \cos^{-1} \theta D_{i-}A_{i+} \\ &\quad + D_{i-}B_{i+}, \\ D_f^r + jD_f^i &= B_{i-}C_{i+} + \cos \theta B_{i-}D_{i+} + \cos^{-1} \theta D_{i-}C_{i+} \\ &\quad + D_{i-}D_{i+}. \end{aligned} \quad (22)$$

The superscripts r and i of $A_f^r, A_f^i, B_f^r, jB_f^i, C_f^r, C_f^i, D_f^r, jD_f^i$ indicate the real and imaginary parts of a complex number. Inserting the i th layer's transition matrix $\begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix}$ into (21),

$$\begin{aligned} (A_f^r + D_f^r) \cos(Vd_b) + \left(B_f^i Z + \frac{C_f^i}{Z} \right) \sin(Vd_b) \\ + j \left[(A_f^i + D_f^i) \cos(Vd_b) - \left(B_f^r Z + \frac{C_f^r}{Z} \right) \sin(Vd_b) \right] \\ = \frac{2}{T_V}. \end{aligned} \quad (23)$$

Then, according to the principle of the complex number's equation, the inversion formula of the thickness of i th layer can be expressed as follows:

$$\begin{aligned} d_{ib} &= \frac{1}{V_i} \left[\arcsin \frac{\text{imag}(2/T_V)}{\sqrt{(A_f^i + D_f^i)^2 + (B_f^r Z + C_f^r/Z_i)^2}} \right. \\ &\quad \left. - \arctan \frac{A_f^i + D_f^i}{B_f^r Z_i + C_f^r/Z_i} \right]. \end{aligned} \quad (24)$$

FIGURE 3: Microstrip antenna array used in the simulation (mm).

TABLE 1: The thicknesses and material parameters of the CLAS.

	Thickness (mm)	Relative permittivity	Loss tangent
Glass fiber skin top	0.5	4.0	0.030
Honeycomb	2.5	1.1	0.0
Bonding films	0.2	3.0	0.025
PCB laminate	0.5	2.2	0.0009
Glass fiber skin bottom	0.5	4.0	0.030

For single-layer radome, the thicknesses of $i - th$ and $i + th$ are 0, their transition matrix $\begin{bmatrix} A_{i-} & B_{i-} \\ C_{i-} & D_{i-} \end{bmatrix} = \begin{bmatrix} A_{i+} & B_{i+} \\ C_{i+} & D_{i+} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ inserts them into formula (21), and then formula (17) could be obtained. So the single layer is a special case of multilayer radome, which also indicated the validity of the derivation.

Then, the inversion model from far field data to flaws of the CLAS could be obtained by combining formulae (12) and (18) or (24). The thicknesses of discrete points of the radome could be inversed by the inversion model.

3. The Example of Conventional Process

3.1. The Design of an Experimental CLAS. For the purpose of experiment, a 12.5 GHz CLAS was designed and manufactured. In Figure 1, the structure of the CLAS is illustrated in the left part, all components before hot pressing are in the right part, and the completed CLAS is in the red box of right part. The photo and specific parameters of the microstrip antenna array used in the CLAS are illustrated in Figure 3. The design of microstrip antenna is mostly based on Hwang's work [31], and some ungiven parameters in the references were designed by the authors via HFSS software. The length and width of the substrate are 120 mm and 90 mm. Same four microstrip antennas composed the array. The seven holds in the edge are mounting holes for measurement. The thicknesses and material parameters of the CLAS are in Table 1.

3.2. The Measured Results and Comparison. The electric performances of the microstrip antenna array and CLAS were calculated by HFSS software. The 3D electric field patterns

FIGURE 4: The 3D patterns of CLAS.

are presented in Figure 4. It is obvious that the antenna array has better directivity in ZOY-plan (H -plan) than ZOX-plan (E -plan). So in the following more attention is paid to the pattern in H -plan. The exact figures are listed in Table 2. We can see that after packaging the side lobe level rose and half-power beam width extended. In this work, far field data is used for inversion, and thus more attention is paid to the far field pattern.

The electric performances of the microstrip antenna array and CLAS were measured in microwave anechoic chamber. The near field measurement method was used in this experiment as presented in Figure 5. The far field data could be obtained based on far field data; the imaging of an electric field in the near field and far field has been discussed in [32].

