Research on simulation consistency between NEC and HFSS on strange antenna for evolving antenna

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Abstract: Evolutionary algorithm (EA) is a promising technology in automatic antenna design and it can invent new and strange antennas which are more effective than would otherwise be developed. However, a challenge in evolving antenna is that evaluating antenna fitness in the EA algorithm is usually time-consuming due to the time-consuming electromagnetic simulations. Numerical electromagnetics code (NEC) is a moment method solver with high computing speed and the code is publicly available for general use. It is then usually used to evaluate antenna fitness in evolving antenna. However, it does not go through a full reliability test yet, then it needs reliability test in simulating an antenna, especially a strange antenna before it is adopted to evolve antenna. This is the focus of this paper. And the reliability test is achieved by the simulation consistency between NEC and HFSS since HFSS is a commercial finite element method solver with high reliability. We find that NEC is reliable in simulating strange wire antennas, however, unreliable in simulating surface (patch) antennas.

Keywords: evolutionary algorithm; EA; antenna design; evolved antenna; wire antenna; surface antenna.

Reference to this paper should be made as follows: Zeng, S., Ye, H., Li, H., Li, Z. and Jing, H. (2013) 'Research on simulation consistency between NEC and HFSS on strange antenna for evolving antenna', *Int. J. Modelling, Identification and Control*, Vol. 18, No. 1, pp.76–87.

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1 Introduction

Bio-inspired techniques such as evolutionary algorithms (EAs) [genetic algorithm (Holland, 1975), evolution strategy (Rechenberg, 1973), evolutionary programming (Fogel et al., 1966) and genetic programming (Koza, 1992)] have been widely used. Many new bio-inspired algorithms have been developed recently such as differential evolution (DE) (Storn and Price, 1997), particle swarm optimisation (PSO) (Kennedy and Eberhart, 1995), bat algorithm (Yang, 2011), eagle strategy (Yang and Deb, 2012), cuckoo search (Layeb, 2011) and so on. Those techniques have been widely applied in solving complicated real-world optimisation problems such as in traffic management system (Pal et al., 2012), economic dispatch (Sun et al., 2009), reducing the risk of malfunctions (De La Cruz et al., 2009), multilayered composite plate (Amrita and Mohan Rao, 2011), reconfiguration of shipboard power system (Wang et al., 2012), fuzzy system identification (Li et al., 2011), flexible manipulator systems (Elkaranshway et al., 2011), and so on.

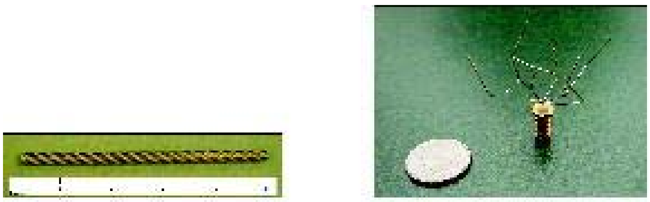
They have also been used in the antenna design and optimisation since mid-1990s (Rahmat-Samii and Michielssen, 1999; Haupt, 1994; Linden and Altshuler, 1996). For example, antenna arrays (Haupt, 1994) designed by Haupt, wire antennas designed by Linden and Altshuler (1996), quadrifilar helix antenna (QHA) (Lohn et al., 2011) designed by Lohn, an evolved X-band antenna for NASA's Space Technology 5 (ST5) spacecraft (Gregory et al., 2011) designed by Gregory's group which had been adopted in the final flight and became the first evolved hardware in space. The new achievements in the field of EA are soon applied in evolving antenna. Ramos et al. (2003) designed antenna with multi-objective EA, Kadri and Bendimered (2009) design complex excitation antenna array synthesis with fuzzy genetic algorithm, Jin and Rahmat-Samii (2007) design the antenna with particle swarm algorithm, Singh and Kumar (2010) design Yagi-Uda antenna with BBO algorithm which proposed in 2008, Gregory and Werner (2010) designed ultrawideband antenna with genetic algorithms, and Chen et al. (2008) design the microstrip array antenna with parallel genetic algorithm.

A typical application is that an evolved antenna was designed for the NASA's Space Technology 5 (2006) spacecraft and has been applied flawlessly. The requirements of the ST5 antenna are listed in Table 1. Two antennas were designed for the ST5 spacecraft. One was designed by the hand of experts on antenna design in New Mexico State University. It is a QHA antenna shown in the left of the Figure 1. The current practice of designing and optimising antennas by hand is limited in its ability to develop new and better antenna designs because it requires significant domain expertise and is both time and labour intensive. With this approach, an antenna engineer will select a particular class of antennas where in the design of the ST5 antenna, a QHA antenna was chosen, and then spend weeks or months in testing and adjusting a design, mostly in simulation using electromagnetic modelling softwares. The other was evolved by computer scientists in Ames Research Center, NASA. It is a strange novel antenna shown in the right of the Figure 1. EA can be used to search the design space and automatically find novel antenna designs that are more effective than would otherwise be developed. Figure 2 and Figure 3 are the comparison plots of minimum and maximum gain at transmit and receive frequency for those two antennas. The QHA antenna designed by conventional method is rather difficult to meet the design requirements in Table 1 and barely able to use. Moreover, its need impedance matching and phase networks, see in Figure 4. The evolved antenna has novelty structure, wide frequency band, high efficiency, small volume, light weight, low cost, fast responses for new design requirements, easy to make, it does not need impedance matching and phase networks and so on. It had been applied successfully in 2006 and became the first evolved hardware in space. For the technical details of the evolved antenna for the ST5 missions see the first article in the first issue of *Evolution Computation* journal (Hornby et al., 2011).

Table 1 Antenna design specifications of NASA ST5 antenna

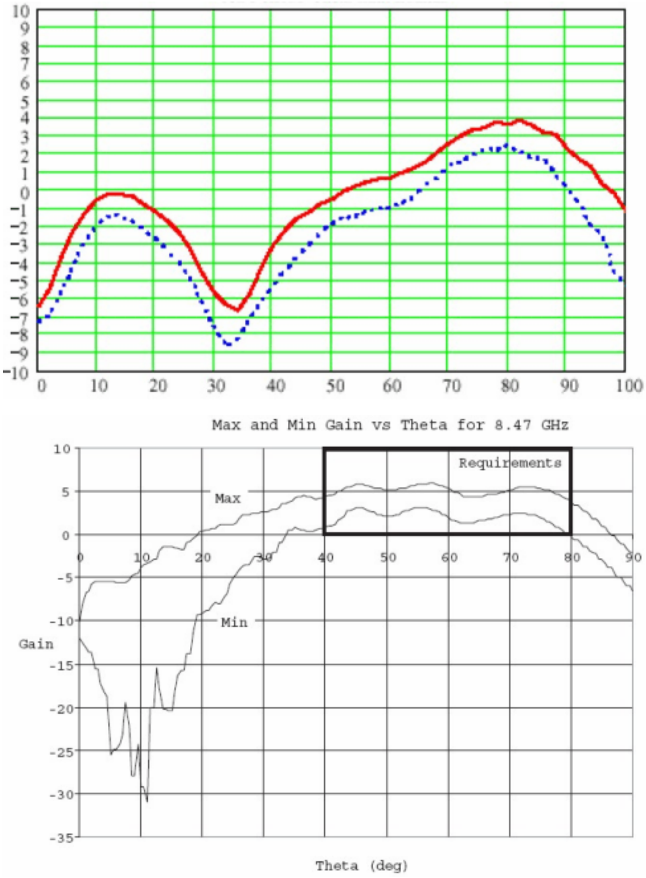
Property	*Specifications*
Transmit frequency	8,470 MHz
Receive frequency	7,209 MHz
Polarisation	Right-hand circular
VSWR	Transmit frequency: < 1.2 Receive frequency: < 1.5
Gain mode	≥ 0 dBic, $40° \leq \theta \leq 80°$ $0° \leq \phi \leq 360°$
Input impedance	50 Ω
Height	< 15.24 cm
Quality	< 165 g
Ground plane diameter	< 15.24 cm

