

Analysis Of The Directional Characteristics Of Loop Antennas And Their Applications In Aeronautical Engineering

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Abstract—This paper investigates the structure of loop antennas, derives the induced electromotive force (EMF), and analyzes their directional characteristics. The study focuses on the relationship between antenna geometry and received signal amplitude under different incident angles. MATLAB simulations are performed to evaluate the directional patterns for different loop dimensions. The results show that when the loop size is much smaller than the wavelength, the antenna exhibits a clear figure-eight radiation pattern with distinct maxima and minima. This property makes loop antennas highly suitable for aeronautical direction-finding applications. In particular, loop antennas are widely used in radio compasses to determine the bearing of ground-based navigation stations. The study confirms that combining loop antennas with omnidirectional antennas improves directional accuracy and resolves ambiguity in bearing determination.

Keywords—Loop antenna; Radio compass; Directional characteristic; EMF; Aeronautical navigation.

I. INTRODUCTION

Aircraft navigation requires accurate determination of the direction of ground-based radio stations. This is achieved by measuring the angle between the aircraft longitudinal axis and the direction of arrival of the electromagnetic wave, measured clockwise, known as the relative bearing (KYP). To determine this angle, onboard systems employ antennas with high directional sensitivity. The directional performance strongly depends on antenna geometry [1]. Among various antenna types, loop antennas are widely used due to their simple structure and distinct directional characteristics [1], [2]. Therefore, studying the structure and directional behavior of loop antennas is essential for improving the performance of aeronautical navigation systems, particularly in radio compass applications.

II. METHODOLOGY

This study analyzes the structure and operation of loop antennas and derives the induced EMF based on electromagnetic wave interaction [1], [3].

A. Loop antenna structure

A loop antenna consists of one or multiple rectangular wire loops, typically wound around a ferrite core. For simplicity, a single rectangular loop is considered. The antenna has height h and width b (Fig 1).

The electromagnetic wave propagates toward the antenna along direction S , lying in the horizontal plane and forming an angle θ with the normal to the plane of the loop antenna.

B. Induced EMF analysis

The instantaneous electric field at the loop center is given by:

$$e_0(t) = E_0 \sin \omega_0(t) \quad (1)$$

The induced electromotive force (EMF) on the loop antenna $e_p(t)$ is the sum of the EMFs induced on each side of the loop:

$$e_p(t) = e_{BA}(t) + e_{CB}(t) + e_{DC}(t) + e_{AD}(t) \quad (2)$$

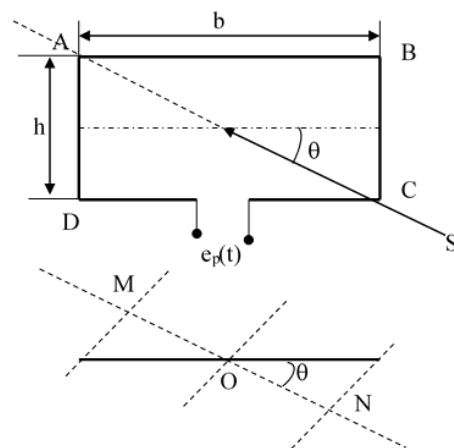


Fig. 1. Signal reception on a single loop of a loop antenna.

The EMFs induced on sides BA and DC have equal magnitudes but opposite directions; therefore, their total contribution is zero:

$$e_{BA}(t) + e_{DC}(t) = 0 \quad (3)$$

Since the electromagnetic wave propagates along direction S, the signal at side CB leads in phase compared to the center point (O), while the signal at side AD lags by an angle φ . The induced EMFs on these two sides are given by:

$$e_{CB}(t) = hE_0 \sin(\omega_0 t - \varphi) \quad (4)$$

$$e_{AD}(t) = hE_0 \sin(\omega_0 t + \varphi) \quad (5)$$

The output voltage is obtained from the difference between the EMFs on these two sides [1]:

$$e_p(t) = 2hE_0 \cos \omega_0 t \sin \varphi \quad (6)$$

The electromagnetic wave propagates from the equiphase plane passing through point O to the equiphase plane passing through point M, corresponding to a propagation distance OM in space. From the loop geometry, the propagation distance from the center of the loop to one side is:

$$OM = \frac{b}{2} \cos \theta \quad (7)$$

Thus, the total path difference between the two vertical sides of the loop is:

$$\Delta = b \cos \theta \quad (8)$$

During the propagation over this distance, the phase of the electromagnetic wave changes by an amount φ . According to electromagnetic field theory [4], when a wave propagates a distance equal to one wavelength λ_0 , the phase shift is 2π . Therefore, the phase difference is given by:

$$\varphi = \frac{2\pi \frac{b \cos \theta}{2}}{\lambda_0} = \frac{\pi b \cos \theta}{\lambda_0} \quad (9)$$

Where:

φ : phase shift of the electromagnetic wave at the equiphase plane passing through point M;

b : width of the loop antenna;

θ : angle between the incident wave direction S and the normal to the plane of the loop antenna;

λ_0 : wavelength of the electromagnetic wave.

