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RESEARCH ON ELECTROMECHANICAL FIELD COUPLING MODEL AND SOLUTION STRATEGY OF LARGE REFLECTOR ANTENNAS

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Abstract. *The overriding design goal of reflector antennas is accomplishing an acceptable electromagnetic performance. However, the success of this goal lies — for a substantial part — in the construction of mechanical structure, which ensures and restricts the achievement of its electrical properties simultaneously. The reflector antenna is a system that combines electromagnetic fields with structural deformation fields, in which electromechanical coupling problems exist. The high precision expected makes the coupling phenomenon more serious as reflector antennas develop towards a situation of large diameter and high band. Therefore it is necessary to do some research about the electromechanical coupling problems, establish precise field coupling model and get the solution strategies. This paper presents a electromechanical field coupling model based on the method of surface current. The model includes the systematic error, with considering all-around displacement of each node, based on which the interior surface deformation of elements could be got by the interpolation with shape function. The vertex normals of distorted curve are then applied to the surface current density to investigate its impact on the far-field electrical performance. The investigation of the coupling model and solution strategy led to an improvement of design level and to a better performance of reflector antennas.*

1. INTRODUCTION

Reflector antennas, as the microwave and millimeter wave high-gain antenna, are widely used in the field of communication, radar, navigation, radio astronomy and meteorology, etc. [1]. The reflector antenna is a system that combines electromagnetic fields with structural deformation fields, in which electromechanical coupling problems exist. With the amplitude and scope of deformation becoming closer to the wavelength, the coupling phenomenon gets more significant when the antenna towards the direction of larger diameter and higher band. So it is necessary to study the electromechanical coupling problems, establish accurate electromechanical coupling model, find the solving strategies and methods close to the actual case, accurately predict the effect made by the deformation to electrical properties, in order to provide a reference for its compensation.

The errors of reflector surface include random error and systematic error. The systematic error is the deformation of antennas under the influence of weight, environmental temperature, wind and other external environmental loads. It would be a deterministic error if not considering the random wind load and could be gained by finite element analysis. Random error is brought in the process of manufacturing and assembly of panel, back-up structure and central body. Some researchers home and abroad have studied the effect of errors to the electrical performance of reflector antennas. For example, the literature [2-7] studied the effect of random error to the average power pattern of reflector antennas and drew some meaningful conclusions. As to systematic errors, the literature [8-9] analyzed the deformed surface with the best-fitted parabolic method (BFP). However, but this approach does not fully reflect the local deformation, not to mention its special effect to electrical performance of the antenna, based on which, the Coons-surface blocked fitting method proposed by the literature [10-11] reflects the deformation of the reflecting surface comprehensively. Literature [12] investigated the effect of partial deformation to the reflector antenna's electrical performance, but it is not general without from the view of field coupling. Literature [13] studied the impact of deformation to the electrical performance of antennas under different Taylor series, with approximating the surface errors using the superposition by a series of surface-expanded function, unfortunately, the method is effective only in the accuracy range of 0.1λ. The above literature, or being fitted based on the structural deformation data, or analyzing the surface deformation using the experience approximately, all caused errors more or less to the electrical performance forecast. Literature [14] studied the effect of random error and systematic error to the reflector antenna electrical performance from the view of electromechanical coupling, but limited on the impact of antenna efficiency.

The electromechanical field coupling model is presented in this paper based on the method of surface current. The deformation of antennas under the environmental loads could be got with element analysis software. Then we can obtain the interior surface deformation of elements by the interpolation with shape function to meet the grid accuracy when calculating the electrical performance. Finally, the structural displacement field of the whole reflector surface could be got. Therefore it is helpful for the electromagnetic design and structural design of antennas to analyze the effect of structural errors to electrical performance quantitatively based on the electromechanical coupling model established before. So we can accomplish general excellence of mechanical and electromagnetic performance of microwave antenna. In addition, the model could also provide certain reference for other electronic equipments.

