

An Inductor Model for Analyzing the Performance of Printed Meander Line Antennas in Smart Structures

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Abstract

Meander line antenna has been considered desirable on flight vehicles to reduce drag and minimize aerodynamic disturbance; however, the antenna design and performance analysis have made mostly by trial-and-error. An inductor model by simulating the meander line sections as electrical inductors and the interconnecting radiation elements as a quasi-monopole antenna is developed to analyze the antenna performance. Experimental verifications of the printed meander line antennas embedded in composite laminated substrates show that the inductor model is effective to design and analyze. Of the 4 antennas tested, the discrepancy of resonant frequency in simulation and experiment is within 4.6%.

Keywords

Inductor Model, Meander Line Antenna, Smart Structure

1. Introduction

Composite laminated substrates embedding fiber optic sensor [1], piezoelectric sensor/actuator [2] [3], and smart layer module [4] have demonstrated the capabilities to measure and respond to operating conditions. Smart structure embedding low-profile antenna has also been proposed, where conformal Load-bearing Antenna Structures (CLAS) are desirable over conventional dipole or monopole antenna. The performance of a rectangular microstrip antenna embedded in composite laminated is found to be dependent upon the substrate's electromagnetic properties [5]; however, design and analysis of meander line antenna have mostly assumed that the substrate is isotropic [6] [7]. The concept of smart skin by embedding microstrip antenna in composite structures was often based on uniform, isotropic substrate properties [8] [12].

Design of meander line antenna is mainly by folding a monopole or dipole antenna into a zigzag pattern. Nakano *et al.* [13] investigated the shortening ratio, radiation pattern and input impedance of meander line antennas. Warnagiris and Minardo [14] improved the antenna performance by switching the phase of a meander line. The above works assumed that the antennas are installed in free space. In many applications, however, the antennas have to be integrated with the feed lines on the same substrate. Suh and Chang [15] and Tong *et al.* [16] found that the size of a dipole antenna on a dielectric substrate was reduced as compared to that in free space. A recent study showed that performance of meander line antenna is also influenced by the substrate properties [17]. Computation methods have been proposed to simulate meander line antenna applications [18]-[20]. Design and analysis of printed meander line antennas by trial-and-error are tedious, if not fruitless. An effective model to analyze the antenna performance is necessary.

2. An Inductor Model of Meander Line Antenna

A monopole or dipole antenna can be implemented by meander line antenna integrated on flexible printed circuit substrate. Figure 1(a) shows the configuration of a meander line antenna of size $L_1 \times W$ with line width D printed on the substrate layer of thickness h and dielectric constant \mathcal{E}_r . The electrical signals are fed by a microstrip line of length L_2 and width w. The effect of the meander line sections is similar to a load, and they are considered as shorted-terminated transmission lines as shown in Figure 1(b). Each section can be modeled by an equivalent electrical inductor with inductance calculated by the geometrical parameters: the pitch of the meander line sections A, width W, and line width w. The radiation pattern is determined by the current distribution on the meander line. The current in the x-axis constructively contribute to the field in the E-plane, but that in the y-axis direction cancels out in the E-plane. Thus, the radiation field of a meander line antenna will



Figure 1. (a) Configuration of a printed meander line antenna; (b) the inductor model of a meander line section; and (c) the radiation parts of a modeled line antenna modeled by a quasi-monopole antenna.

be only from the parts along x-axis constituting an equivalent quasi-monopole antenna with radiation characteristics similar to a monopole antenna as shown in Figure 1(c).

