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Millimeter-Wave Antenna Array Performance Sensitivity to Structural Distortion Using Coupled Structural-Electromagnetic-Statistical Technique

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Abstract—In wireless communication systems, active array antennas are the major components whose efficiency and effectiveness determines the capacity of communication systems. However, deformation or distortion in the array structure which is inevitable in the fabrication and operation process of the antennas causes random positioning of the elements in the array. Accounting for the impacts of structural deformation is key towards effective array structural design and optimization. Based on the concept of electromechanical coupling, a new and robust coupled structural-electromagnetic-statistical model which accounts for the random element positioning is presented to adequately evaluate array pattern sensitivity to structural deformation. The model is compared with the generally acceptable Ansoft HFSS software's result, and there is a good agreement between the two results. Also, a 10×10 microstrip patch antenna array is designed to illustrate the application of the model in accessing array performance with random position error and saddle shape distortion. The results demonstrate the sidelobe level and gain variation with different random errors and different distortion degrees respectively. These valuable results obtained provide a theoretical guidance for engineers in the determination of the optimal performance-driven structure tolerance. It finds good applications in radar systems, communication systems, and aerospace.

1. INTRODUCTION

Impacts study of structural distortion and random error on the electromagnetic field performance of array antenna is of great importance in research domain towards highly optimized antennas. Antenna array with high detection and tracking capacity, multifunctional, and highly reliable has been employed in different applications [1, 2]. With the trend in technology, the demand for accurate mechanical design and optimization of antenna array is on a high side. The beamwidth, gain, sidelobe, boresight pointing accuracy of antenna are the determinants of the performances of array antennas [3]. Also, random error emanated from fabrication/manufacturing, assembling procedure, and structural/mechanical deformation are caused by vibration, impact force, and high thermal power results in displacement of elements, and consequently affects the performance of the antenna, such as higher sidelobe level, gain loss, inaccurate boresight pointing, and beamwidth broadening [4–7]. The effect is more serious at higher frequency of operation and will be more in the implementation process of future 5G technology (i.e., at millimeter-wave frequency band). The combination of systematic distortion and random position error causes random element positioning which results in degraded electromagnetic performance of the array [8–12]. It causes shortened communication distance and low resistance to interference which

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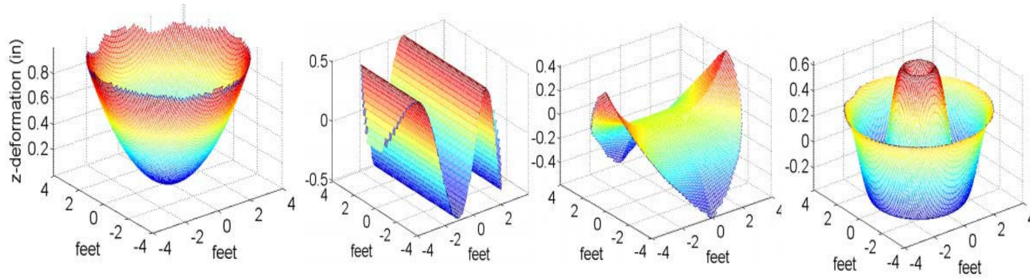
severely limit high performance actualization of antenna array. Hence, structural errors or deformation limits realization of desired antenna array performance. So, deeply exploring the relationship between structural error and EM performance of antenna array with the impact of the randomness in the position of element is necessary [13, 14].