The simulated and measured results of beam width and side lobe level are in Table 2. The results of simulation are in good agreement with measured results for microstrip antenna array. The difference between simulated and measured results of the CLAS is a litter bigger than the difference of microstrip antenna array. The measured left SLL is 0.5 dB higher than the right one. But the simulated SLL is almost the same and maybe more reasonable, because the CLAS has a symmetrical structure and should have a symmetrical pattern. The difference of 0.5 dB is acceptable error in

TABLE 2: The simulation and measurement results of some electrical parameters.

	Beam width (°)		Left SLL (dB)		Right SLL (dB)	
	Simulation	Measurement	Simulation	Measurement	Simulation	Measurement
Microstrip antenna array	14.0	14.6	-12.9	-12.7	-13.0	-12.8
CLAS	14.4	14.6	-10.35	-9.9	-10.38	-10.4

FIGURE 5: The photo of measurement.

FIGURE 6: The measured and simulated patterns of CLAS.

engineering. Manufacturing errors may be the main reason. The patterns comparison of CLAS between measurement and simulation results is illuminated in Figure 6. The two curves are very close on the whole.

3.3. Influence of the Flaw. It is profoundly difficult to get a CLAS with artificial and exact flaws; however, it is easy in the simulation. Since the simulation results are in good agreement with the measured results as present in Section 3.2, in the stage of theoretical research, the far field data of CLAS with known flaws obtained by simulation is a reasonable

TABLE 3: Influence of flaw's location on the far field pattern.

Location	Beam squint (°)	Raise of left SLL (dB)	Raise of right SLL (dB)
Node 1	-0.1	-0.09	-0.08
Node 2	0	-0.06	0.09
Node 3	0	0.14	0.13
Node 4	-0.2	0.49	0.41
Node 5	0	0	-0.03
Node 6	0	0.06	0.06

FIGURE 7: Distribution of the electric field on the microstrip antenna array by HFSS.

alternative. The simulation data also has the advantage of no manufacturing errors.

The influence of flaws on CLAS's far field pattern will be researched in this section by simulation. A rectangular air bubble in the bonding films is assumed to be the flaw. The location and dimension of the flaw are the key points.

Different location of the air bubble in bonding films will lead to different influences on the antenna's far field pattern. The near field (electric amplitude) on the antenna array (also the inner surface of the bonding films) calculated by HFSS is illustrated in Figure 7.

Assume that the air bubble is rectangular with the dimension of 6 mm × 3 mm, which is large enough to influence the far field pattern. According to the electric field intensity distribution, the air bubble flaw is set to 6 different locations as illustrated in Figure 7. The far field pattern is distorted due to the existence of the air bubbles. Some key parameters, which could indicate the distortion of the far field pattern such as the squint of the beam and the raise of the SLL (side lobe level), can be seen in Table 3.

As can be seen from Table 3, the flaw at node 4, where the largest electric field intensity is distributed, leads to the most distorted far field pattern. In other words, the larger the electric field intensity at the flaw's location is, the more

TABLE 4: Influence of flaw's dimension on the far field pattern (At node 4).

Dimension of flaws (mm)	Beam squint (°)	Raise of left SLL (dB)	Raise of right SLL (dB)
6×3	-0.2	0.49	0.41
1.5×1.5	-0.1	0.21	0.16
3×3	-0.2	0.28	0.3
6×6	-0.3	0.53	0.52
12×12	-0.5	0.57	0.54

influence the flaw will have on the antenna's far field pattern. Note that the subject investigated here was the antennas, and the microstrip lines are ignored, and even the nearby electric field intensity is large enough. Finally, node 4 was the location which led to the maximum influence and was chosen to set the flaw in the following.

The influence of different air bubble's dimensions on the far field pattern of antennas is also worthy of studying. Five different dimensions are selected (including the $6 \text{ mm} \times 3 \text{ mm}$) as illustrated in Table 4. The locations of the flaws are all set to node 4. The squint of the beam and the rise of the SLL can be seen in Table 6.

As can be seen from Table 4, it is clear that large flaw leads to more distorted far field pattern. Since the wavelength of the antenna was 24 mm , it is found that when the flaw's dimension is larger than $\lambda/8$, the influence cannot be ignored; and when the flaw's dimension is larger than $\lambda/4$, the influence became significant.