The inductance of each meander line section (L_{in}) is determined by the transmission line model; *i.e.*, a printed meander line section is similar to a pair of coplanar strips of equal width D at distance A on a dielectric substrate as shown in Figure 2(a). Because of the complementary nature, the effective dielectric constant can be calculated by the conformal mapping method,

$$\varepsilon_{\rm re} = 1 + \frac{\varepsilon_r - 1}{2} \cdot \frac{G(g_2)}{G'(g_2)} \cdot \frac{G'(g_1)}{G(g_1)} \tag{1}$$

where $g_1 = A/(2D + A)$ and $g_2 = \sinh(\pi A/4h)/\sinh(\pi(2D + A)/4h)$. $G(\cdot)$ and $G'(\cdot)$ are the complete el-



Figure 2. (a) A printed meander line section simulated by a pair of coplanar strips and its impedance as a function of pitch A when D = 2 mm, h = 1.6 mm and $\varepsilon_r = 4.4$, and (b) illustration of the radiation reactance of a monopole approximated by a linear function when $\lambda/3 \le L_1 \le \lambda/2$.

liptic integrals of the first kind and its complement, $G(g) = \int_{0}^{1} dt / ((1 - g^2 t^2)(1 - t^2))^{\frac{1}{2}}$ and G'(g) = G(g')

with $g' = \sqrt{1 - g^2}$. The impedance of a pair of coplanar strips can be then derived as

$$Z_{o} = \frac{120\pi}{\sqrt{\varepsilon_{re}}} \cdot \frac{\pi}{\ln\left(2\left(1+\sqrt{g'}\right)/\left(1-\sqrt{g'}\right)\right)} \quad \text{for } 0 \le g \le 1/\sqrt{2}$$

$$\tag{2}$$

$$Z_{o} = \frac{120\pi}{\sqrt{\varepsilon_{\rm re}}} \cdot \frac{1}{\pi} \cdot \ln\left(2\left(1+\sqrt{g}\right)/\left(1-\sqrt{g}\right)\right) \text{ for } 1/\sqrt{2} \le g \le 1$$
(3)

For the given line width D = 2 mm, Figure 2(a) also illustrates that the impedance of a meander line section on the substrate (h = 1.6 mm and $\varepsilon_r = 4.4 \text{ mm}$) is dependent upon the pitch A. One can calculate the impedance of a meander line section on a substrate by

$$Z_{\rm in} = j Z_o \tan(kW) \tag{4}$$

where $k = k_o \sqrt{\varepsilon_{re}}$, k_o is the wave number in free space. The equivalent inductance L_{in} of each meander section is

$$L_{\rm in} = \frac{1}{\omega} Z_o \tan\left(kW\right) \tag{5}$$

and ω is the operating frequency. For an antenna with *M* meander line sections, the total inductance is $M \cdot L_{in}$.

It has been known that any attempt to reduce the size of a monopole while preserving the same natural frequency leads to bandwidth deterioration, pattern distortion, and gain reduction. Thus an antenna's dimension must be on the same order as the wavelength to radiate at maximum efficiency. Given a quasi-monopole antenna of reduced length L_1 as shown in **Figure 1(c)**, its reactance may be similar to that of a monopole antenna and can be obtained by the induced electromagnetic field,

$$X = \frac{\eta}{4\pi} \Big\{ 2S(kL_1) + \cos(kL_1) \Big[2S(kL_1) - S(2kL_1) \Big] - \sin(kL_1) \Big[2C(kL_1) - C(2kL_1) - C(2ka^2/L_1) \Big] \Big\}$$
(6)

where $\eta = \sqrt{\mu/\varepsilon}$ is an intrinsic impedance, μ is permeability, ε is permittivity, $C(kL_1)$ and $S(kL_1)$ are the cosine and sine integrals, $C(kL_1) \equiv \int_{\infty}^{kL_1} \frac{\cos y}{y} dy$ and $S(kL_1) = \int_{0}^{kL_1} \frac{\sin y}{y} dy$, and a is the equivalent

radius of the antenna. Figure 2(b) illustrates that the radiation reactance is negative if the antenna length $L_1 \leq \lambda/2$, and it will decrease further as L_1 becomes smaller, hence reducing the antenna efficiency. At $\lambda/3 \leq L_1 \lambda/2$, the reactance can be approximated by a linear function. The meander line sections with positive inductance are therefore required to compensate the printed meander line antenna by

$$X + MZ_o \tan(kW) = 0 \tag{7}$$

where X is the radiation reactance of a quasi-monopole antenna and M is the number of meander line sections of the antenna. In antenna design within a given area, L_1 is first defined and the radiation reactance of the quasi-monopole antenna is calculated by Equation (6), then the number (M) and geometry (A and W) of the meander line section can determined by the inductor model in Equation (5).