Figure 1 The QHA antenna designed by conventional method and the evolved antenna (see online version for colours)



However, a challenge in evolving antenna is that the evaluation of the fitness of the antenna is usually time-consuming due to the time-consuming electromagnetic simulation. HFSS is a commercial finite element method solver with relatively high reliability but likely time-consuming simulation. And the code of HFSS is protected due to its commercial. Suppose HFSS and some other commercial simulation softwares were used by an EA algorithm in designing antenna, then months or even years time would be taken for finishing a run of the EA algorithm since a run usually requires many thousands of simulations and each simulation takes minutes or hours time. In this way, those commercial simulation softwares like HFSS are not practical for evolving antenna, although they are high reliable and very convenient for manual use. NEC solver runs fast in simulation and its source code is publicly available. Then, we usually use NEC to evaluate antenna in evolving antenna. However, the NEC solver is not so reliable in precise simulation, especially in simulating strange antennas where EA almost always produces strange antennas. In this way, the reliability of the NEC solver must be tested before being adopted to evaluate antenna in evolving antenna. It can be achieved by testing the simulation consistency between the HFSS solver and the NEC solver because the HFSS solver is high reliable. This paper focuses on the consistence test.

Figure 2 Maximum and minimum gain at transmit frequency: the left is of the QHA antenna, the right is of the evolved antenna (see online version for colours)



The remainder of this paper is organised as follows. Section 2 makes a programme for the consistence test. Experiments on the consistence test and result analysis are given in Section 3. An application of the reliability of the NEC solve in evolving ST5 antenna is presented in Section 4. The paper is concluded in Section 5.

Figure 3 Maximum and minimum gain at receive frequency: the left is of the QHA antenna, the right is of the evolved antenna (see online version for colours)

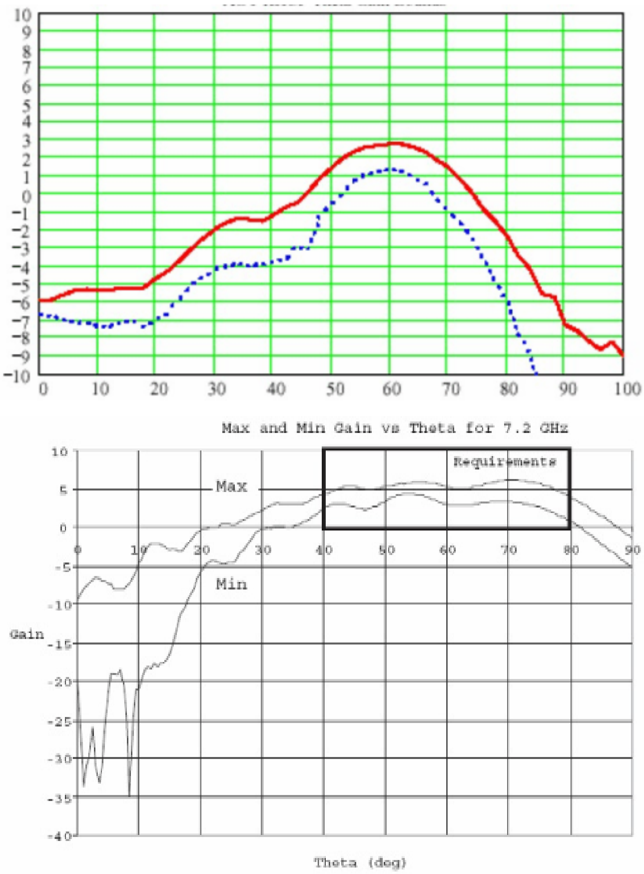
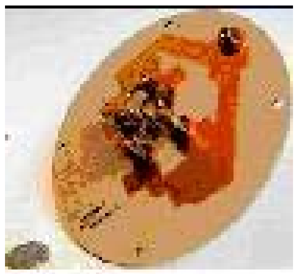


Figure 4 The circuit of impendence matching and phase networks for the QHA antenna (see online version for colours)



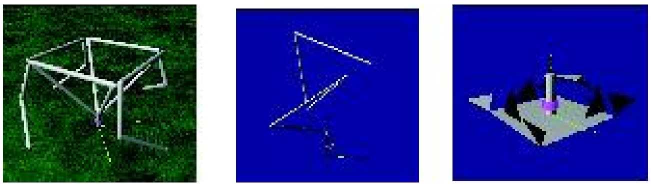
2 Programme for the consistence test

Simulation of the antennas with normal geometrical structures, such as monopole, yagi and so on, by NEC, are regarded reliable. This paper investigates the reliability of NEC in simulating strange antennas. Two kinds of strange antennas are considered: strange wire antennas and surface antennas. The reliability is verified by the consistence between HFSS and NEC in simulating the strange antennas. The consistence has been tested on lots of strange antennas over a wide region of frequency. However, only results of three antennas are shown in this paper due to the limited space. These three antennas are twisted four-arm wire antenna, twisted single-arm antenna and a surface antenna.

2.1 Geometrical structures of selected antennas

Three strange antennas are selected for the consistence test. The geometrical structures are in Figure 5. The left is a twisted four-arm wire antenna, the middle is a twisted single-arm antenna and the right is a surface antenna (the surface antenna is a square surface with many small triangular patches, and a wire connects vertically to the square at the centre for excitation).

Figure 5 Structures of antenna: the left is a twisted four-arm wire antenna, the middle a twisted single-arm antenna, the right a surface antenna (see online version for colours)



2.2 Parameter settings for the consistence test

Parameter settings for the consistence test are as follows:

1 Twisted four-arm wire antenna
- Frequency: 8.5 GHz
- Test angle: Theta: –90°~90°, Phi: 0°~360°
- Test goal: total gain, vertical gain, horizontal gain, VSWR (8.5 ± 0.5 GHz).

2 Twisted single-arm wire antenna
- Frequency: 2 GHz
- Test angle: Theta: –90°~90°, Phi: 0°~360°
- Test goal: total gain, vertical gain, horizontal gain, VSWR (2 ± 0.5 GHz).

3 Surface antenna
- Frequency: 8.5 GHz
- Test angle: Theta: 0°~180°, Phi: 0°~360°
- Test goal: total gain, vertical gain, horizontal gain, VSWR (8.5 ± 0.5 GHz).

2.3 Manners of showing the consistence test

The consistence of the electromagnetic simulation results between HFSS and NEC will be shown in two manners.

The first manner is a qualitative one by comparison of the graphs of the simulation results calculated by HFSS and NEC. The two results of one attribute of the antenna simulated separately by the two solvers will be plotted in a figure. If the graphs of the two results are very close to each other, then the simulations of HFSS and NEC are consistent in calculating this attribute.

The second manner is a quantitative one. The differences between the two results of one attribute of the antenna calculated by the two solvers will be calculated. Then the mean and the standard deviation (Std) of the differences are calculated. If the mean and the Std are very close to zero, then the simulations of HFSS and NEC are consistent in calculating this attribute.

