FROM MAGNETIC RESONANCE TO THE LOW EARTH ORBIT: SIMULATION AIDED DESIGN OF BIRDCAGE ANTENNA WITH APPLICATION IN THE ATMOSPHERE-BREATHING ELECTRIC PROPULSION ENGINE

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Abstract: This paper deals with the design and validation of the birdcage coil and with the proposal of its implementation into the Atmosphere-Breathing Electric Propulsion Engine (ABEP). The coil was designed, analysed, and tuned using ANSYS HFSS software and the results were evaluated against the measurement of the prepared prototype. The difference between the measured and required frequency was approximately 2.7%. Although the coil needs to be further optimized, the ability to achieve the desired frequency was demonstrated.

Keywords: MRI, birdcage, RF coil, ABEP, electric propulsion, numerical analysis

1 INTRODUCTION

Utilization of Very Low Earth Orbits (VLEO) for satellite operations would bring a wide range of benefits. The observation of Earth through the reduced thickness of the atmosphere leads to improved resolution, signal-to-noise ratio (SNR), and is enabling novel technologies and approaches. Moreover, thanks to the constant drag of the atmosphere, the satellites cannot become space debris, they will quickly fall after the end of their lifetime.[1]

However, the presence of the atmosphere brings several challenges as well. The constant friction makes a demand for a source of a continuous thrust, which will compensate it. If the standard concept of propulsion engines was used, there would be a need for an enormous amount of propellant, or the lifetime of such a device would be significantly reduced. This problem is addressed by the utilization of atmospheric particles. Then, there is an infinite source of the propellant, which only must be properly ionized and accelerated to produce the thrust.

The mentioned conditions pose strict requirements on such an engine. At VLEO, there is a low density of atmospheric particles, moreover, they are composed mainly of oxygen and nitrogen. While the first condition requests high ionization efficiency, the later one requires the corrosion resistance of the whole system, even to the oxygen ions and radicals. In the ideal case, the electrodes should be placed outside the discharge channel to prolong the operation time. [1][2]

Among many attempts to address these challenges, the solution proposed by Romano et al. is one of the most promising. Their approach consists of employing the birdcage coil for ionization of the atmosphere particles and their acceleration by the variable electromagnetic field of the birdcage coil, in addition to an external static magnetic field. The frequency 40.68 MHz for driving the birdcage was used. [3]

The combination of the variable electromagnetic field, together with the static magnetic field leads to the formation of helicon waves and acceleration of both ions and electrons together. [3],[4]
2 BIRDCAGE COIL THEORY

Birdcage coils generally consist of two end rings, connected by equally spaced legs and capacitors. There are a few different ways of birdcage coil construction. The two most used are low-pass resonator, where the capacitors are placed in the middle of the coil legs, and high-pass design (shown in Figure 1), where the capacitors are placed in the end rings, between the legs.

The concept of Birdcage coils was originally developed for use in Magnetic Resonance Imaging (MRI). The main advantages are the great signal-to-noise ratio and excellent rf field homogeneity in the whole volume of the coil. Since the resonant frequency depends on several mutually independent variables (coil diameter, length and width of the legs, capacitor values, etc.), the frequency can be broadly tuned to different values for a single set of its dimensions. [5]

Every birdcage coil has N/2 resonance modes (where N is the number of its legs), for high-pass design, there is one extra, so-called antiresonance (AR) mode. Each mode has a different distribution of electromagnetic field inside the coil, only the first resonance mode provides the homogeneous magnetic field. For low-pass design, the first mode corresponds to the lowest frequency, while for the high-pass coils, the frequency of the first mode is the second highest (after the AR peak). [3],[5]

![Figure 1: A high-pass birdcage coil with its electric (E) and magnetic (B) fields. The static magnetic field B is externally applied to accelerate the charged particles. Adapted from [3].](image)

3 EXPERIMENTAL

We decide to base our ABEP system on the widely used frequency 13.56 MHz, due to the availability of signal generators, amplifiers, and other high-frequency parts.