There are some previous studies which concentrate on the impact of mechanical distortion and random position error on array performances. Analyzing random position error, it is generally assumed that impacts of element's position errors reflect on the effects of excitation's amplitude and phase errors. Hence, it is believed that excitation amplitude and phase errors have normal distribution profile, and the relationship that exists between variances and single electrical variables like sidelobe level was derived by employing statistical approach [14–18]. But the impacts of random position error as a type of structural error cannot be quantified easily by phase and amplitude tolerances. Reference [19] worked on symmetrical and asymmetrical bend's influence on antenna array performance. The impacts of antenna array plane distortions which includes potato chip, sag, Bessel and sinusoidal profile is presented in [20] (see Figure 1). However, [19, 20] took systematic error into consideration without accounting for the random position errors which are inevitable in fabrication and operation processes. Furthermore, some works were also tailored towards influences on random error, such as [21] which evaluated the impact of random errors on hexagonal active phased array antenna performance, and gave some useful guides. However, systematic distortion was not considered in this work. References [22, 23] show that the influence of random error is the same as the effect of excitation current errors, and the impacts of random current errors on antenna performance were critically looked into, but no direct relationship was given between random error and performance of the antenna. Furthermore, reference [24] estimated subarray position error and its effect on array performance employing theoretical statistical probability. In this method, many repeated computations are needed to determine antenna statistical performance. [25] and [26] present a linear relationship between systematic distortion and random error to evaluate their influence of the performance of antenna. However, practically the amounts of systematic error and random error show big differences, so linear relationship mitigates the impacts of random error when there is a large difference between the two errors. Also, random error is stochastic in nature while systematic error is deterministic; the combined errors lead to random performance of electromagnetics. Therefore, whenever random error exists, it is more accurate or better to determine the electromagnetic performance from statistical approach. This paper therefore proposes a method which considers randomness in the array element's position to efficiently access the statistical performance of antenna array. From the perspective of electromechanical coupling, a coupled structural-electromagnetic statistical model is presented, and the model corroborates Ansoft HFSS model-based results, which is generally used by engineers for different EM designs.



(a) (b) (c) (d)

Figure 1. Antenna array deformation mode. (a) Sag, (b) Potatoes chip, (c) Saddled, (d) Bessel.

2. PROPOSED COUPLED STRUCTURE-ELECTROMAGNETIC STATISTICAL MODEL

Figure 2 shows the configuration of antenna array elements whose numbers are $M \times N$, with equal spacing. d_y and d_x are the intervals between the elements along x and y directions. (θ, ϕ) is the far-field target direction relative to $Oxyz$ coordinate system as indicated in Figure 3, with cosine direction as $(\cos\alpha_x, \cos\alpha_y, \cos\alpha_z)$ [27].

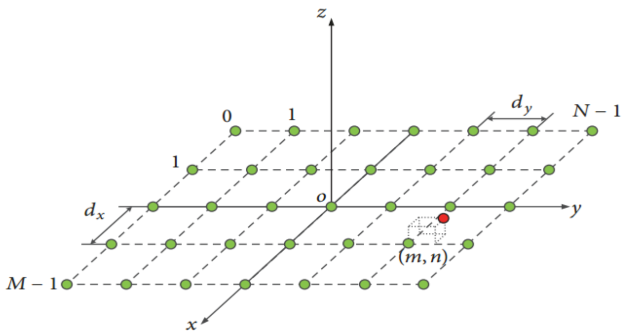


Figure 2. Configuration of planar antenna array element.

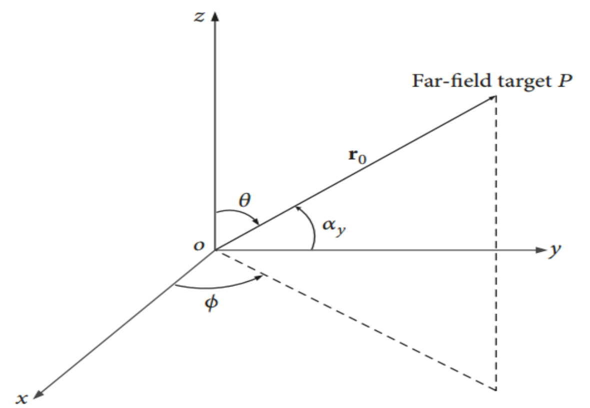


Figure 3. Geometrical spacing relationship of the target far-field.