2. ESTABLISHMENT OF ELECTROMECHANICAL TWO COUPLING MODEL

The surface current method and aperture field method are often used to analyze the radiation patterns of reflector antennas. Some scholars [6] have established the electromechanical two coupled model based on the latter method. In this study, the two coupling model established based on the surface current method is addressed, and the corresponding solution strategy. As is shown in Fig. 1, the radiation integral formulation for the ideal reflector antenna is given by

$$\vec{E} = \iint_S \vec{J}_s^e \bullet \mathrm{e}^{\mathrm{j}k\vec{r}'\bullet\hat{r}_0} dS \qquad (1)$$

Where $\vec{J}_s^e = 2\hat{n}\times\vec{H}_s$ is the current density of the reflector surface. The vector $\vec{r}'$ locates the integration points, the unit vector $\hat{r}_0$ is in the observation direction.

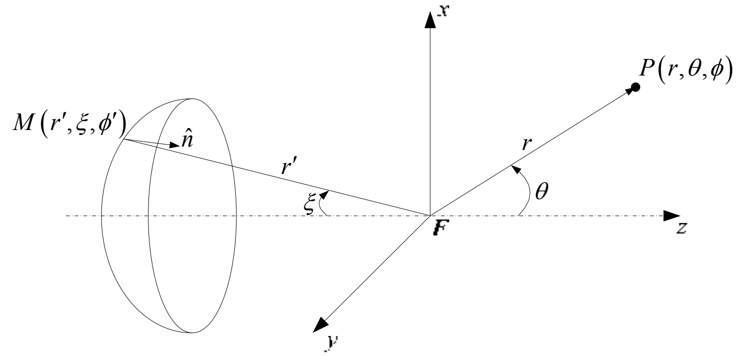


Figure 1: geometric relation of paraboloid

However, because of the working environment of antennas, the design structure of antennas will be influenced by the external loads, thus affecting the electrical properties, which is the coupling of structural displacement field and electromagnetic field. Therefore, the additional items caused by structural displacement should be considered in the formula (1). The reflector surface will be deformed under the influence of external environmental loads (see Fig. 2), which deviate from the original ideal design surface. The vector that locates the integration point on the distorted surface is $\vec{r}'_d = \vec{r}' + \vec{d}$. Where, $\vec{d}$ is the difference of the corresponding points between the distorted surface and the desired undistorted reflector, which could be got by the stiffness equation $\boldsymbol{Kd} = \boldsymbol{F}$.

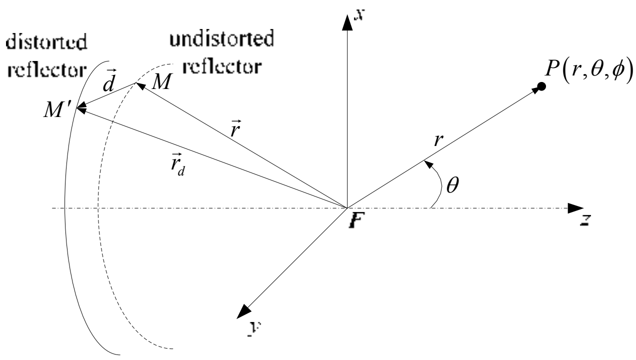


Figure 2: defining the vector that locate the points on the distorted reflector and the undistorted reflector

Since $\left|\vec{r}_d'\right| \gg \left|\vec{d}\right|$, r_d can be approximated as

$$r_d = \left|\vec{r}_d'\right| = \left|\vec{r}' + \vec{d}\right| \approx \left|\vec{r}'\right| + \frac{\vec{d} \bullet \vec{r}'}{\left|\vec{r}'\right|} \qquad (2)$$

Using the amplitude approximation, the current-term $\vec{J}_{sd}^e$ could be approximated by

$$\vec{J}_{sd}^e = 2\hat{n}_d \times \vec{H}_s\left(\vec{r}'\right) \approx 2\hat{n}_d \times \vec{H}_s \bullet \mathrm{e}^{-\mathrm{jk}\frac{\vec{d}\bullet\vec{r}'}{\left|\vec{r}'\right|}} = \vec{J}_{snd}^e \bullet \mathrm{e}^{-\mathrm{jk}\frac{\vec{d}\bullet\vec{r}'}{\left|\vec{r}'\right|}} \qquad (3)$$