4. Inversion of the Flaw

In order to validate the effectiveness of the inversion method in Section 2, some numerical examples are presented in this section.

For the inversion, three known conditions are necessary: near field data of the CLAS's inner surface, far field data of the CLAS, and radome's transmission coefficient of the CLAS with no flaws. In practical engineering, the design of the CLAS is known. Thus, the near field data could be obtained by a full-wave method (in this work, the HFSS software was used), and the transmission coefficient could be obtained by ray tracing approach proposed in Section 2.1. The far field data should be obtained by measurement. But, in this section, simulated far field data is used instead of measured data. The reason has been explained in Section 3.3.

There are two ways to get simulated far field data of CLAS. One is by HFSS and the other is by formula (9). There must be some difference between the far field data by two different ways. Far field data by formula (9) is used as an ideal condition and could test the precision of the inversion method. Far field data by HFSS is used as an error condition, and the difference between far field data by formula (9) and HFSS could be treated as the measurement error of the measured far field data of the CLAS with specific flaws. So two numerical examples are presented here.

TABLE 5: Errors of the inversed results.

	Mean of errors (mm)
Flaw bonding films area 90 points	$0.29e - 16$
Ideal bonding films area 2899 points	$5.3e - 4$

FIGURE 8: Inversed results of the thicknesses of the bonding films and flaws.

4.1. Inversion of Multilayer Radome in Ideal Conditions. The CLAS in this example is the same one used in Section 3.1. According to the conclusions in Section 3.3, some specific flaws are added. Four rectangular air bubbles in the bonding films with the same dimension of $8.0 \text{ mm} \times 8.0 \text{ mm}$ are all set to the lower corners of the left two microstrip antennas as illustrated in Figure 3 (black boxes).

The near field data of CLAS's inner surface is calculated by HFSS. The location and dimension of the flaws are known. From formula (9), the far field data is also calculated. Then, the transmission coefficient can be calculated by formula (12) and the thickness of the bonding films layer can be obtained by formula (24). Finally, comparing the inversed thickness with the known dimensions of flaws and bonding films (0 mm of flaw and 0.2 mm of bonding films), the results of the comparison could indicate the validity of the inversion method.

The near field of antenna array was divided into 2989 points with a discrete distance of 2 mm . The sampling precision of near field is enough relative to the wavelength of 24 mm (12.5 GHz). There are 90 points in the flaw area (the thickness is 0 mm) and 2899 points in ideal bonding films area (the thickness is 0.2 mm). In this simulation, no error source was included except the numerical error, and so it is the ideal condition. The inversion is done by a MATLAB program, which was written by the authors.

The inversed results are illustrated in Figure 8. It is a 3D view, the X-axis and Y-axis indicate the location, and the Z-axis indicates the thickness. It is a good agreement with the known condition of Figure 3. The distribution and mean of the inversed error are presented in Figure 9 and Table 5 separately. It is obvious that errors of the border nodes are more than those of the central nodes, and the precision of the inversion method is really high in the ideal condition.

TABLE 6: Comparison of far field parameters between HFSS and this formula.

	Left SLL of HFSS (dB)	Right SLL of HFSS (dB)	Beam squint of HFSS (°)	Left SLL of formula (9) (dB)	Right SLL of formula (9) (dB)	Beam squint of formula (9) (°)
Ideal bonding films	-11.19	-11.17	0	-10.98	-11.02	0
Flaw bonding films	-10.76	-12.49	0.80	-9.44	-12.23	0.90

TABLE 7: Inversed results from far field pattern by HFSS.

	Ideal thickness (mm)	Inversed thickness (mm)	Error	Remarks
Flaw bonding films area	0	$0.4e - 4$	$0.4e - 4$ mm	Relative errors
Ideal bonding films area	0.2	0.173	13.5%	Absolute error

FIGURE 9: The distribution of the inversed error.

4.2. Inversion of Single Radome in Error Conditions. Since formula (24) of multilayer radome has been verified in Section 4.1, formula (18) of single layer will be tested here. So the radome of the CLAS in Section 3.1 is removed, but the bonding films is retained. The flaws are set to the bonding films in the same locations with the same dimension as in Section 4.1.