The Birdcage Builder software [6] was used for the first estimation of the coil parameters. The coil diameter, as well as the width of the end rings and the legs, were fixed to the desired values (which were derived from the diameter of the ABEP discharge channel and the available copper tape width respectively). Other parameters, the type (High-pass vs. Low-pass), coil length, and the value of the capacitors were roughly tuned to meet the desired frequency of 13.56 MHz. The first concept consisted of an eight-leg high-pass coil with a diameter of 5 cm and length 6.2 cm, with the legs and end rings 1.2 cm wide, and the capacity of the capacitors 6.8 nF.

These values were subsequently used for building the model in ANSYS HFSS software. The capacitors were modelled using Lumped RLC boundary condition. Since there are only a few discrete capacity values of the capacitors widely available on the market, the capacity was fixed to 6.8 nF and the only remaining degree of freedom consists of the length of the coil. Using finite element method (FEM) analysis, the accurate value of the length was found. The length was corresponding to the first resonance peak at the frequency 13.56 MHz, and it was determined to be 8.75 cm (see the difference compared to the results of the Birdcage Builder app).
To confirm the model’s fidelity, the birdcage coil with calculated parameters was built. Polyvinylchloride (PVC) tube was used as a supporting structure. The tube was covered with the self-adhesive copper tape, following the layout of the model (see Figure 2). The endrings were thoroughly soldered to the individual legs to ensure good conductivity even at high frequencies. In the endrings gaps, the SMD capacitors in the 1206 housing of capacity 6.8 nF were used.

Finally, the coil was equipped with a BNC connector and its parameters were measured using the vector network analyser Rohde & Schwarz ZVL 9 kHz – 6 GHz.

**Figure 2:** Left: the model of the coil created in ANSYS HFSS; right: prototype of the coil.

### 4 RESULTS AND DISCUSSION

Figure 3 shows the results of the numerical analysis of the coil and the values obtained from the real measurement of the prepared prototype. In both spectra, there are clearly visible the first resonance peak at a frequency of around 13.5 MHz, the second peak located around 11.5 MHz, and the anti-resonant peak at the frequency around 20.5 MHz. The other peaks are clearly visible in the simulation only. In the measured data, the two highest peaks are broadened and overlapped.

Using the FEM, the frequency of the first peak was determined at 13.56 MHz, while the measured data shows the peak located at 13.93 MHz. The difference is 2.73 %. The major deviation between the numerical analysis results and the measured values lies in the return loss at the resonance frequencies. The difference can be explained as the capacitors were considered ideal in the simulation.

Moreover, the impedance of the coil was not matched to 50 Ω. The impedance matching, as well as the fine-tuning of the frequency, is the next task in the development of the high-frequency part of the propulsion engine. The task will not be trivial, because of the need for an auto-matching network since the plasma ignition will strongly alter the impedance of the whole system.

**Figure 3:** Simulated and Measured $S_{11}$ parameters of the Birdcage coil.
To support our assumption, the peak at 13.56 MHz corresponds to the right resonance mode, the magnetic field magnitude and direction were plotted for this frequency. The results, shown in Figure 4 were plotted perpendicularly to the coil axis, in the middle of the coil length. There is clearly visible uniformity of the magnetic field inside the volume of the coil.

![Figure 4: First resonance mode; left: the magnitude of the magnetic field; right: Magnetic field direction. Top view (XY plane). Plots were obtained using ANSYS HFSS.](image)

To confirm the findings, the magnetic field amplitudes were also plotted for frequencies corresponding to other resonance modes. As it is clearly visible in Figure 5, the other resonance modes, located at a) 10.33 MHz, b) 10.57 MHz and c) 11.52 MHz for the higher resonance modes and at d) 20.02 MHz for the anti-resonant modes do not provide homogeneous magnetic field across the coil.

![Figure 5: Distribution of magnetic field magnitude for a) 4th, b) 3rd, c) 2nd resonance and d) anti-resonance modes. Top view (XY plane). Plots were obtained using ANSYS HFSS.](image)
5 CONCLUSION AND OUTLOOK

To sum up, within this work the Birdcage coil operating at 13.56 MHz was designed and created. Its parameters were measured and compared with the results of the numerical analysis results. The first resonance mode lies at the frequency of 13.93 MHz, which makes the difference 2.73 % compared to the results of the analysis and the desired frequency. The birdcage coil will be subsequently tuned, matched, and employed in the atmosphere-breathing electric propulsion engine. This may require an automatic matching network since the impedance of the low-pressure gas and plasma case might differ strongly.

REFERENCES