Using (2), (3) in (1) gives

$$\vec{E} \approx \iint_S \vec{J}_{snd}^e \bullet \mathrm{e}^{-\mathrm{jk}\frac{\vec{d}\bullet\vec{r}'}{\left|\vec{r}'\right|}} \bullet \mathrm{e}^{\mathrm{jk}\vec{r}_d'\bullet\hat{r}_0} dS \qquad (4)$$

Also, because

$$\mathrm{e}^{\mathrm{jk}\vec{r}_d'\bullet\hat{r}_0} = \mathrm{e}^{\mathrm{jk}\left(\vec{r}'+\vec{d}\right)\bullet\hat{r}_0} = \mathrm{e}^{\mathrm{jk}\left(\vec{r}'\bullet\hat{r}_0+\vec{d}\bullet\hat{r}_0\right)} \qquad (5)$$

Using this in (5) and substituting into (4) gives

$$\vec{E} \approx \iint_S \vec{J}_{snd}^e \bullet \mathrm{e}^{\mathrm{jk}\vec{r}'\bullet\hat{r}_0} \bullet \mathrm{e}^{\mathrm{jk}\left(\vec{d}\bullet\hat{r}_0-\frac{\vec{d}\bullet\vec{r}'}{\left|\vec{r}'\right|}\right)} dS \qquad (6)$$

which is the electromechanical two coupled model for the distorted reflector antenna, where $\vec{J}_{snd}^e$ takes into account the impact of changes in surface normal vector and the irradiation magnetic field distribution from the feed caused by the deformation.

3. SOLVING STRATEGIES AND METHODS OF ELECTROMECHANICAL COUPLING MODEL

The establishment of electromechanical coupling model is just a basis, how to solve it accurately is still a key issue. Because the structural displacement data in the model is from the finite element analysis, the results of which are discretized, the double integral expression can only be calculated approximately using numerical integration methods. This calculation will need two sets of different girds, the structural grids and electromagnetic grids, the requirements to which in the form and number are different, resulting in the mismatch between grids. The electromagnetic calculating couldn't be done based on the grid data got from the structural analysis, which can preserve the details of the structural deformation, but the accuracy certainly can not meet the requirements, because the latter calculation requires a denser and more uniform grid. Some scholars use the data from the structural analysis to fit the deformed reflector surface, upon which the electromagnetic grid is re-divided, then the calculation is done. The disadvantage of this approach is the introduction of a new fitting error to cause the mismatch of the calculated with actual deformation, which makes the calculated results of electrical performance different from the actual case. The innovation of this paper is data interpolation to the structural displacement field with the shape function of elements in the element analysis, which is not only in line with the actual deformation of the structure, but also to meet the precision requirements of electromagnetic analysis. The specific process is detailed below:

（1）The finite element model of the reflector antenna need to be built first, then we can get the deformation information of the antenna structure after applying the load and structure analysis according to the working environment. This deformation information should contain the full displacement $\vec{\boldsymbol{d}}$ of all nodes.

（2）First, the structural deformation information $\boldsymbol{d}_i$, $\boldsymbol{d}_j$, $\boldsymbol{d}_k$ should be extracted (see Fig. 3), then we can get the actual surface deformation of all elements by selecting the corresponding shape function to interpolate to obtain all the interior displacement $\boldsymbol{d}_m = N_i\boldsymbol{d}_i + N_j\boldsymbol{d}_j + N_k\boldsymbol{d}_k$.