3. Antenna Design and Experiment

Consider a printed meander line antenna operating at 900 MHz on a substrate $\varepsilon_r = 4.4$. For D = 2 mm, A = 5 mm, and W = 20 mm, the impedance of the meander line section from Equation (5) is $L_{\text{in}} = 130.8 \Omega$. Two meander line sections (M = 2) are to compensate the radiation reactance of the quasi-monopole antenna, and the antenna of length 54 mm with $X = -261.6 \Omega$ can be predicted by the interpolation in Figure 2(b). Table 1 lists six printed meander line antennas operating at the same frequency. For an antenna of length $L_1 = 54 \text{ mm}$, one can have 2 meander line sections of $20 \times 5 \text{ mm} (W \times A)$ or 3 meander line sections of

 16×3 mm as shown in Figure 3(a) and Figure 3(b). Both achieve the same operating frequency. Similarly for the antenna of length $L_1 = 63$ mm, there are two designs for the same frequency: 3 meander line sections at 16×1 mm or 2 at 17.5×2 mm. For the meander line antenna of length $L_1 = 70$ mm, either 2 meander line sections at 13.5×3 mm or 1 at 20×7 mm is capable to operate at 900 MHz. These analyses validate the inductor model in predicting the inductance of the meander line sections and in approximating the reactance of the quasi-monopole. The radiation pattern of a meander line antenna is similar to that of a monopole antenna as illustrated in Figure 3(c).

The meander line antenna aims at reducing the physical dimension while maintaining the required electrical length. However, because of the corner effects between the adjacent meander line sections, the antenna length will be higher than $\lambda/4$ of monopole. The effects of the number of the meander line sections are illustrated as follows. Consider a printed monopole antenna of length 89.5 mm at 900 MHz. Multiple meander line sections with A = 5 mm at different W and M are added to the monopole while keeping the total length constant. By using the inductor model, the inductance of the meander line sections can be calculated, and the resonant frequency is shown to decrease with increasing A and W as listed in **Table 2**. The reactance of the quasi-monopole and the resonant frequency are plotted in **Figure 4**, where they are shown within acceptable accuracy as predicted by the inductor model. These results indicate that if the geometry limit of a meander line antenna is known, then the antenna length and reactance can be calculated and the meander line section can be determined.

4. Experimental Verification

Smart structures integrating sensor/actuator offer many potential advantages in vibration control and structural health monitoring. A smart layer module utilizing flexible printed circuit process to encapsulate sensor/actuator and electrical circuit in polyimide layers has been recently developed [4], and an antenna embedded in composite laminated substrate has been shown to achieve better performance oven that attached on an isotropic sub-

Quasi-monopole			Antonno				
<i>L</i> ₁ (mm)	Radiation reactance $X (\Omega)$	Antenna width W (mm)	Section space <i>A</i> (mm)	Input reactance $L_{\rm in}$ (Ω)	Number of meander line section M	Total input reactance (Ω)	resonant frequency (MHz)
54	-261.6	16	5	130.8	2	261.6	900
54	-261.6	16	3	87.4	3	262.2	910
63	-194	16	1	64.4	3	193.2	890
63	-194	17.5	3	96.9	2	193.8	905
70	-142.9	13.5	3	72.3	2	144.6	905
70	-142.9	20	7	143.1	1	143.1	905

Table 1. The dimension of a printed meander line antenna operating at 900 MHz.

Table 2. The resonant frequency (MHz) of a meander line antenna as function of the number of meander line sections M and width W (mm) at pitch A = 5 mm.