For consistence test on the gain, we shall adopt the data directly in radiation energy ratio for all directions, not in decibel unit (dB) due to the dB unit greatly enlarging the abstract value of a very small ratio. Since the gain's unit is usually in dB unit while the consistence test requires data in energy ratio, then the unit needs to be converted from dB to radiation energy ratio. Let $P_A(\theta, \varphi)$ be the gain in energy ratio calculated by solver A and $G_A(\theta, \varphi)$ be the gain in dB unit. The conversion is equation (1):

$$P_A(\theta,\varphi) = 10^{\frac{G_A(\theta,\varphi)}{10}} \tag{1}$$

Denote $\xi_{P,A,B}$ and $\delta_{P,A,B}$ as the mean and the Std of the differences of the gains over all directions between solver A and solver B, then we have equation (2) and equation (3):

$$\xi_{P,A,B} = \frac{1}{180 \times 360} \sum_{\theta=1^\circ}^{180^\circ} \sum_{\varphi=1^\circ}^{360^\circ} \left| P_A(\theta,\varphi) - P_B(\theta,\varphi) \right| \tag{2}$$

$$\sigma_{P,A,B} = \sqrt{\frac{1}{180 \times 360} \sum_{\theta=1^\circ}^{180^\circ} \sum_{\varphi=1^\circ}^{360^\circ} \left(\left| P_A(\theta,\varphi) - P_B(\theta,\varphi) \right| - \xi_{P,A,B} \right)^2} \tag{3}$$

Given φ, denote $\xi_{P,\varphi,A,B}$ and $\delta_{P,\varphi,A,B}$ as the mean and the Std of the differences of the gains at φ over $0° \leq \theta \leq 180°$ between solver A and solver B, then we similarly have equation (3) and equation (4):

$$\xi_{P,\varphi,A,B} = \frac{1}{180} \sum_{\theta=0^\circ}^{180^\circ} \left| P_A(\theta,\varphi) - P_B(\theta,\varphi) \right| \tag{4}$$

$$\sigma_{P,\varphi,A,B} = \sqrt{\frac{1}{180} \sum_{\theta=1^\circ}^{180^\circ} \left(\left| P_A(\theta,\varphi) - P_B(\theta,\varphi) \right| - \xi_{\overline{P},A,B} \right)^2} \tag{5}$$

Denote $VSWR_A(f)$ as the VSWR at frequency f calculated by solver A, $VSWR_b(f)$ by solver B, we can similarly calculate the mean $\xi_{VSWR,A,B}$ and the Std $\delta_{VSWR,A,B}$ of the differences of the VSWRs over a region of frequency between solver A and solver B.

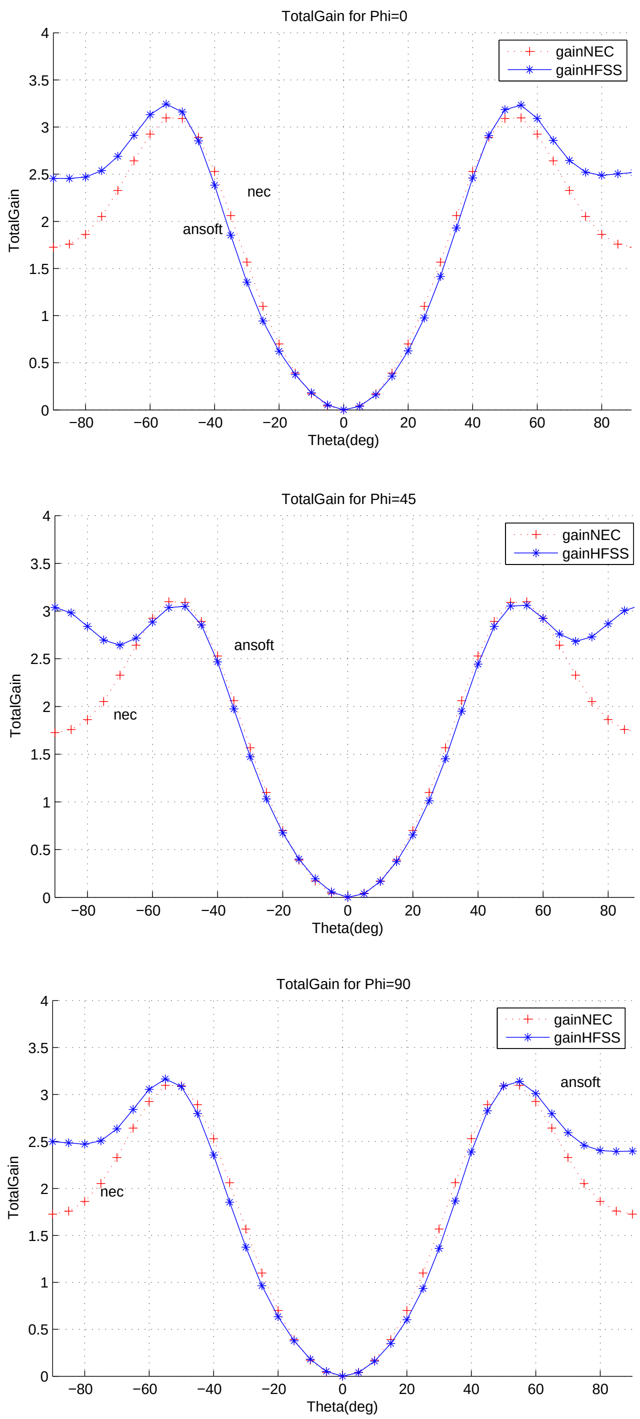
3 Experiments on the consistence test

3.1 Consistence on twisted four-arm wire antenna

In the qualitative manner, the gains over $-90° \leq \theta \leq 90°$ at $\varphi = 0°$, $\varphi = 45°$ and $\varphi = 90°$ at frequency = 8.5 GHz calculated by NEC and HFSS are plotted in figures. The total gains are shown in Figure 6, and the vertical gains are shown in Figure 7, the graph from NEC is very close to that from HFSS over almost all the region of θ except a relatively big distance near $\theta = \pm 90°$. And the horizontal gains are shown in Figure 8, the graph from NEC is very close to that from HFSS over all the region of θ. The VSWRs of the twisted four-arm wire antenna over the frequency from 8,000 MHz to 9,000 MHz are calculated by

NEC and HFSS, and the graphs are shown in Figure 9. The graph of the VSWRs from NEC is close to that from HFSS over the frequency region.

Figure 6 The comparison plots of total gain of twisted four-arm wire antenna at frequency = 8.5 GHz of NEC and HFSS at $\varphi = 0°$, $\varphi = 45°$ and $\varphi = 90°$ (see online version for colours)



In the quantitative manner, the differences of both the gains from NEC and the gains from HFSS over $-90° \leq \theta \leq 90°$ are calculated, and the difference of the VSWRs is calculated as well. Then the mean and the Std of the differences are calculated and listed in Table 2. The data in the Table 2 show that the values of the means of the gains are less than 0.5, and the Std values of the gains stay at about 0.1, and for the VSWR values, the mean value is less than 0.3 and the Std value is less than 0.1.

Figure 7 The comparison plots of vertical gain of twisted four-arm wire antenna at frequency = 8.5 GHz of NEC and HFSS at $\varphi = 0°$, $\varphi = 45°$ and $\varphi = 90°$ (see online version for colours)