Substituting the phase angle φ into the EMF expression, we obtain:

$$e_p(t) = 2hE_0 \sin \frac{\pi b \cos \theta}{\lambda_0} \cos \omega_0 t = E_p(\theta) \cos \omega_0 t \quad (10)$$

Where:
 (11)

$$E_p(\theta) = 2hE_0 \sin \frac{\pi b \cos \theta}{\lambda_0}$$

$E_p(\theta)$: the signal amplitude of the loop antenna depends on the direction of arrival of the incident wave.

III. MODELING AND ANALYSIS

The directional characteristics of the loop antenna are analyzed using MATLAB simulations under three cases.

Case 1: $b > \lambda_0 (b = 1,5\lambda_0)$.

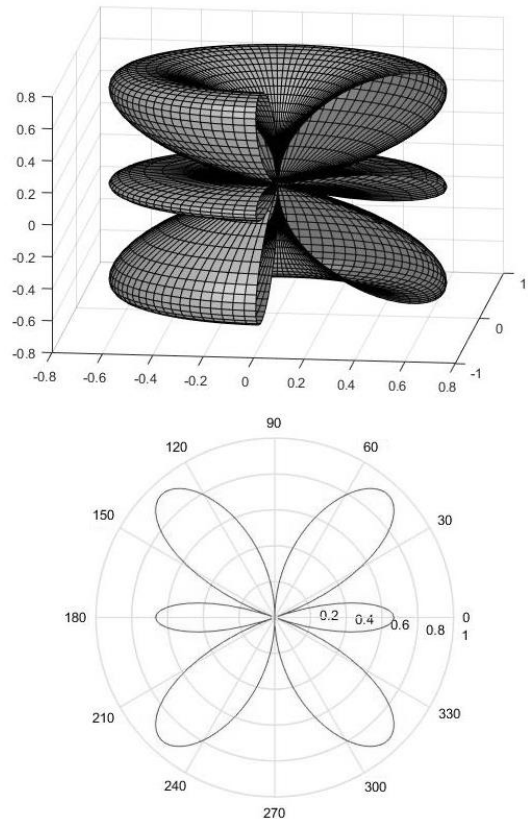
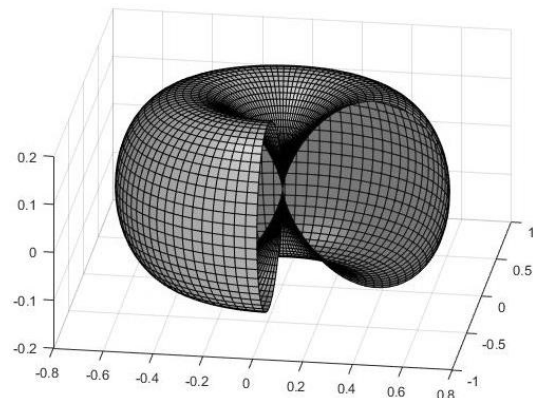


Fig. 2. Directional characteristics of the loop antenna for $b = 1,5\lambda_0$.

Case 2: $b = \lambda_0$.



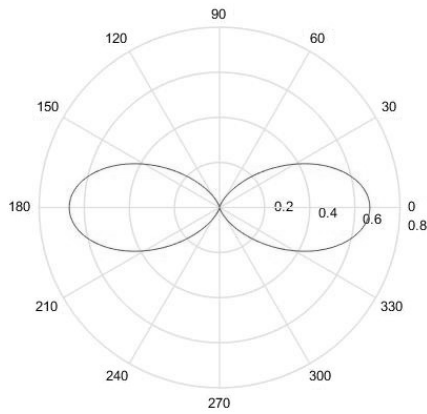


Fig. 3. Directional characteristics of the loop antenna for $b = \lambda_0$.

Case 3: $b < \lambda_0$ ($b = 0,001\lambda_0$).