Width (W)	Quantity (M)					
width (<i>w</i>)	1	2	3	4		
12	825	792	762	734		
14	809	767	732	698		
16	796	748	708	666		
18	786	736	684	634		
20	780	716	656	610		
20 (experimental result)	797	734	701	623		



Figure 3. Configuration of the printed antennas operating at 900 MHz, (a) $L_1 = 54 \text{ mm}$, $M = 2 \quad W \times A = 20 \times 5 \text{ mm}$ and (b) $L_1 = 54 \text{ mm}$, M = 3, $W \times A = 16 \times 3 \text{ mm}$ and (c) the antenna pattern of a meander line antenna similar to that a monopole antenna.



Figure 4. The reactance of a quasi-monopole due to length reduction can be compensated by the meander line sections with A = 5 mm at different W and number of section M.

strate [5]. By the smart layer concept, the printed meander line antennas (W = 20 mm, A = 5 mm, and D = 2 mm) are embedded inside the [45/-45/45/-45/45] symmetric substrate of thickness h = 2.0 mm to verify the inductor model.

The substrate is composed of woven fiber glass prepreg tapes with Young's modulus 36 GPa, shear modulus 5.7 GPa, Poisson ration 0.24, and average density 1681 Kg/m³ in \pm 45° symmetric cross-ply. The polyimide layer for the antenna and flexible printed circuit consists of two layers: a dielectric base layer (CRI-0512S, DuPont) of

12.5 µm thickness and a copper layer of 17.5 µm thickness. Shielding is by the copper film on the back side of the polyimide layer to reduce back-radiation. An SMA (subminiature version A) connector of 50 Ω impedance is attached at the feed line (length $L_2 = 15$ mm and width w = 3.06 mm) on the polyimide layer. Figures 5(a)-(d) shows the resonant frequency comparison of the prediction by the inductor model and the measurement by the network analyzer (Agilent 8714ET). The experimental results of the resonant frequency are at 797, 734,



Figure 5. Measurement of the return loss of the printed meander line antennas, (a) illustration of a meander line antenna embedded in the composite laminated substrate; (b) M = 1 with $\omega = 797$ MHz; (c) M = 2 with $\omega = 734$ MHz; (d) M = 3 with $\omega = 701$ MHz; and (e) M = 4 with $\omega = 623$ MHz

701, and 623 MHz, respectively, for the meander line antennas M = 1 to 4, and they are also listed on **Table 2**. The predictions from the inductor model are in good agreement, and the discrepancies are within 6.4%. These validations confirm that the inductor model is effective to design and analysis of a printed meander line antenna. It should be noted that the bandwidth of printed meander line antennas decreases with the antenna length. The radiation pattern is determined by the current distribution on the meander line. As a consequence of the current cancellation and reinforcement, a number of high resonances may be present in meander line antenna. Care has to be taken since these resonances often result in low voltage standing wave ratio (VSWR) when embedding the antenna in composite laminated substrate.

5. Conclusions

1) Recent smart structure development of Conformal Load-bearing Antenna Structure (CLAS) by embedding microstrip antenna inside composite laminated substrates has been considered desirable to have sufficient structural and antenna performance. Meander line antenna can be installed in airframe to eliminate air drag and minimize aerodynamic disturbance. An inductor model is developed to facilitate systematic design and analysis of the antenna. The meander line sections providing positive inductance are modeled by the inductors while the radiation parts are by a quasi-monopole of much shorter length.

2) The inductor model shows that the reactance of a quasi-monopole antenna can be calculated by a linear function at $\lambda/3 \le L_1 \lambda/2$. The reactance can be compensated by that of the meander line sections, which are determined by the geometry parameters *A*, *D*, *W* and *M*. The polarization of a meander line antenna is similar to a monopole antenna when the length of the meander line section (*W*) is small compared to the antenna length. Based on the smart layer concept, four meander line antennas (W = 20 mm, A = 5 mm, D = 2 mm, M = 1, 2, 3 and 4) on polyimide layer are developed, and they are embedded in [45/-45/45/45/-45/45] symmetric composite laminated substrates. Discrepancies of resonant frequency between the prediction of the inductor model and the measurement results are within 4.6%.

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