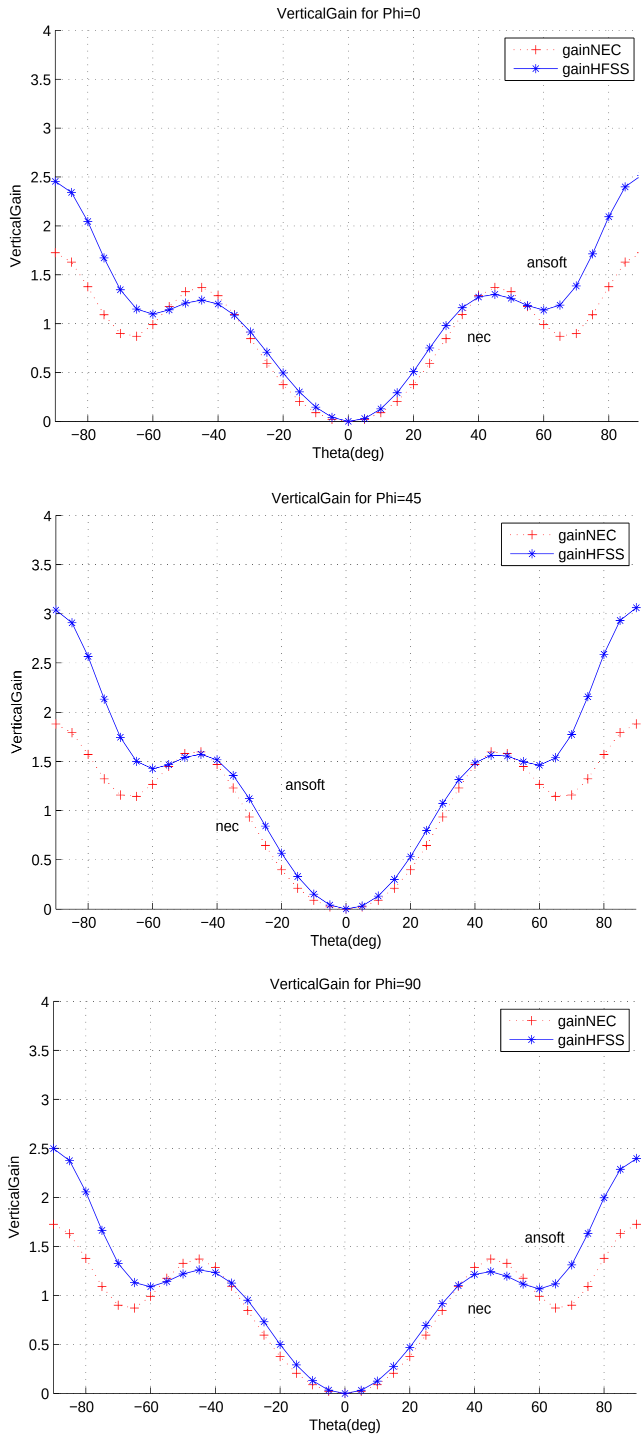


Figure 8 The comparison plots of horizontal gain of twisted four-arm wire antenna at frequency = 8.5 GHz of NEC and HFSS at $\varphi = 0°$, $\varphi = 45°$ and $\varphi = 90°$ (see online version for colours)

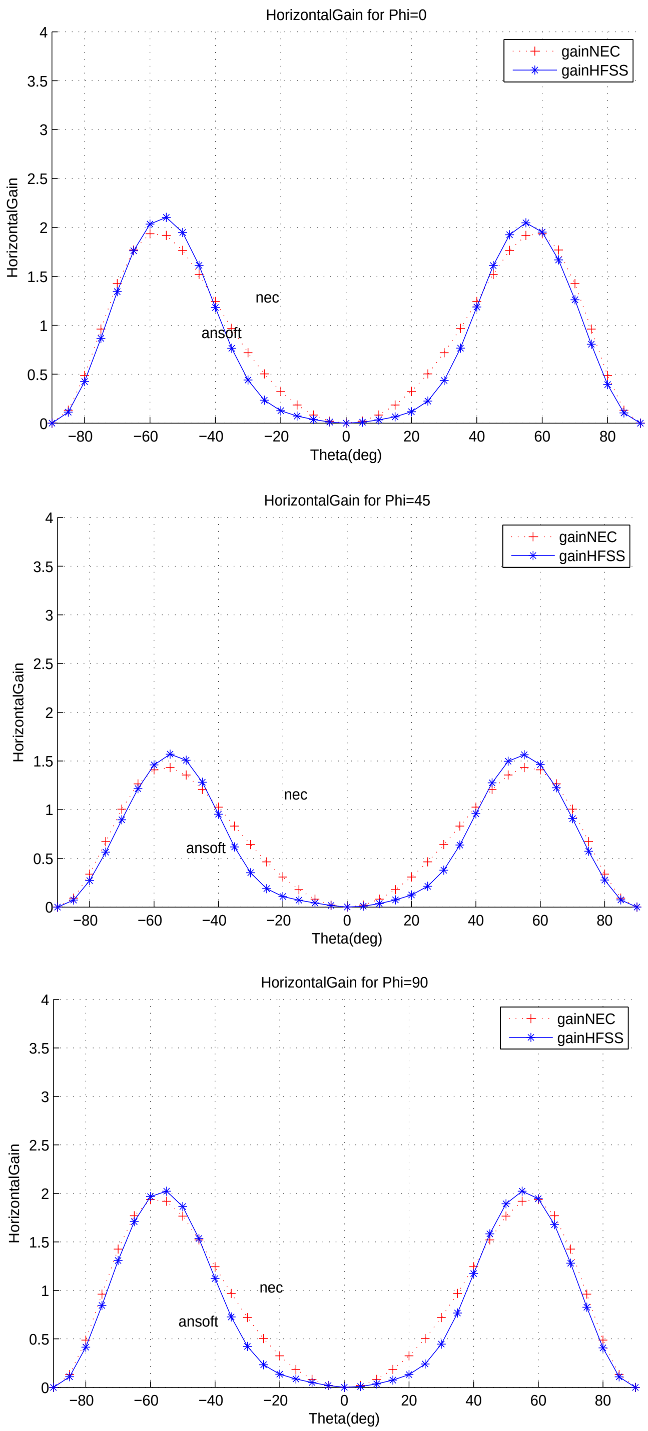
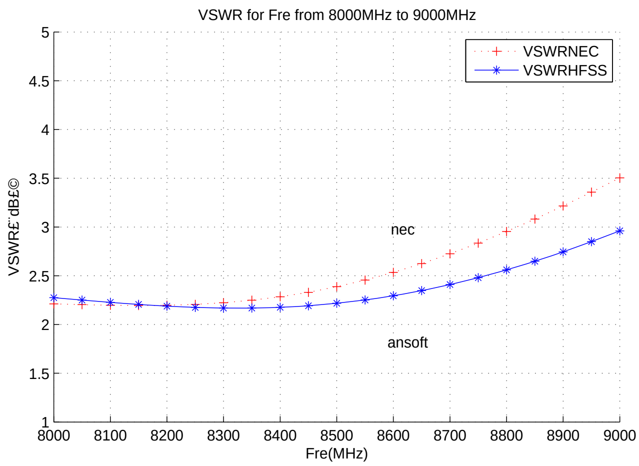


Table 2 The means and the Stds of differences of the results of NEC and HFSS in simulating twisted four-arm wire antenna

		Mean	*Std*	*Time*
TOT	$\Phi = 0°$	0.2331	0.0565	NEC: 0.75 s
	$\Phi = 45°$	0.2822	0.1829	
	$\Phi = 90°$	0.2134	0.0506	
VER	$\Phi = 0°$	0.2434	0.0693	
	$\Phi = 45°$	0.3331	0.1582	
	$\Phi = 90$	0.2265	0.0607	
HOR	$\Phi = 0°$	0.1123	0.0074	HFSS: 2,189 s
	$\Phi = 45°$	0.1028	0.0067	
	$\Phi = 90°$	0.104	0.0073	
	$\Phi = 90$	0.0919	0.0048	
VSWR		0.2133	0.0305	

Figure 9 The comparison plot of VSWRs of twisted four-arm wire antenna over frequency from 8,000 MHz to 9,000 MHz (see online version for colours)



3.2 *Consistence on twisted single-arm wire antenna*

In the qualitative manner, the gains over $-90° \le \theta \le 90°$ at $\varphi = 0°$, $\varphi = 45°$ and $\varphi = 90°$ at frequency = 2 GHz calculated by NEC and HFSS are plotted in figures. The total gains are shown in Figure 10, the graph from NEC is very close to that from HFSS over the region of θ. The vertical gains are shown in Figure 11, and the horizontal gains are shown in Figure 12, the graphs from NEC are very close to those from HFSS over the region of θ. The VSWRs of the twisted four-arm wire antenna over the frequency from 1,500 MHz to 2,500 MHz are calculated by NEC and HFSS, and the graphs are shown in Figure 13. The graph of the VSWRs from NEC is close to that from HFSS over the frequency region.