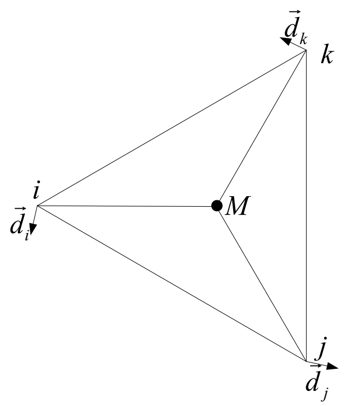


Figure 3: interior displacement of the element with three nodes

（3）Based on the original element, the following rules is abided to fractionize the triangular elements automatically. That is, on the basis of original element, node number and node coordinate, we can fractionize each triangular element to four smaller and similar triangular elements again and again, until meeting the precision requirements of electromagnetic calculation. The vertex normals of distorted curve and feed are then applied to get the distribution of the surface current density.

（4）Set the primary feed pattern function or caliber field distribution function in accordance with the discrete accuracy of the far-field determined by the main beam width of the antenna.

（5）With the fields coupling model established before, we can get the get the far-field pattern and main indexes of electrical performance.

4. SIMULATION ANALYSIS AND EXPERIMENTAL VERIFICATION

4.1 Experimental object

We use a Cassegrain dual-reflector antenna with 3.7m-diameter (see Fig. 4), C/Ku dual frequency band and ring focus to verify the correctness of two-field coupling model. The sub-reflector surface has a diameter of 0.44m, focus-diameter ratio of 0.35, operating frequency of 12.5GHz，feed of dielectric loaded horns, the distribution function of caliber field is

$$f_{s'}\left(\bar{\rho}'\right)=\begin{cases}1-0.9\exp\left(\bar{\rho}'^2-1\right), & \bar{\rho}'\geq 0.5\\ 1-0.85\exp\left(0.13-\bar{\rho}'\right), & \bar{\rho}'<0.5\end{cases}$$

Where $\bar{\rho}'\in[0,1]$ is the normalized radius. Therefore, we can get the equivalent normalized pattern function of the feed

$$F_1\left(\xi\right)=\begin{cases}\dfrac{1}{\cos^2\left(\xi/2\right)}\left(1-0.9\exp\left(\left(\dfrac{\tan\xi}{\tan\xi_0}\right)^2-1\right)\right), & \xi\geq\xi'\\ \dfrac{1}{\cos^2\left(\xi/2\right)}\left(1-0.85\exp\left(0.13-\dfrac{\tan\xi}{\tan\xi_0}\right)\right), & \xi<\xi'\end{cases}$$

Where $\xi_0=2\arctan\left(\dfrac{D}{4f}\right)$ is the aperture angle of the antenna and $\xi'=\arctan\left(0.5\tan\xi_0\right)$

(a) front view (b) back view

Figure 4: a C/Ku band 3.7m-diameter reflector antenna

The main antenna reflector surface consists of 12 the same fan-shaped panels (see Fig. 5) and its back frame includes 12 radial beam, 1 ring beam and central body. Each fan-shaped panel connects with the radial beam by 13 bolts and L-ring beam with 5 bolts (see Fig. 6).