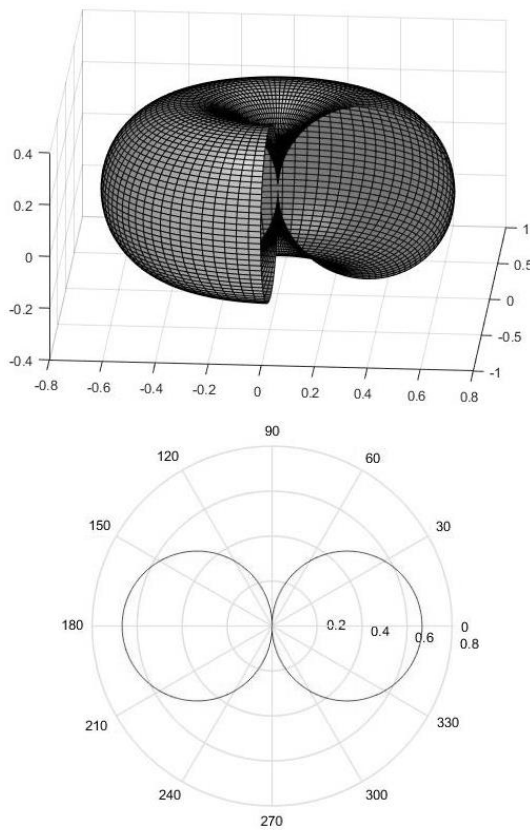


Fig. 4. Directional characteristics of the loop antenna for $b = 0,001\lambda_0$.

From the simulation results, in the case 3, the loop antenna exhibits clearly defined maxima and minima at 90° , 270° , 0° and 180° .

When the effective height of the antenna is constant ($h = \text{const}$), and both the wavelength and the electric field intensity at the receiving point remain unchanged, if $b \ll \lambda_0$, the amplitude of the signal received by the loop antenna becomes a function of the angle of incidence:

$$E_p(\theta) = 2hE_0 \sin \frac{\pi b \cos \theta}{\lambda_0} \approx 2hE_0 \frac{\pi b \cos \theta}{\lambda_0} = E_{Pm} \cos \theta \quad (12)$$

$$e_p(t) = E_{Pm} \cos \theta \cos \omega_0 t \quad (13)$$

These expressions indicate that the signal amplitude is proportional to $\cos \theta$, confirming that the loop antenna exhibits a figure-eight directional pattern [2], [7].

IV. RESULTS AND DISCUSSION

The simulation results demonstrate that the loop antenna has maximum signal amplitude when the incident wave is aligned with the normal to the antenna plane, and minimum amplitude when the wave is perpendicular to the normal.

Specifically:

Minimum occurs at $\theta = 90^\circ$ and $\theta = 270^\circ$.

Maximum occurs at $\theta = 0^\circ$ and $\theta = 180^\circ$.

This directional behavior allows the determination of the direction of arrival of the electromagnetic wave [6], and consequently the direction of the transmitting station.

Application in Aeronautical Systems:

Due to its high directivity and stable directional characteristics over a wide frequency range, the loop antenna is widely used in aircraft radio compass systems (ADF, APK) [6], [5].

To eliminate directional ambiguity, the loop antenna is combined with an omnidirectional antenna to form a composite antenna system. The resulting radiation pattern is cardioid-shaped [2].

Depending on whether the signals from the loop antenna and the omnidirectional antenna are in phase or out of phase, the cardioid pattern is oriented either to the left or to the right.

V. CONCLUSION

The investigation of loop antenna directional characteristics plays an important role in the development and operation of aircraft radio compass systems.

In this study, the induced EMF expression of the loop antenna was derived, and its directional characteristics were analyzed. MATLAB simulations confirmed the theoretical results [1] and highlighted the advantages of loop antennas in aeronautical direction-finding applications.

The results demonstrate that loop antennas, especially when combined with omnidirectional antennas, provide accurate and reliable determination of signal direction, making them suitable for use in aircraft navigation systems.

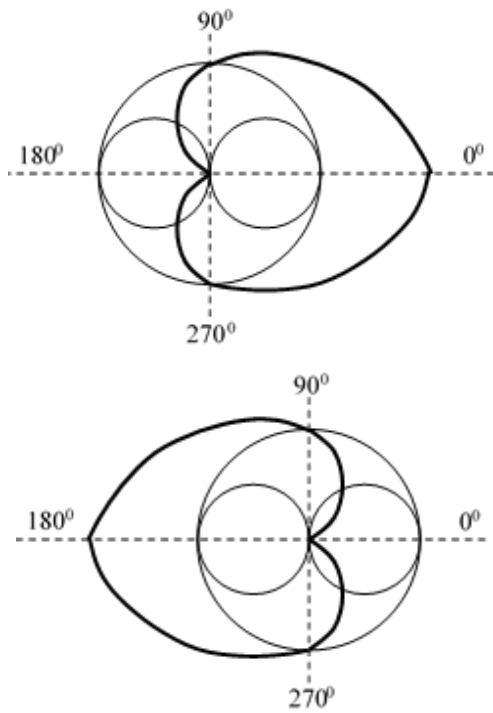


Fig. 5. Directional characteristics of the composite antenna

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