Figure 10 The comparison plots of total gain of twisted single-arm wire antenna at frequency = 2 GHz of NEC and HFSS at $\varphi = 0°$, $\varphi = 45°$ and $\varphi = 90°$ (see online version for colours)

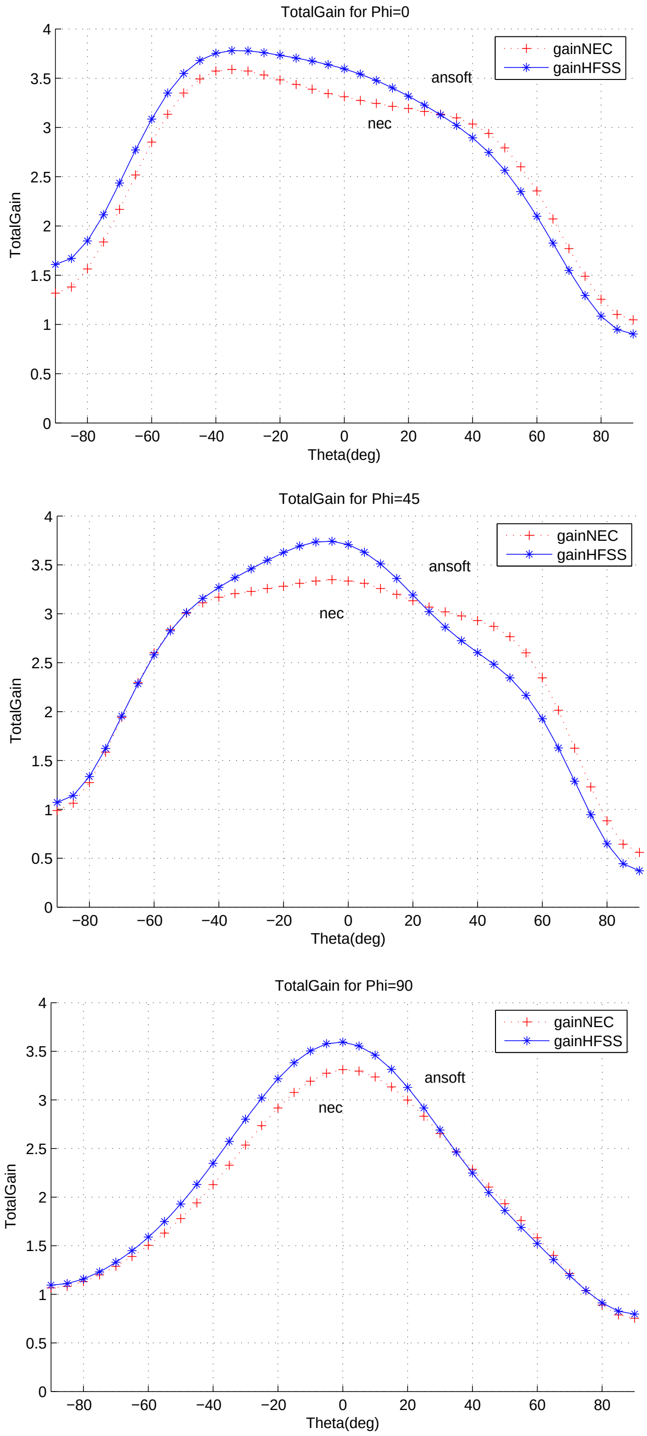


Figure 11 The comparison plots of vertical gain of twisted single-arm wire antenna at frequency = 2 GHz of NEC and HFSS at $\varphi = 0°$, $\varphi = 45°$ and $\varphi = 90°$ (see online version for colours)

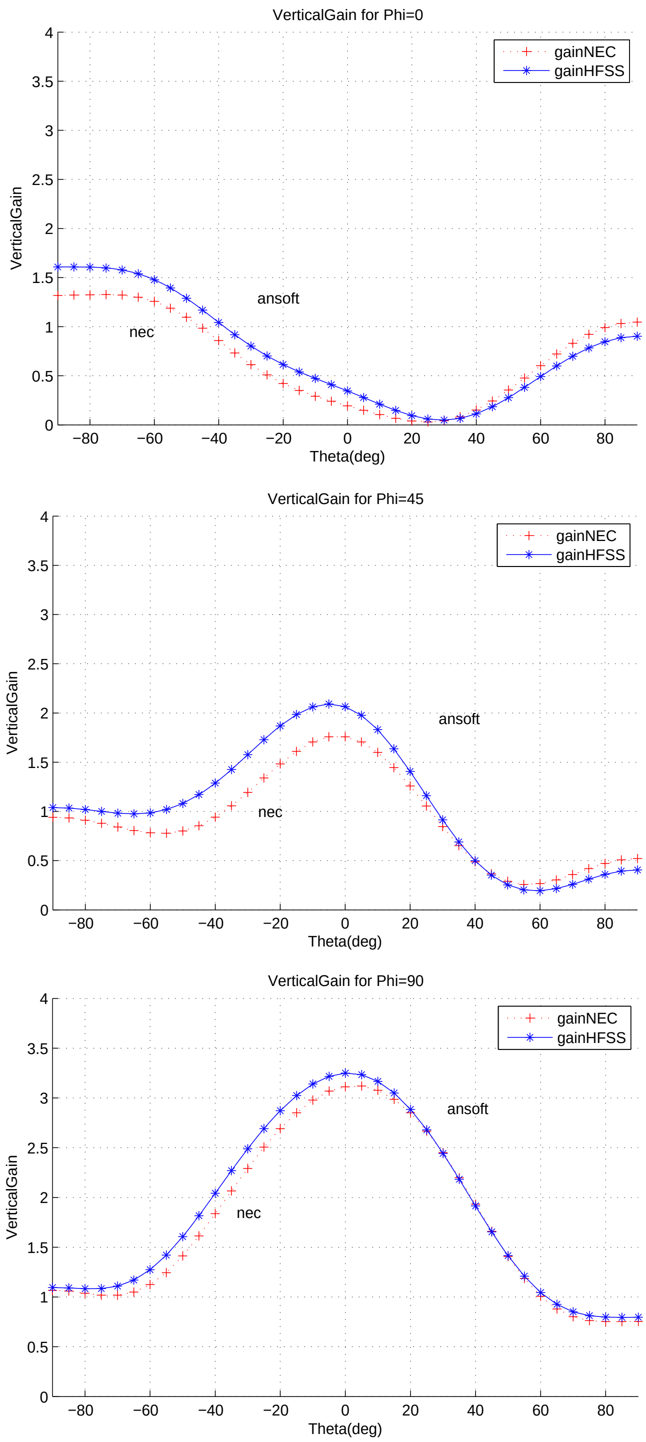
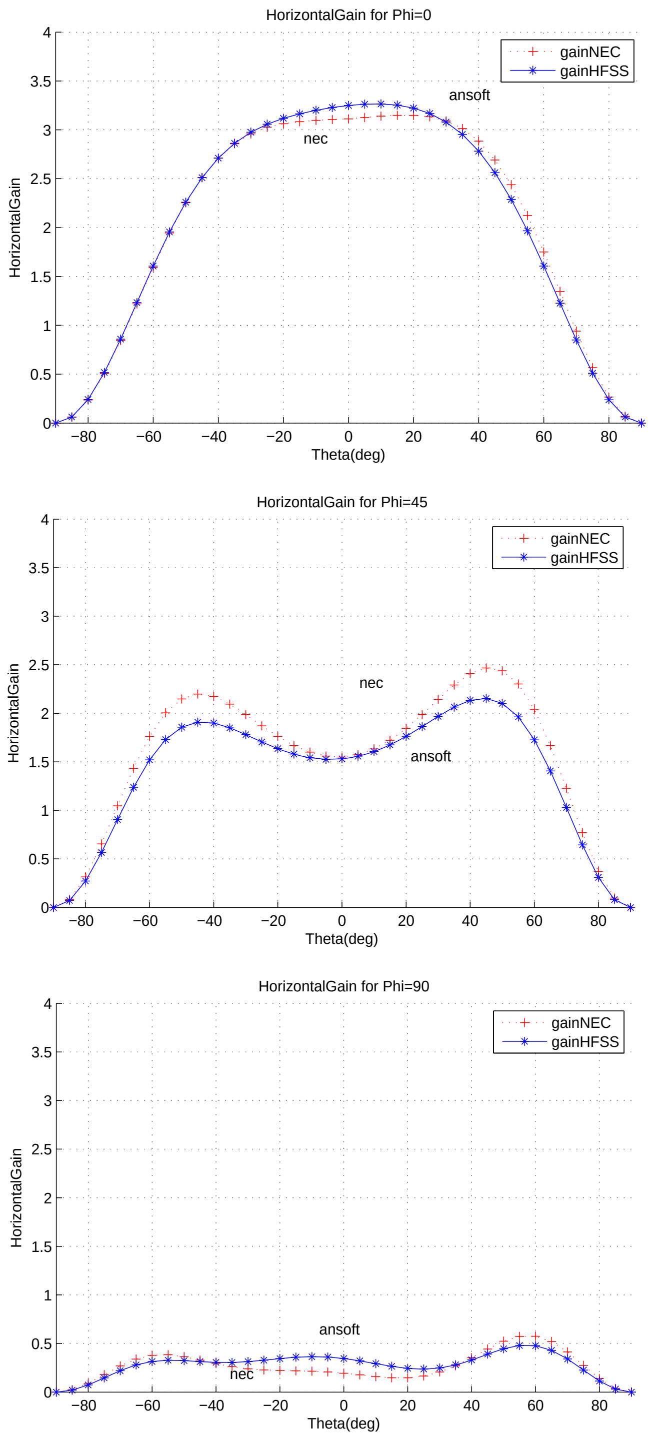