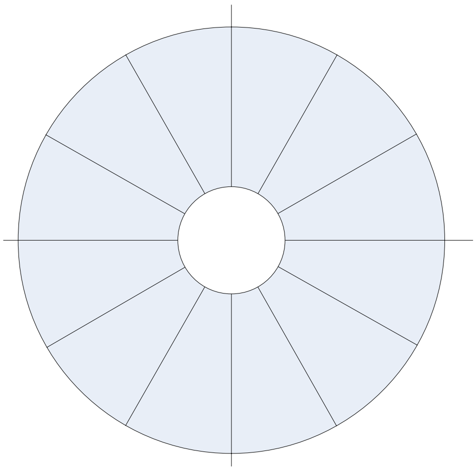


Figure 5: reflector antenna panels

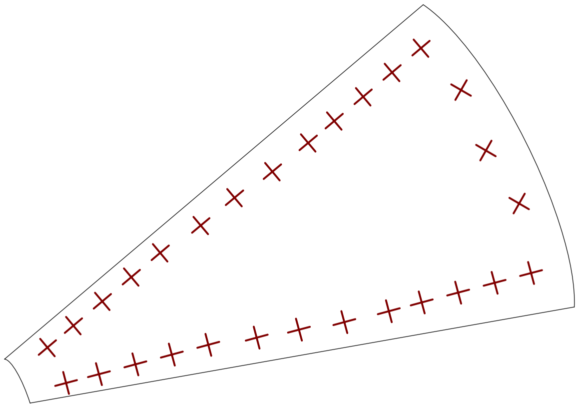


Figure 6: distribution of panel skin and back-up connecting bolts

4.2 Experimental procedures and analysis of the results

To verify the correctness of the electromechanical coupling theory, the premise is to get the deformation information of the reflecting surface deformation under its own weight and other environmental loads. As the self-weight deformation of the selected test subjects, the 3.7m antenna, is very small, the difference of the electrical properties is not obvious with the direct measurement and calculation.

So, we draw the idea in the literature [15] that makes the deformation with pasting metal rings to simulate the impact of different surface errors to the electrical performance of antenna. The reflecting surface is divided into 3 rings from inside to outer and every ring is given the metal shim with different thickness to make the panel away from its original position, thereby generating different distribution of deformation errors. As shown in Fig. 7, there are gaskets with 0.5mm, 1mm and 2mm thickness to make the experiment, which is measured with a micrometer (see Fig. 8).

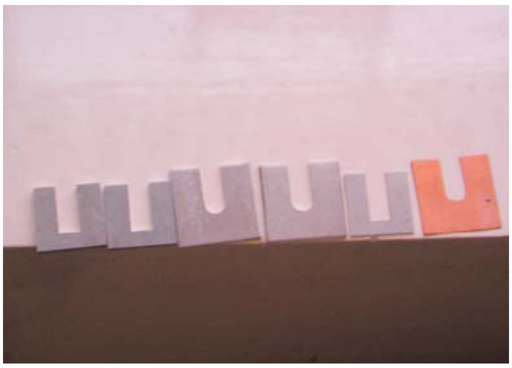
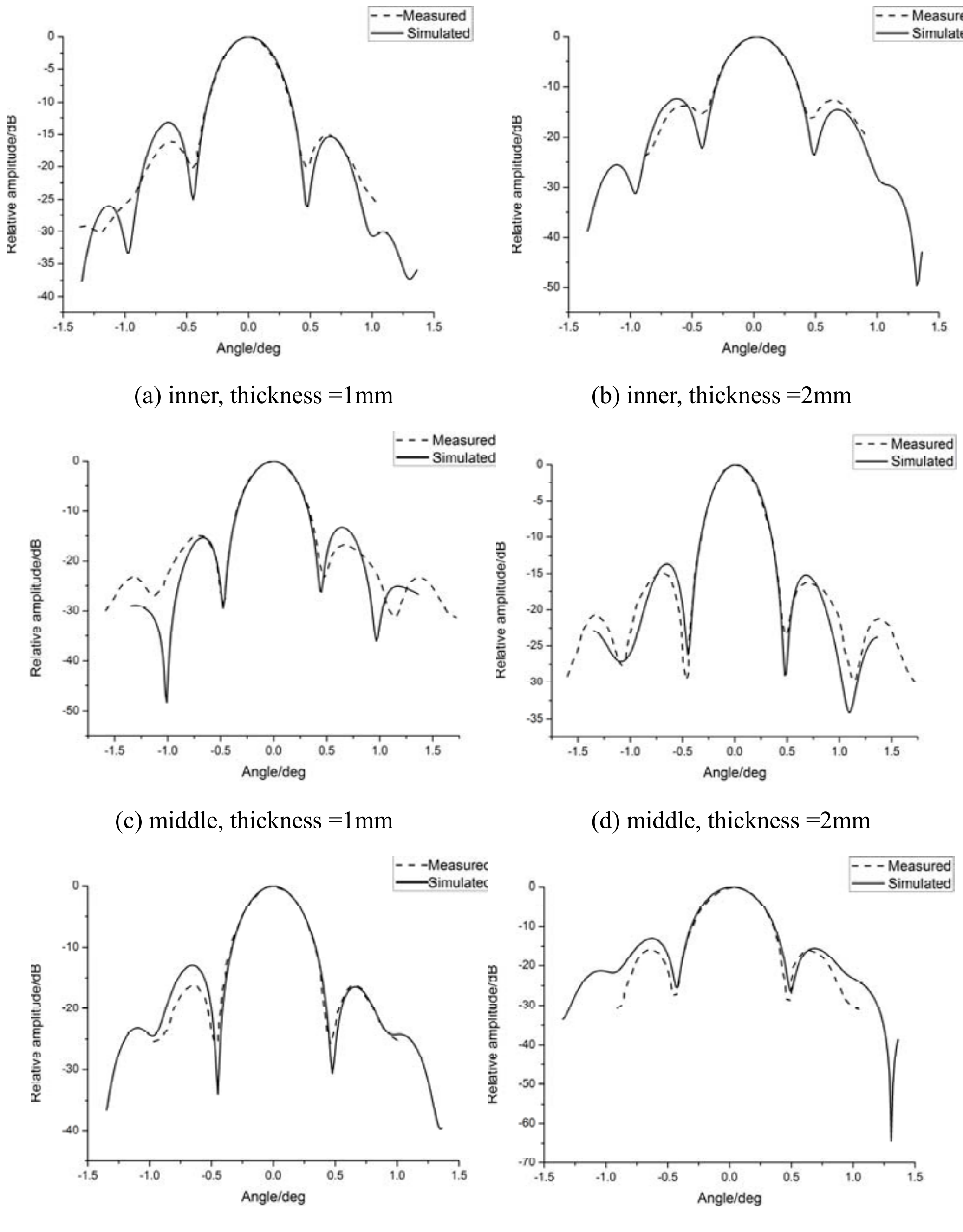