Antenna fabrication and operating process result in structure errors, which include systematic distortion and random error. Assuming that the element (m, n), $(0 \leq m \leq M-1,\ 0 \leq n \leq N-1)$ has random error of $(\Delta x^r_{mn}, \Delta y^r_{mn}, \Delta z^r_{mn})$, phase difference $\Delta\Phi^r_{mn}$ with respect to Figure 1's coordinate origin is expressed as

$$\Delta\Phi^r_{mn} = k\left(\Delta x^r_{mn}\sin\theta\cos\phi + \Delta y^r_{mn}\sin\theta\sin\phi + \Delta z^r_{mn}\cos\theta\right) \tag{1}$$

Also, assume that the systematic distortion of element (m, n) is given as $(\Delta x^s_{mn}, \Delta y^s_{mn}, \Delta z^s_{mn})$. The phase difference $\Delta\Phi^s_{mn}$ with respect to Figure 1's coordinate origin is given as

$$\Delta\Phi^s_{mn} = k\left(\Delta x^s_{mn}\sin\theta\cos\phi + \Delta y^s_{mn}\sin\theta\sin\phi + \Delta z^s_{mn}\cos\theta\right) \tag{2}$$

Based on the antenna array superposition principle without coupling, the planar rectangular active antenna array field pattern density function with random position error and systematic distortion is presented as

$$E_{sr}(\theta,\phi) = f_e(\theta,\phi)\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} I_{mn} e^{j\left(\Delta\Phi_{mn}+\Delta\Phi^r_{mn}+\Delta\Phi^s_{mn}+\varphi_{mnB}\right)} \tag{3}$$

where $f_e(\theta, \phi)$ is the free space element pattern function, I_{mn} the element (m, n) amplitude excitation current, φ_{mnB} the inherent phase difference of array decided by phase shifter, and $\Delta\Phi_{mn} = kmd_x \sin\theta\cos\phi + knd_y \sin\theta\sin\phi$ the initial spatial phase distribution. Practically, elements random position errors are probabilistic variables in nature; it becomes important to statistically analyze the characteristic of electromagnetic for antenna array including random error. Let random position errors in x, y, and z directions be Δx^r_{mn}, Δy^r_{mn}, and Δz^r_{mn} subjected to normal distribution, with zero means and σ^2_x, σ^2_y, and σ^2_z variances, respectively. Hence, the random phase difference $\Delta\Phi^r_{mn}$ in Eq. (1) is a normal distribution function, and the variance is expressed as

$$E_{sr}(\theta,\phi)\,\sigma^2_{\Phi_r} = k^2\left[\sigma^2_x(\sin\theta\cos\phi)^2 + \sigma^2_y(\sin\theta\sin\phi)^2 + \sigma^2_z(\cos\phi)^2\right] \tag{4}$$

Any random parameter with normal distribution given as $x \sim N(0, \sigma_x)$, the associated relations $\overline{\cos x}$ and $\overline{\sin x}$ is presented in reference [28, 29]. Employing the function relations, the mean exponential function $\overline{e^{jx}} = e^{-\sigma^2_x/2}$. Hence, the mean field density pattern function $E_{sr}(\theta, \phi)$ in Eq. (3) is given as

$$\overline{E_{sr}(\theta,\phi)} = f_e(\theta,\phi)\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} I_{mn} e^{j\left(\Delta\Phi_{mn}+\Delta\Phi^s_{mn}+\varphi_{mnB}\right)}\overline{e^{j\Delta\Phi^r_{mn}}} = E_s(\theta,\phi)e^{-\left(\frac{1}{2}\right)\sigma^2_{\Phi_r}} \tag{5}$$

$E_s(\theta, \phi)$ is the field density of the pattern function with associated systematic distortion. The antenna array mean power pattern function is derived based on variance property $\sigma^2_{E_{sr}} = \overline{E_{sr}(\theta,\phi)E^*_{sr}(\theta,\phi)} - \overline{E_{sr}(\theta,\phi)}\,\overline{E^*_{sr}(\theta,\phi)}$ as

$$\overline{P_{sr}(\theta,\phi)} = \overline{E_{sr}(\theta,\phi)E^*_{sr}(\theta,\phi)} = \sigma^2_{E_{sr}} + \overline{E_{sr}(\theta,\phi)}\,\overline{E^*_{sr}(\theta,\phi)} \tag{6}$$