Figure 12 The comparison plots of horizontal gain of twisted single-arm wire antenna at frequency = 2 GHz of NEC and HFSS at $\varphi = 0°$, $\varphi = 45°$ and $\varphi = 90°$ (see online version for colours)



In the quantitative manner, the differences of both the gains from NEC and the gains from HFSS over $-90° \le \theta \le 90°$ are calculated, and the difference of the VSWRs is calculated as well. Then the mean and the Std of the differences are calculated and listed in Table 3. The data in Table 3 show that the values of the means of the gains are less than 0.5, and the Std values of the gains stay at about 0.1, and the mean and the Std of the VSWRs are about 0.5.

Figure 13 The comparison plot of VSWRs of twisted single-arm wire antenna over frequency from 1,500 MHz to 2,500 MHz (see online version for colours)

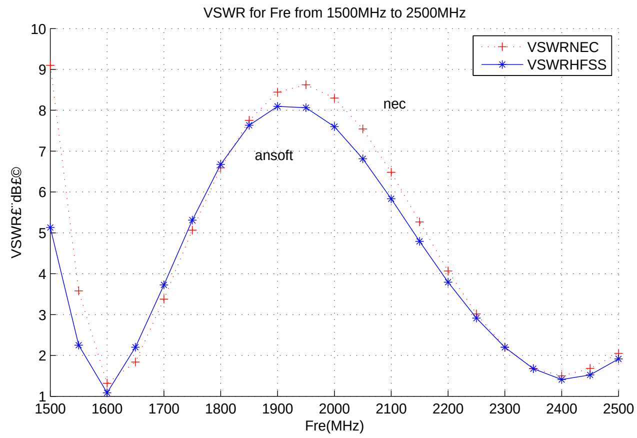


Table 3 The means and the Stds of differences of the results of NEC and HFSS in simulating twisted single-arm wire antenna

		Mean	*Std*	*Time*
TOT	$\Phi = 0°$	0.212	0.0045	NEC: 0.11 s
	$\Phi = 45°$	0.2139	0.021	
	$\Phi = 90°$	0.126	0.112	
VER	$\Phi = 0°$	0.154	0.0057	
	$\Phi = 45$	0.1863	0.146	
HOR	$\Phi = 0°$	0.06	0.0029	HFSS: 3,038 s
	$\Phi = 45°$	0.1545	0.122	
	$\Phi = 90$	0.0671	0.0021	
VSWR		0.5534	0.6468	

3.3 Consistence on surface antenna

In the qualitative manner, the gains over $0° \le \theta \le 180°$ at $\varphi = 0°$, $\varphi = 45°$ and $\varphi = 90°$ at frequency = 8.5 GHz calculated by NEC and HFSS are plotted in figures. The total gains are shown in Figure 14, the graph from NEC is very close to that from HFSS over the region of θ. The vertical gains are shown in Figure 15, and the horizontal gains are shown in Figure 16, the graphs from NEC are very close to those from HFSS over the region of θ. The VSWRs of the twisted four-arm wire antenna over the frequency from 8,000 MHz to 9,000 MHz are calculated by NEC and HFSS, and the graphs are shown in Figure 17. However, the difference of the VSWRs between NEC and HFSS is very large over the frequency region.

In the quantitative manner, the differences of both the gains from NEC and the gains from HFSS over $0° \le \theta \le 180°$ are calculated, and the difference of the VSWRs is calculated as well. Then the mean and the Std of the differences are calculated and listed in Table 4. The data in the Table 4 show that the values of the means of the gains are about 0.1, and the Std values of the gains stay at about 0.01, however, the difference on VSWR is much big.

Figure 14 The comparison charts of total gain of surface antenna at frequency = 8.5 GHz of NEC and HFSS at $\varphi = 0°$, $\varphi = 45°$ and $\varphi = 90°$ (see online version for colours)