Figure 7: the metal gaskets with different thickness

Figure 8: micrometer used to measure the thickness of shims

The far-field pattern of reflector antennas could be got with the electromechanical two-field coupling model. Table 1 shows the comparison of the calculated and measured results when the inner, middle and outer panels are given the gaskets with the 0.5mm, 1mm, 2mm thickness separately. The figures show that the measured and calculated results are very close in the vicinity of the main lobe, slightly different around the first side lobe, and the difference is gradually increased with the extension of the side lobe.



(a) inner, thickness =1mm (b) inner, thickness =2mm

(c) middle, thickness =1mm (d) middle, thickness =2mm

(e) outer, thickness =1mm (f) outer, thickness =2mm

Figure 9: calculated and measured radiation pattern for a reflector antenna

Case			Gain(dB)	3dB	Left Side Lobe	Right Side Lobe
inner	1mm	Simulated	52.94	0.399	-13.180	-15.340
		Measured	51.96	0.396	-16.07	-15.05
	2mm	Simulated	52.77	0.396	-12.240	-14.520
		Measured	52.08	0.396	-13.660	-12.550
middle	1mm	Simulated	52.60	0.398	-15.365	-13.197
		Measured	51.66	0.408	-15.030	-16.620
	2mm	Simulated	52.26	0.400	-13.687	-15.185
		Measured	51.80	0.408	-14.860	-16.140
outer	1mm	Simulated	52.94	0.399	-13.000	-16.479
		Measured	52.01	0.382	-16.160	-16.170
	2mm	Simulated	52.81	0.399	-13.092	-15.545
		Measured	52.09	0.390	-15.750	-16.010

Table 1: comparison of analysis and measurements for a 3.7m-dimeter reflector antenna in different case

Table 1 shows the measured and calculated index results of electrical performance of the antenna in various conditions. The conclusion can be drew when the calculated results of electromechanical coupling model compare with the actual measured results, the maximum relative error of which is 1.89%, 4.45% , 19.55% and 15.70% in gain of antenna, main beam width, left and right first side lobe level. So the rightness and rationality of electromechanical two-field coupling theory model can be acquired. From the table 2, we can draw the conclusion that the error between the calculated and measured results get smaller with the increase of the gasket thickness, which is mainly due to the existence of initial random errors on the main reflector surface of the antenna.