Putting $\overline{E_{sr}(\theta,\phi)}$ function into Eq. (6), the mean power of pattern function is derived as

$$\overline{P_{sr}(\theta,\phi)} = \sigma^2_{E_{sr}} + |E_s(\theta,\phi)|^2 e^{-\sigma^2_{\Phi_r}} \tag{7}$$

$\sigma^2_{E_{sr}}$ defines the variance of $E_{sr}(\theta,\phi)$, and its equation can be deduced. According to [24], $E_{sr}(\theta,\phi)$ can be expressed in real and imaginary parts. Let $X = \sum_{m=0}^{M-1}\sum_{m=0}^{N-1} X_{mn}$ and $Y = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} Y_{mn}$ represent the real and imaginary parts, respectively. The variance $\sigma^2_{E_{sr}}$ is estimated as

$$\sigma^2_{E_{sr}} = \sigma^2_X + \sigma^2_Y = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1}\sigma^2_{X_{mn}} + \sum_{m=0}^{M-1}\sum_{n=0}^{N-1}\sigma^2_{Y_{mn}} \tag{8}$$

where $\sigma^2_{X_{mn}} = \overline{X^2_{mn}} - \overline{X_{mn}}^2$ and $\sigma^2_{Y_{mn}} = \overline{Y^2_{mn}} - \overline{Y_{mn}}^2$. The variance $\sigma^2_{X_{mn}}$ is given as:

$$\begin{aligned}\sigma^2_{X_{mn}} &= |f_e(\theta,\phi)|^2 I^2_{mn}\left(\frac{1+\cos(2\Delta\Phi_{mn}+2\Delta\Phi^s_{mn}+2\varphi_{mnB})\,e^{-2\sigma^2_{\Phi_r}}}{2}\right.\\&\quad\left.-\frac{1+\cos(2\Delta\Phi_{mn}+2\Delta\Phi^s_{mn}+2\varphi_{mnB})}{2}e^{-\sigma^2_{\Phi_r}}\right) \end{aligned}\tag{9}$$

$$\overline{Y_{mn}} = f_e(\theta,\phi)\,I_{mn}\sin(2\Delta\Phi_{mn}+2\Delta\Phi^s_{mn}+2\varphi_{mnB})\,e^{-\left(\frac{1}{2}\right)\sigma^2_{\Phi_r}} \tag{10}$$

$$\overline{Y^2_{mn}} = |f_e(\theta,\phi)|^2 I^2_{mn}\frac{1-\cos(2\Delta\Phi^s_{mn}+2\Phi_{mnB})e^{-2\sigma^2_{\Phi}}}{2} \tag{11}$$

$$\begin{aligned}\sigma^2_{Y_{mn}} &= |f_e(\theta,\phi)|^2 I^2_{mn}\left(\frac{1-\cos(2\Delta\Phi_{mn}+2\Delta\Phi^s_{mn}+2\varphi_{mnB})\,e^{-2\sigma^2_{\Phi_r}}}{2}\right.\\&\quad\left.-\frac{1-\cos(2\Delta\Phi_{mn}+2\Delta\Phi^s_{mn}+2\varphi_{mnB})}{2}e^{-\sigma^2_{\Phi_r}}\right)\end{aligned} \tag{12}$$

Substituting Eqs. (9) and (12) into Eq. (8), $\sigma^2_{E_{sr}}$ then results in

$$\sigma^2_{E_{sr}} = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1}\sigma^2_{X_{mn}} + \sum_{m=0}^{M-1}\sum_{n=0}^{N-1}\sigma^2_{Y_{mn}} = |f_e(\theta,\phi)|^2\left(1-e^{-\sigma^2_{\Phi_r}}\right)\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} I^2_{mn} \tag{13}$$