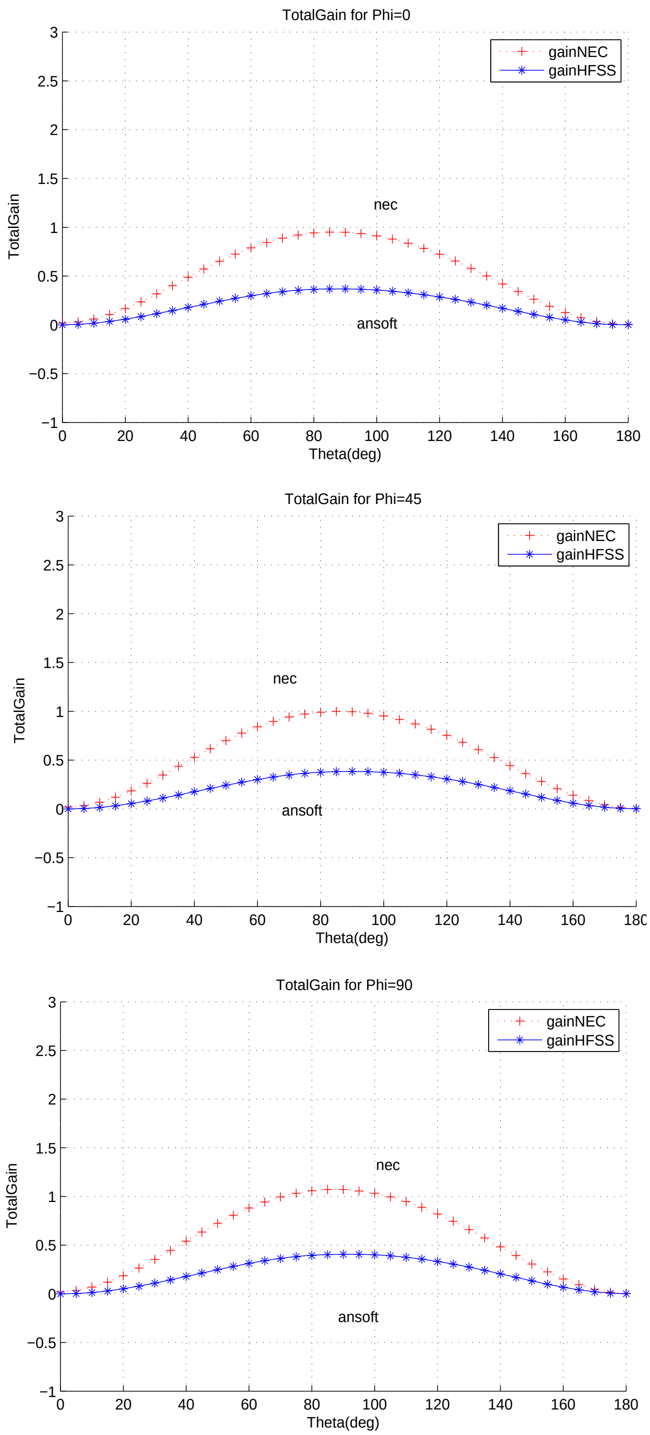


Figure 15 The comparison charts of vertical gain of surface antenna at frequency = 8.5 GHz of NEC and HFSS at $\varphi = 0°$, $\varphi = 45°$ and $\varphi = 90°$ (see online version for colours)

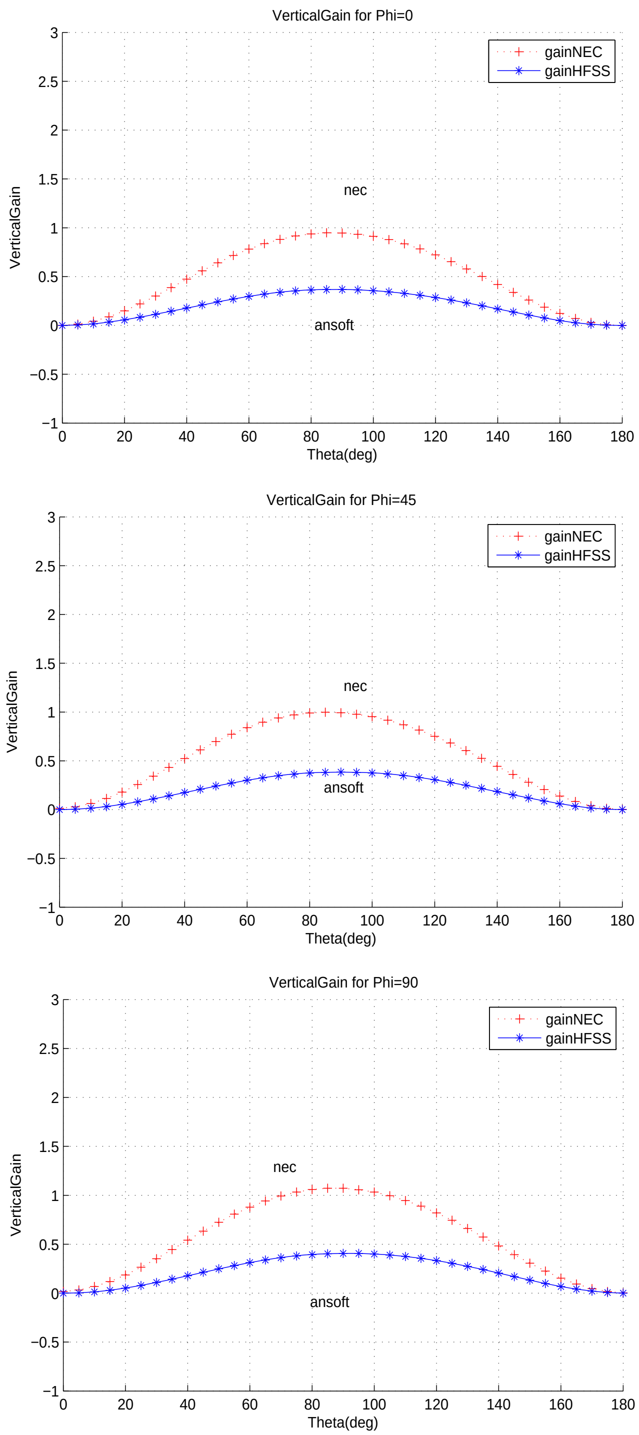
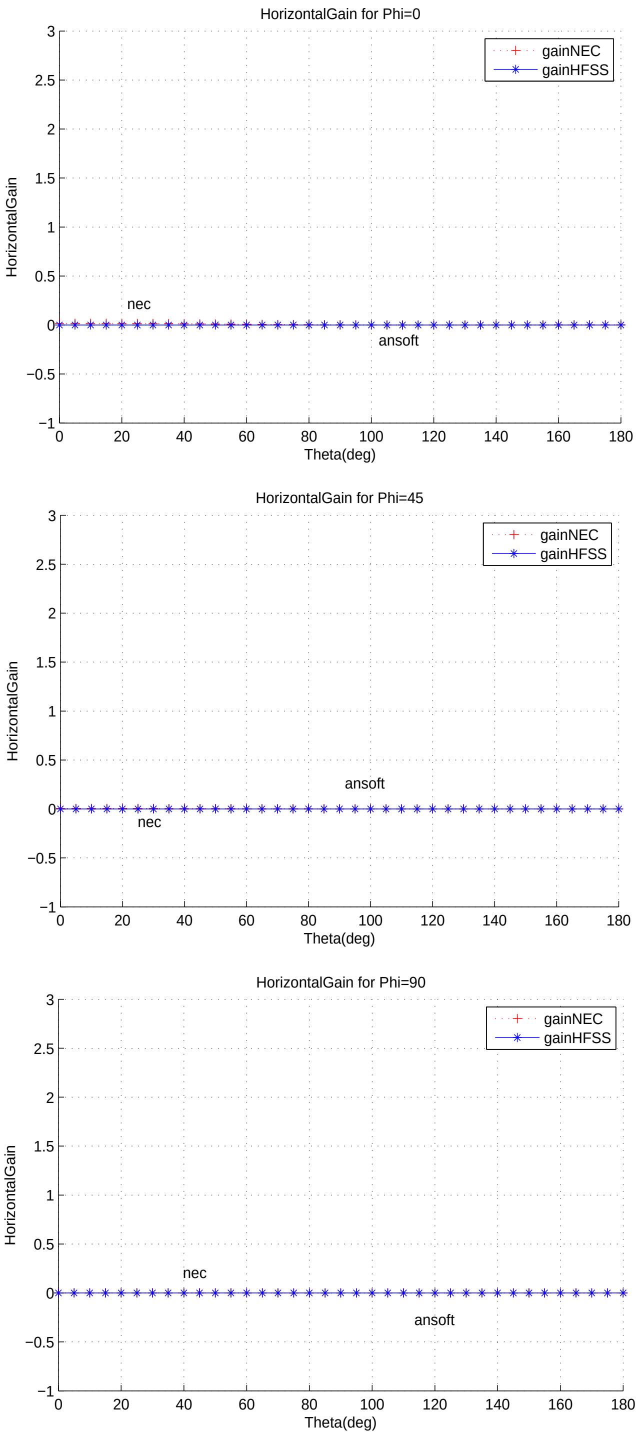


Figure 16 The comparison charts of horizontal gain of surface antenna at frequency = 8.5 GHz of NEC and HFSS at $\varphi = 0°$, $\varphi = 45°$ and $\varphi = 90°$ (see online version for colours)



3.4 *Summary of the consistency test*

From above experiments and the analysis of the experimental results, the gains and the VSWRs of the NEC solver are close to those of the HFSS solver in simulating the twisted wire antenna. Then we summarise that the NEC solver and the HFSS solver are consistent in calculating twisted wire antennas. Therefore, the NEC solver is reliable in simulating twisted wire antennas.

