keys is also displayed in the table as seen in Fig. 2. After the user has set the position of the keys, a graph is plotted in the web interface illustrating the output voltage obtained from the eclectic circuit. By sequentially turning on the electronic keys, the user can observe changes in the voltage characteristic. This will allow the user to remotely study the behavior of the rectifier with a filter.

To conclude, the considered web interface makes it easy for students to interact with a remote laboratory. This web interface allows students to perform any laboratory work remotely. We will use this web interface in the laboratory of elements and devices of robotic systems in TUSUR.

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EVALUATING THE IMPACT OF SINGULARITY EXTRACTION APPROACHES ON THE EFFICIENCY OF ANTENNA SIMULATION BY THE METHOD OF MOMENTS

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This study investigates different methods for singularity extraction in antenna simulations by the method of moments. The methods are considered in terms of their impact on the accuracy and computational time while simulating a flat-symmetric half-wave dipole. Our results show that the numerical approach provides the highest level of accuracy, while the analytical approach provides the shortest computational time.

Keywords: antenna, computational electromagnetics, numerical methods, method of moments, singularity extraction.

The development of antenna elements with improved radio characteristics is a key task in the design of modern radio electronics. Therefore, computer-aided design (CAD) systems based on numerical methods of electrodynamics have been widely used [1, 2]. Among these methods, the method of moments (MoM) has become a popular choice in practice [3, 4]. This paper is devoted to one of the features of the MoM – the problem of singularity in the solution of electric field integral equations. The first part of the paper provides a brief overview of the MoM, explaining the singularity mechanism and discussing various approaches for its extraction. In the second part of the paper, we will review the results of numerical simulations using different approaches and discuss the accuracy and computational time.

In the MoM, the conductive surfaces of the antenna are replaced by equivalent surface currents, which are then used to solve the electromagnetic field excitation problem. To approximate the curved boundaries of antenna surface geometries, they are often represented as triangular polygonal meshes. The current within each mesh cell is described by Rao-Wilton-Glisson (RWG) basis functions. Each function is associated with a common edge between two adjacent triangles T_n^+ and T_n^- [5]. This function of the edge element approximately corresponds to a small but finite electric dipole [6]. The problem is reduced to solving a system of linear equations of the form **ZI** = **V**, where **Z** is the impedance matrix, **V** is the voltage excitation vector, and **I** is the desired vector of current density distribution on the model surface. The impedance matrix **Z** describes the interaction between different elementary dipoles. If the edge elements *m* and *n* are treated as small electric dipoles, the matrix element z_{mn} describes the contribution of dipole *n* (through the radiated field) to the electric current of dipole *m*, and vice versa [6]. This interaction is described by integrating the Green's function over the source triangles $T_n^{\pm}$ with observation points at the midpoint of the triangles $T_m^{\pm}$:

$$\int_{T_n} g(\mathbf{r})dS = \int_{T_n} \frac{\exp\left(-jk|\mathbf{r}-\mathbf{r}'|\right)}{|\mathbf{r}-\mathbf{r}'|} dS ,$$

where $\mathbf{r}$ is the observation point and $\mathbf{r}'$ is the source point. However, when computing the diagonal elements of the matrix **Z**, a singularity occurs due to the fact that $\mathbf{r}$ and $\mathbf{r}'$ are located at the same position, causing $|\mathbf{r} - \mathbf{r}'|$ being equal to 0.

Several approaches based on numerical and analytical solutions of integral equations are known to extract this computational specificity. The numerical approach involves dividing the triangular mesh element used for integration into nine sub-triangles [6, 7]. Assuming that the integrand remains constant within each sub-triangle, the original integral can be simplified as follows:

$$\int_{T_n} g(\mathbf{r})dS = \frac{S_n}{9}\sum_{k=1}^{9} g(\mathbf{r}_k^c)\,,$$

Where $\mathbf{r}_k^c$, $k = 1, \ldots, 9$ are the midpoints of nine sub-triangles and S_n is the area of the primary triangles.

An alternative approach is to calculate integrals in an analytical form [7–9]. This approach first simplifies the problem by using a Taylor series expansion [10, 11]. Afterwards, analytical expressions are used to evaluate the integral [12].