The proposed coupled structure-electromagnetic statistic model which is the mean power pattern function with associated element position randomness is stated as

$$\begin{aligned}\overline{P_{sr}(\theta,\phi)} &= |E_s(\theta,\phi)|^2 e^{-\sigma^2_{\Phi_r}} + |f_e(\theta,\phi)|^2\left(1-e^{-\sigma^2_{\Phi_r}}\right)\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} I^2_{mn}\\ &= |E_s(\theta,\phi)|^2 e^{-k^2\left[\sigma^2_x(\sin\theta\cos\phi)^2+\sigma^2_y(\sin\theta\sin\phi)^2+\sigma^2_z(\cos\theta)^2\right]}\\ &\quad + |f_e(\theta,\phi)|^2\left\{1-e^{-k^2\left[\sigma^2_x(\sin\theta\cos\phi)^2+\sigma^2_y(\sin\theta\sin\phi)^2+\sigma^2_z(\cos\theta)^2\right]}\right\}\cdot\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} I^2_{mn}\end{aligned} \tag{14}$$

3. COUPLED STRUCTURE-ELECTROMAGNETIC STATISTICAL MODEL VALIDATION

Ansoft HFSS software has been tested and trusted. It provides accurate electromagnetic solutions and used for reliable and efficient antenna designs. Therefore, it is in order to validate the appropriateness of the proposed coupled structure-electromagnetic statistic model by comparison with the widely used HFSS software simulations. To illustrate the validity, an 8×8 microstrip patch antenna array which operates at millimeter wave frequency is designed and simulated. It has the same intervals of 0.75λ along x and y directions as presented in Figure 4. Each patch element has the length $L = 3.953\,\text{mm}$ and width $W = 3.160\,\text{mm}$, and the total size of the array is $60\,\text{mm} \times 60\,\text{mm}$.

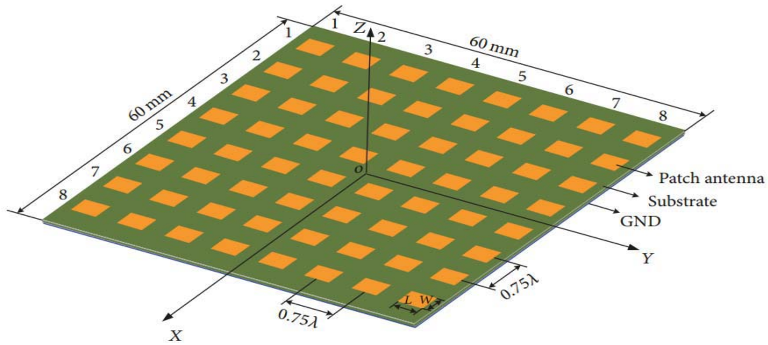


Figure 4. Millimeter-wave microstrip patch antenna array designed for verification purpose.

Amplitude and phase of the initial excitation current are equal. Initiating structure errors random samples, a saddle-shaped distortion is introduced with minimum displacement $\lambda/6$ in z direction as systematic distortion. It is equally assumed that random position errors along x, y, and z planes satisfy normal distribution with $\lambda/30$ variance and 0 mean. The performance of array with associated structure error sample is separately simulated using HFSS software without element coupling effect. The mean antenna performance is computed by finding the average of the total performances estimated from all the samples of structure error. One thousand (1000) samples (structure error) were considered because there is no further change in the results when the mean of array performance is more than 1000 samples. The computed performance of the proposed model is compared with the result generated from HFSS. The parameters are listed in Table 1, and and the compared results are as shown in Figure 5.