Figure 17 The VSWR's comparison figure of surface antenna with NEC and HFSS (see online version for colours)

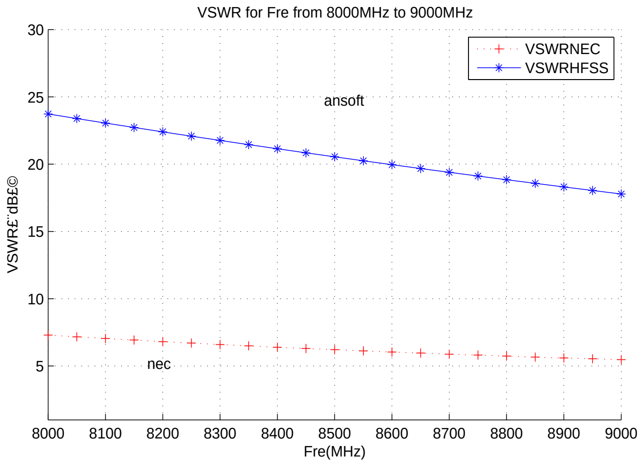


Table 4 The means and the Stds of differences of the results of NEC and HFSS in simulating surface antenna.

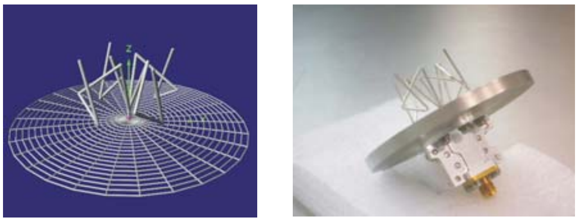
		Mean	*Std*	*Time*
TOT	Φ = 0°	0.3037	0.0424	NEC: 0.078 s
	Φ = 45°	0.3265	0.047	
	Φ = 90°	0.3492	0.0551	
VER	Φ = 0°	0.2988	0.0434	
	Φ = 45°	0.3247	0.0472	
	Φ = 90	0.3490	0.00551	
HOR	Φ = 0°	0.006	0.0029	HFSS: 29 s
	Φ = 45°	0.0018	0.122	
	Φ = 90°	2.973E-04	5.1614E-08	
VSWR		14.3461	1.5608	

But, the VSWRs of the NEC solver are much different from those of the HFSS solver in simulating the surface antenna, although the gains are close to each other. We then summarise that the NEC solver and the HFSS solver are inconsistent in calculating surface antennas. Therefore, the NEC solver is unreliable in simulating surface antenna.

4 Application of reliability of NEC

Based on the above consistence test, we are assured that the NEC solver is reliable in simulating twisted wire antenna. Then in the case of evolving ST5 antenna, we specified the class of twisted four-arm wire antennas as geometrical structure, and the NEC solver was adopted to evaluate the fitness of the antenna in the population of the EA. The evolved antenna is plotted in the left of Figure 18. The RHCP gains of the evolved antenna at two frequencies are shown in Figure 19 and Figure 20, and the VSWRs of the evolved antenna over frequency from 7 GHz to 9 GHz are shown in Figure 21. Those three, Figures 19, 20 and 21, show that the evolved antenna meets NASA ST5 antenna's design requirements (see in Table 1). The photograph of the prototype of the evolved antenna is shown in the right of Figure 18.

Figure 18 Evolved ST5 antenna: (a) geometry structure by NEC, (b) photograph of prototype of the evolved antenna (see online version for colours)



(a) (b)

Figure 19 RHCP gain of evolved ST5 antenna at frequency = 7,209 MHz (see online version for colours)

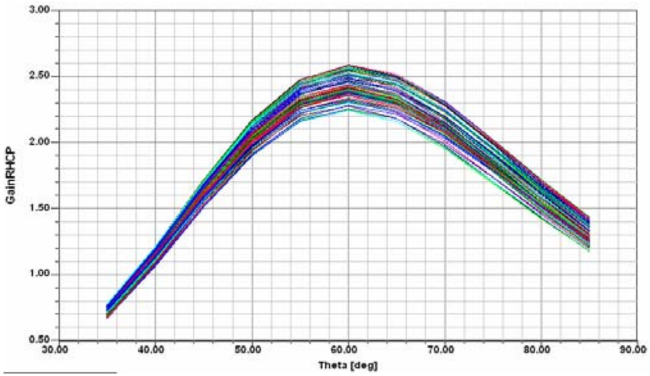


Figure 20 RHCP gain of evolved ST5 antenna at frequency = 8,470 MHz (see online version for colours)

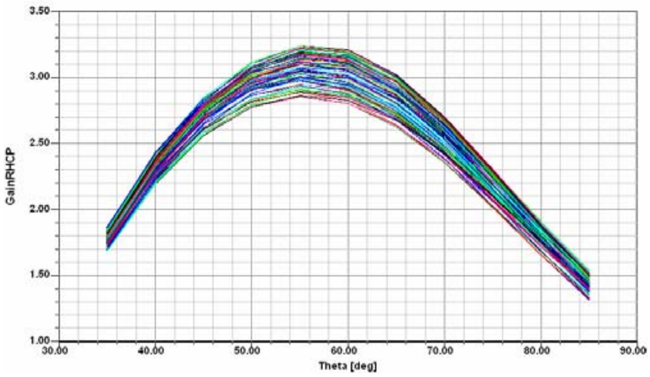
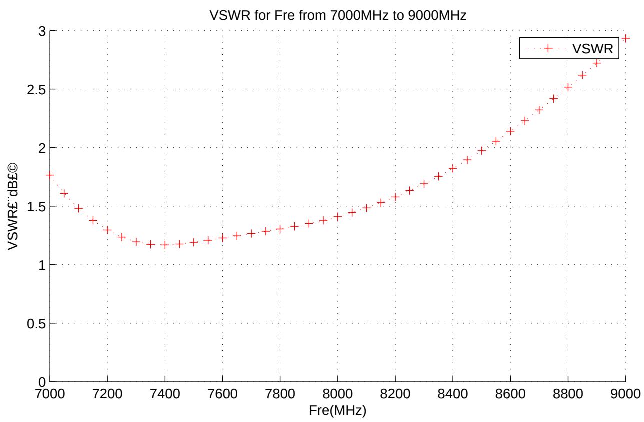


Figure 21 Graph of VSWRs of the evolved antenna over frequency from 7 GHz to 9 GHz (see online version for colours)



5 Conclusions

A challenge in evolving antenna is that the evaluation of antenna fitness is usually time-consuming due to the time-consuming electromagnetic simulations. NEC is a fast solver and the code is publicly available, then it is usually used to evaluate antenna in evolving antenna for handling the challenge. However, it needs full reliability test, especially in testing simulation of strange antenna. This paper focuses on testing the reliability of NEC in simulating strange antenna, and this is achieved by simulation consistency between NEC and HFSS since HFSS is a commercial finite element method solver with high reliability.

From the experiments and the analysis of the experimental results, we found that the gains and the VSWRs of the NEC solver are close to those of the HFSS solver in simulating the twisted wire antennas, then we summarise that the NEC solver and the HFSS solver are consistent in calculating twisted wire antennas. Therefore, the NEC solver is reliable in simulating twisted wire antennas. But, the VSWRs of the NEC solver are much different from those of the HFSS solver in simulating surface antenna, then we summarise that the NEC solver and the HFSS solver are inconsistent in calculating surface antennas. Therefore, the NEC solver is unreliable in simulating surface antennas.

Based on the reliability of the NEC solve in simulating twisted wire antenna, we then are assured that NEC solver can be adopted to evolve ST5 antenna where the geometrical structure of the antennas is specified as twisted four-arm wire antennas. An antenna was evolved and it meets NASA ST5 antenna's design requirements.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Nos.: 60871021, 60473037).

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