To be as close to the practice as possible, the far field data calculated by formula (9) used in Section 4.1 is replaced by the far field data calculated by HFSS. Then, the thickness of bonding films is inversed by formula (18). The comparison of far field patterns by HFSS and formula (9) is illustrated in Figure 10. Two conditions are compared: the first is microstrip antenna array with ideal bonding films and the second is antenna array with flaws bonding films. Some key parameters, which could indicate the distortion of the far field pattern, can be seen in Table 6.

It could be seen from Figure 10 that there are some differences between the far field pattern by HFSS and formula (9). There are also some differences between a measured far field data and the ideal far field data. So the far field by HFSS

could be used to simulate a measured far field data, which will be used in practice.

In Figure 6, the curves of far field patterns are very close, especially in the angle region of $[-35^\circ, 35^\circ]$. So only the far field data in the region of $[-35^\circ, 35^\circ]$ are selected for the inversion. Because of the error of far field data, the numerical characteristic of the inverse matrix in formula (12) degraded, and there is no full rank. Then, the inversion of formula (12) failed.

The solution is to reduce the inversed discrete points in near field. All discrete points in near field should be divided into two groups: the first group consists of the significant near field points (the points in the area of large electric field intensity) and the second group consists of the relatively insignificant points (the points in the area of low electric field intensity). Only the first group will be inversed. According to the research conclusion in Section 3.3, insignificant points mean that, even though there are flaws in these point, there will be less influence on the far field pattern.

The left-hand side of formula (12) is replaced by the transmission coefficients of the points in the first group, and the inverse matrix of the coefficients on the right-hand side of formula (12) is replaced by the ones of the points in the same group. The far field pattern on the right-hand side of formula (12) should be computed as follows:

$$F_x^p(\theta_m, \phi_m) = F_x(\theta_m, \phi_m) - F_x^u(\theta_m, \phi_m), \quad (25)$$

where F_x^u is the far field data of the second group, which could be calculated by formula (9). The superscript p indicates the first group, and F_x^p could not be obtained by formula (12), because transmission coefficients of this group are unknown. In practice, F_x was measured, but F_x^p could not be measured. Formula (25) is an indirect way to get F_x^p .

In this case, only a small area in the two dashed rectangles (as illustrated in Figure 7) is selected to inverse. According to the analysis of Section 3.3, the discrete distance between two inversed points could increase to 4 mm. At least, there are only 16 inversed points in left dashed rectangle (flaw area) and 16 points in right dashed rectangle (ideal bonding films area). And these points could be inversed by formula (12). The results and relative errors can be seen in Table 7. For

TABLE 8: Influence of far field data's error on the transmission coefficient.

Relative errors of far field amplitude (%)	Relative errors of far field amplitude (dB)	Relative errors of transmission coefficient (%)	Absolute errors of far field phase (°)	Relative errors of transmission coefficient (%)
1	0.09	0.8	± 3	6.7
5	0.45	4.5	± 5	8.5
10	0.92	11.6	± 10	12.3
15	1.41	18.2	± 15	15.8

FIGURE 10: Comparison of far field pattern between HFSS and this formula (component F_x).

the points in flaw bonding films area, it is the absolute error in the table.

From Table 7, the conclusion is that, for the error condition, the inversion model in this paper is still valid with acceptable precision, so it has good potential applications in practice.

In this simulation, the near field is calculated by antenna with ideal bonding films, and the far field data is calculated by antenna with flaw bonding films. The near fields of the three conditions in this section (antenna with no bonding films, ideal bonding films, and flaw bonding films) are few differences, and the reason is that there is a coupling effect between the microstrip antennas and radomes, and the effect depends on the distance between them.

It may be the main reason of the error in this simulation. In other words, the near field data is not the real one which is unknown before inversion. For this case, an iterated operation may become the solution.

5. Error Analysis

The measurement error is inevitable, and so the error analysis of the inversion is important. The inversed error comes from

two parts: one was from the far field data to the transmission coefficient (formula (12)); the other was from the transmission coefficient to the thickness (formula (18) or (24)).

The conclusion of quantitative error analysis could be obtained by the numerical simulation.

5.1. Error Analysis of Formula (12). According to formula (12), the influence of far field's amplitude and phase error on the transmission coefficient is researched.