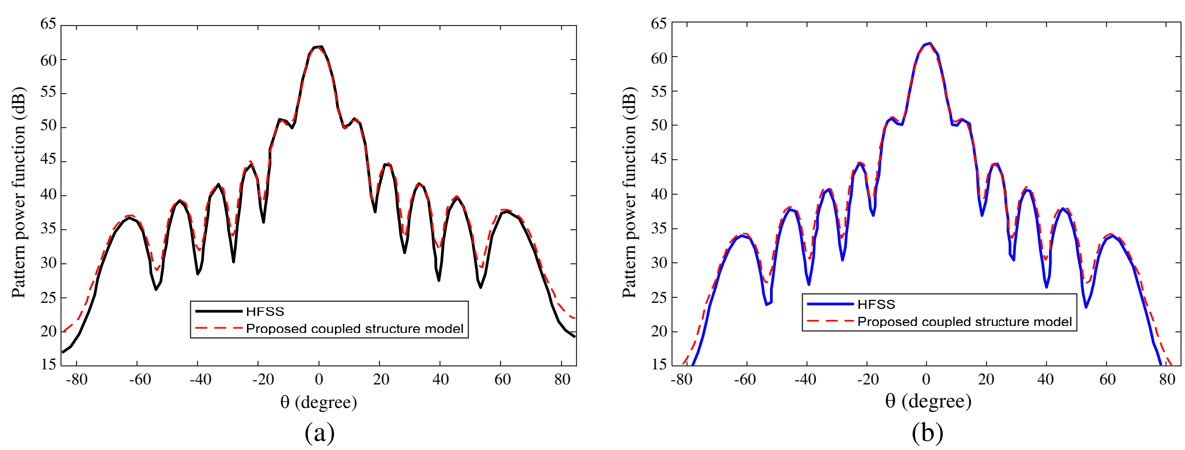


Figure 5. Comparison between the proposed coupled structure model and HFSS-based results for (a) $\phi = 0°$ and (b) $\phi = 90°$ planes.

The coupled structure model and HFSS-based results agree well, and they exhibit consistency in main lobe and side lobe areas. The boresight pointing, beamwidth, and gain are all the same in both planes. It implies that the coupled structured model and HFSS-based results have the same main lobe areas (Figure 5). The first sidelobe shows some differences in absolute figures of 0 dB and 0.09 dB in $\phi = 0°$ and $\phi = 90°$ planes, respectively. On the other hand, for second, third, fourth, and fifth sidelobes, the peak differences in absolute figures are 0.43 dB and 0.48 dB in $\phi = 0°$ and $\phi = 90°$ planes, respectively. The above results prove the effectiveness and efficiency of the proposed model in the analysis of element position randomness effect on electromagnetic radiation performance of antenna array. Therefore, the proposed model can quickly and effectively evaluate the performance of antenna, which consequently provides arrays structural design and optimization guideline.

Table 1. Coupled structure model versus HFSS results parameters (SLL means sidelobe level: all SLL are right SLL.

Performance	Coupled Structure Model Result	HFSS-based result
Boresight pointing (°)		
$\phi = 0°$	0.14	0.14
$\phi = 90°$	0.12	0.12
Beam width (°)		
$\phi = 0°$	8.70	8.70
$\phi = 90°$	8.69	8.69
Gain (dB)	60.32	60.32
First SLL (dB)		
$\phi = 0°$	51.17	51.17
$\phi = 90°$	50.87	50.97
Second SLL (dB)		
$\phi = 0°$	45.20	45.63
$\phi = 90°$	44.88	45.05
Third SLL (dB)		
$\phi = 0°$	42.43	42.81
$\phi = 90°$	41.82	41.95
Fourth SLL (dB)		
$\phi = 0°$	40.56	40.66
$\phi = 90°$	38.71	38.13
Fifth SLL (dB)		
$\phi = 0°$	38.55	39.04
$\phi = 90°$	34.81	35.09