5 Conclusion

Large reflector antennas are more vulnerable to the impact of the external environment, load, and therefore require high-precision calculations. The electromechanical two-field coupling model of reflector antennas is established in this paper using surface current method, based on which the solving strategies and methods are given also. Finally, the correctness and calculation accuracy of this model is verified using a 3.7m diameter antenna, which provides a certain referential significance to the electromechanical coupling analysis of reflector antennas and other electronic equipment.

REFERENCES

[1] Y. Rahmat-Samii, A. Densmore. A history of reflector antenna development: Past, present and future. IEEE MTT-S International Microwave and Optoelectronics Conference (IMOC), Nov. 3-6, 2009, Belem, Brazil.

[2] J. Ruze. Antenna tolerance theory-a review. IEEE Proc, 1966, 54(4): 633-640.
[3] W. Rysch. Surface tolerance loss for dual-reflector antenna. IEEE Transaction on Antennas and Propagation, 1982, 32(4): 784-785
[4] Y. Rahmat-Samii. An Efficient Computational Method for Characterizing the Effects of Random Surface Errors on the Average Power Pattern of Reflectors. IEEE Transactions on Antenna and Propagation, 1983, 31(1): 92-98.
[5] J. W. Kim, B. S. Kim. Computation of the Average Power Pattern of a Reflector Antenna with Random Surface Errors and Misalignment Errors. IEEE Transactions on Antenna and Propagation, 1996, 44(7): 996-999.
[6] L. W. Song, B. Y. Duan and F. Zheng. “The Effect of Surface Error on Reflector Antenna Performance,” (in Chinese) Chinese Journal of Electronics, 2009, 37(3): 552-556.
[7] V.K. Tripp. A new approach to the analysis of random errors in aperture antennas. IEEE Transaction on Antennas and Propagation, 1984, 32(8): 857-863
[8] S. von Hoerner. Homologous Deformations of Tiltable Telescopes. J. Structural Division Proc. ASCE, 1967, 93: 461-486.
[9] S. von Hoerner, Woon-Ying Wong. Gravitational Deformation and Astigmatism of Tiltable Radio Telescopes. IEEE Transactions on Antennas and Propagation, 1975, 23(5):689-695.
[10] C. S. Wang, B. Y. Duan and Y. Y. Qiu. “A novel method for fitting the distorted reflector of a large antenna,” (in Chinese) Journal of Xidian University, 2005, 32(6): 839-843.
[11] C. S. Wang, B. Y. Duan and Y. Y. Qiu. “On New Fitting Method of Large Distorted Antenna Reflectors Based on Coons Surface and B-Spline,” (in Chinese) Journal of Electronics & Information Technology, 2008, 30(1): 233-237.
[12] W. W. Song, X. M. Zhang and F. C. Yuan. “Radiation Pattern Simulation of the Offset Reflector Antennas with Local Protuberant Distortion,” (in Chinese) Modern Electronic Techology, 2008, (7): 1-7.
[13] W. T. Smith and R. J. Bastian. An Approximation of the Radiation Integral for Distorted Reflector Antennas Using Surface-Error Decomposition. IEEE Transactions on Antenna and Propagation, 1997, 45(1): 5-10.
[14] C. S. Wang and B. Y. Duan. On Development and Application of Mechanical-Electromagnetic-Field Coupling Model of Reflector Antennas. Chinese Journal of Electronics, 2011, 39(6): 1431-1435.
[15] H. Rajagopalan, S. H. Xu, and Y. Rahmat-Samii. Reflector Antenna Distortion Compensation Using Sub-Reflectarrays: Simulations and Experimental Demonstration. IEEE Antennas and Propagation Magazine, 2012, 54(3): 235-246.