The error of far field data is obtained by adding a random error to the field's amplitude or phase of the ideal far field data, which is calculated by formula (9). Then, the transmission coefficient is inversed by formula (18) and compared with the ideal transmission coefficient, which is inversed by the ideal far field data. The random error is produced by *RANDN* function of MATLAB software; the mean is 0 and the variance is as in Table 8. The results in Table 8 are the mean values of at least 10 times random analysis. In Table 8, the random error added to the amplitude and phase of far field data is presented. But in practice, the error existed in both amplitude and phase of the far field. Then, the influence of a random error on both amplitude and phase is proposed in Table 9.

TABLE 9: Influence of far field data's error on the transmission coefficient.

Relative errors of far field amplitude (%)	Relative errors of far field amplitude (dB)	Absolute errors of far field phase (°)	Relative errors of transmission coefficient (%)
5	0.45	± 3	8.6
10	0.92	± 5	11.2

TABLE 10: Influence of transmission coefficient's error on the radome's thickness.

Relative errors of transmission coefficient (%)	Relative errors of thickness (%)
1	0.7
5	4.3
10	8.6

From Tables 8 and 9, the conclusion is that when the amplitude error of far field data is less than 0.45 dB and phase error is less than $\pm 5^\circ$, the error of inversed transmission coefficient would be less than 10%. For the existing measurement system of far field data, it is a reasonable required precision.

5.2. Error Analysis of Formula (18). According to formulas (18), the influence of transmission coefficient's error on the radome's thickness is researched.

The transmission coefficient with error could be obtained by multiplying the ideal transmission coefficient by a random factor, which is also produced by *RANDN* function of MATLAB software. The random factors and the error of thickness, which is inversed by the transmission coefficient with error, can be seen in Table 10. The conclusion is that when the error of transmission coefficient is less than 10%, the error of inversed thickness would be less than 10%. The results in Table 10 are still the mean values of at least 10 times random analysis.

Combine the conclusions of Sections 5.1 and 5.2. The final conclusion is that when the amplitude error of far field data is less than 0.45 dB and phase error is less than $\pm 5^\circ$, the error of inversed radome's thickness would be less than 10%.

5.3. Influence of Loss Tangent. In the derivation of formulae (18) and (24), there is an assumption that $\epsilon_b \approx \epsilon'_b$ and became a real number. But in practice, the loss tangent of radome materials $\tan \delta_b \neq 0$. So this assumption would lead to a slight error in formulae (18) and (24). The conclusion of qualitative analysis is obvious; less $\tan \delta_b$ led to less error. The results of quantitative analysis are obtained by the numerical simulation similar to Sections 5.1 and 5.2. Different $\tan \delta_b$ is selected, no error for other parameters, and then the thickness with error is inversed by formula (18), when compared with the ideal thickness. The error of the inversed results can be seen in Table 11.

The conclusion is that when the radome material's $\tan \delta_b < 0.1$, the error of formula (18) is less than 1%. For most

TABLE 11: Influence of $\tan \delta_b$ on the radome's thickness.

$\tan \delta_b$	Relative errors of thickness
0.01	$2.78e - 4$
0.025	$5.77e - 4$
0.075	0.0047
0.15	0.019
0.25	0.054

conventional materials used in radome, $\tan \delta_b < 0.1$ could be satisfied.

In the simulation in Section 4.2, $\tan \delta_b = 0.025$ would lead a relative error of about $5.77e - 4$. Compared with other errors in Table 6, it could be ignored.

6. Conclusion

A novel inversion method is proposed in this work, which could be used to detect the manufacturing flaws in the packaging of CLAS and has potential applications for other types of radomes. The accuracy and validity of the inversion method for both single layer and multilayer radome have been verified by numerical simulations. Finally, the calculation error of the inversion method is discussed, and the application condition in practice is indicated.

In the future, more attention will be paid to the following works.

- (1) The solution of formula (12) depended on the numerical characteristics of the inverse matrix and limited the application of the inversion in practical problems. Some regularization methods (such as singular value decomposition) will be used in the matrix in formula (12).
- (2) More experiments will be done for the CLAS with some flaws, and the inversion method should be verified by a measured far field data instead of a simulated one.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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