4. SIMULATION EXAMPLE AND ANALYSIS

Structural deformation of antenna array in practice usually causes random position error and systematic distortion. The randomness in element position error is quantified as a random variable. Also, the distortion exhibited in practice is generally saddle shaped. According to the surface mathematical properties, the phase centre of a saddle-shaped element in position (m, n) is expressed as

$$\Delta Z_{mn} = \Delta Z_{\max}\left(\frac{x_{mn}^2}{x_{\max}^2} - \frac{y_{mn}^2}{y_{\max}^2}\right) \tag{15}$$

where $\Delta Z_{\max}$ is the maximum displacement of antenna array elements (systematic error) in z-coordinate, and $y_{\max}$ and $x_{\max}$ are array aperture width and half-length, respectively. In this section, antenna array with both element random position error and saddle shape distortion is addressed. Consider a rectangular 10×10 microstrip patch array operating at 28.9 GHz frequency (Figure 6). The element spacing along x and y coordinates is $\lambda/2$. Random errors along x, y, and z coordinates are assumed normal distribution with zero mean and $\lambda/20$ variance. $\lambda/5$ is selected as saddle shape maximum displacement in z plane. The systematic distortion is considered saddle shape, while three random samples (random samples 1–3) are emulated based on the same normal distribution. The pattern power function used is $P_{sr}(\theta, \phi) = E_{sr}(\theta, \phi)E_{sr}^*(\theta, \phi)$ where $E_{sr}(\theta, \phi)$ is the field intensity in Eq. (3). The proposed statistical model is then applied to determine the performance of distorted antenna array, and the results obtained are presented in Figure 7 with the parameters listed in Table 2. The results here can be discussed in terms of beamwidth, sidelobe level, gain, and boresight. a) There is small variations in the beamwidth per random samples, and the values are almost equal to the statistical random error. The maximum changes exhibited are 0.05° and 0.06° in $\phi = 0°$ and $\phi = 90°$, respectively. Therefore, the beamwidth is mainly affected by systematic distortion. b) When there are both random error and saddle shape, the gain is greatly reduced. The magnitude of maximum gain loss is −2.44 dB. The gain error is computed from statistical random error by substituting random errors variances with systematic distortion into the proposed model. It is also computed by adding systematic distortion with the three random samples as total structural error. There is negligible difference between the two results, and the peak difference is 0.41 dB. Hence, the change in gain is a function of systematic distortion.

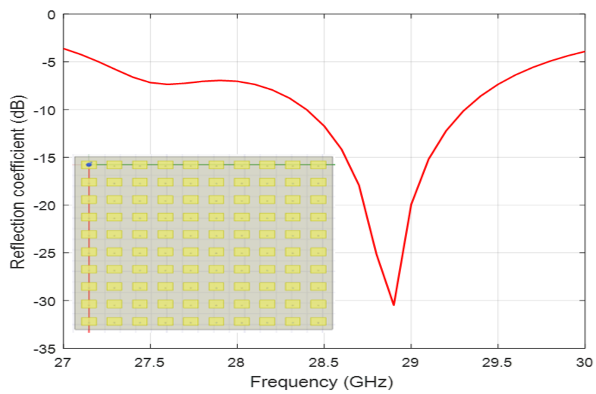
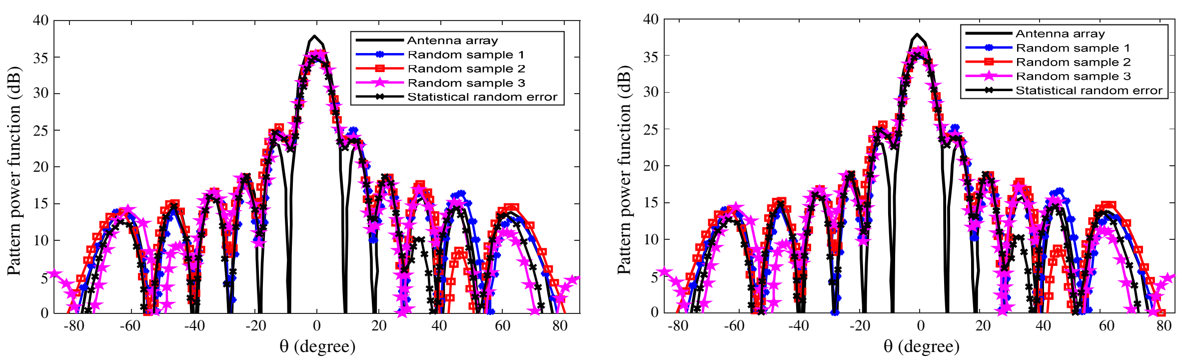


Figure 6. Designed antenna array with reflection coefficient.