To compare the results of these approaches, we considered a model of a flat, symmetrical half-wave dipole at a frequency of 75 MHz. The antenna was simulated with λ/60 cells per wave-length. The obtained characteristics were compared with similar results obtained by finite-difference time-domain (FDTD) simulation in the EMPro software package [13]. In addition to the classical approaches, we also considered their combination. This involves using analytical expressions to calculate the diagonal elements of the matrix, while all other elements are calculated using barycentric subdivision into 9 sub-triangles.

Figure 1 shows a comparison of the antenna radiation pattern (RP) in the *E* and *H* planes. As can be seen, the results of all approaches are in good agreement with those of EMPro. The maximum deviation from the reference values is 0.05. Table shows the calculated values of the antenna input impedance. It can be seen that the numerical approach gives results that are closest to EMPro simulation, with a deviation of 0.18%. The maximum deviation was obtained for the combined approach with a deviation of 1.23%.

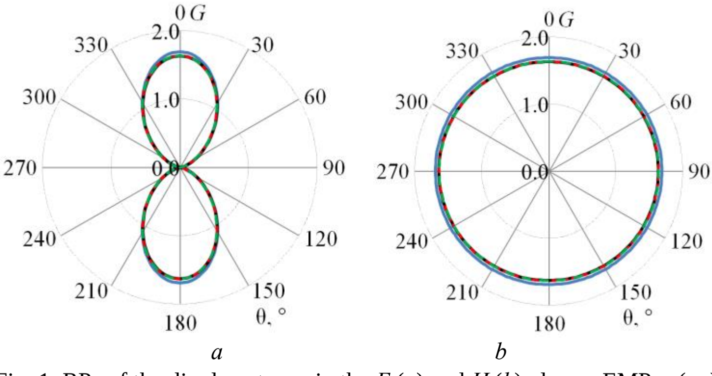

Fig. 1. RPs of the dipole antenna in the *E* (*a*) and *H* (*b*) planes: EMPro (—), analytical (- - -), numerical (- - -), and combined (- - -) approaches

**Calculated values of dipole input impedance (Ohm)
and their deviations (in brackets) compared to EMPro**

Approaches			EMPro
Analytical	Numerical	Combined	
95.32 + j43.52 (0.37%)	95.91 + j42.68 (0.18%)	94.18 + j43.81 (1.23%)	97.51 + j39.4

We estimated the time required to compute the matrix **Z**, which has dimensions of $N \times N$, for each approach as N sequentially increased from 941 to 27528 (Fig. 2). Our results indicate that the time required to compute the matrix **Z** increases exponentially with the matrix dimensions when applying numerical and combined approaches, whereas the analytical approach is more linear in nature. Specifically, when computing the matrix with a dimension of N = 27528, the analytical approach reduced the time required to generate the matrix by a factor of 8.5.

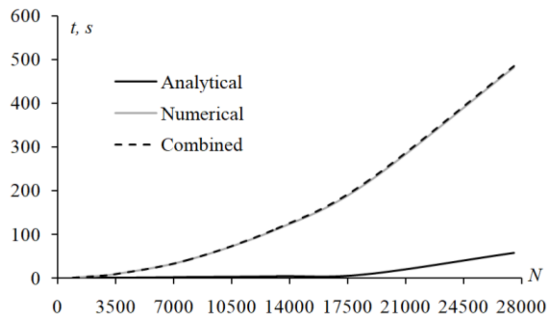

Fig. 2. Time required to compute the matrix **Z** as a function of its dimensionality

An evaluation of the impact of singularity extraction approaches on antenna simulation by the MoM has been conducted. Based on the example of a flat symmetric half-wave dipole, we demonstrated that the numerical approach yields more accurate results, while the analytical approach requires less computational time. Thus, we recommend employing the analytical approach when quick preliminary results are required, and the numerical approach for more accurate calculations.

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ELECTRON BEAM MODIFICATION OF CHARACTERISTICS OF MN-ZN-FERRITE POWDER

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The paper discusses the influence of electron beam processing on the characteristics of Mn-Zn ferrite powder. The plots of spectrum reflec-