(a) (b)

Figure 7. Antenna array performance with different random errors and systematic distortion (a) $\phi = 0°$ and (b) $\phi = 90°$.

c) When the saddle shape is symmetric without any effect on pointing direction, the boresight varies mainly from various random error distributions. Therefore, calculation from statistical performance is more preferable to the method of adding random samples to systematic distortion. d) The sidelobe levels differently vary with the three random samples in both planes. The sidelobe levels from the proposed model is the value of evaluation because they are from mean pattern power function. For all the samples, 1000 rounds of computations were conducted. The average gain loss is −2.44 dB which is equal in value to the proposed statistical model. The boresight changes by 0.31° and 0.23°, beamwidth by 0.34° and 0.46°, sidelobe level by 0.62° and 1.65° in $\phi = 0°$ and $\phi = 90°$ planes respectively. The total errors in both planes are about 0.02 dB, which is almost equal to the values obtained from the proposed model. So, the proposed coupled structure-EM statistical model is a good tool to easily and efficiently evaluate antennas pattern sensitivity to structural error.

Table 2. Performance parameters with various random error samples and systematic distortion (+ implies right hand side of $\theta = 0°$, and $-$ means left hand side of $\theta = 0°$).

Performance	Sample 1	Sample 2	Sample 3	Statistical Random Error
Boresight pointing (°)				
$\phi = 0°$	+0.09	+0.23	−0.22	+0.25
$\phi = 90°$	−0.21	+0.23	+0.28	+0.31
Beam width (°)				
$\phi = 0°$	+0.12	+0.20	+0.23	+0.25
$\phi = 90°$	+0.17	+0.30	+0.23	+0.33
Gain Loss (dB)	−1.99	−2.44	−1.78	−2.14
First SLL (dB)				
$\phi = 0°$	+0.45	+0.31	+0.31	+0.03
$\phi = 90°$	+0.53	+1.54	+1.96	+0.03
Second SLL (dB)				
$\phi = 0°$	−0.41	−1.22	−0.09	−0.64
$\phi = 90°$	+0.82	−0.13	−1.52	−0.89
Third SLL (dB)				
$\phi = 0°$	+0.52	−3.82	+1.14	−0.41
$\phi = 90°$	−1.31	+0.17	+0.57	−0.41
Fourth SLL (dB)				
$\phi = 0°$	+1.65	−0.23	−4.54	−0.24
$\phi = 90°$	−0.81	+1.15	−0.43	−0.24
Fifth SLL (dB)				
$\phi = 0°$	−0.76	−0.43	+0.44	−0.11
$\phi = 90°$	−2.72	−1.78	+1.12	−0.12

5. CONCLUSION

A coupled structure electromagnetic statistical model which accesses antenna pattern power sensitivity to structural error has been proposed in this paper. Structural error causes randomness in array element position, thereby affects the performance of the antenna. This effect has been modeled, analyzed, and compared with parameters taken from systematic distortion plus random samples of errors. The random error causes unpredictable antenna electromechanical performance, particularly the sidelobe levels as compared to the beamwidth and antenna gain. Parameters obtained from the proposed model show higher accuracy than the random sample errors. The performance of the coupled structure electromagnetic statistical model is nearly the same as the performance average of large random samples. The proposed method was validated or benchmarked via the popular HFSS software, and a good agreement was observed. Hence, the model gives guidance for engineer to determine the optimal performance-driven structure tolerance.

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