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ABSTRACT OF THE DOCTORATE THESIS

Simulative Numerical Studies of High-Power Electromagnetic Pulse Penetration into a Small Shielding Enclosure with a Technological Perforation – Shielding Effectiveness of the Enclosure Interior Against Electromagnetic Pulses

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In this doctoral dissertation, the author investigates the issue of subnanosecond high-power electromagnetic (EM) pulse penetration into small metallic shielding enclosures with technological perforations, addressing the need for a deeper understanding of the interaction mechanisms between disturbing EM pulses and metal objects designed to minimize the effects of intentional EM attacks, as well as the need for new quantitative methods for assessing the shielding effectiveness of electronic devices (and components) using these objects. Motivated by this, the author undertakes the task of understanding the process of subnanosecond EM plane wave pulse penetration into the interior of a small not high metallic shielding enclosure with a technological perforation, tracing the formation and development of the EM field inside the enclosure, and developing a quantitative method for assessing the shielding effectiveness of the enclosure's interior against intentional EM disturbances.

The author formulated the following research hypothesis: it is possible to determine the electromagnetic shielding effectiveness of a small not high metallic enclosure with a technological perforation by analyzing the simulation of the subnanosecond high-power EM plane wave pulse penetration process into its interior.

To solve the complex research problem and prove the dissertation hypothesis, the author selected a numerical simulation method.

The research object is a small not high rectangular metallic shielding enclosure with a technological perforation. The external dimensions of the tested enclosure are: width: 455 mm, height: 50 mm, and depth: 463 mm. These dimensions were chosen to accommodate typical electronic devices often cited as requiring electromagnetic shielding (a standard 17-inch laptop, a mobile phone, and two small portable computer storage devices). The walls of the enclosure are assumed to be made of a perfect electric conductor (PEC) with a thickness of 1 mm. A rectangular perforation (hereafter referred to as the aperture), measuring 30 mm x 80 mm, is located in the center of the front wall of the enclosure, simulating a ventilation and cable entry aperture.

The disturbing EM pulse is a subnanosecond EM plane wave pulse with a Gaussian distribution, which serves as a good approximation of a pulse likely to be used in a potential EM attack. The disturbing pulse is assumed to strike perpendicularly to the front wall of the shielding enclosure where the aperture is located. This is referred to as normal incidence. The research includes an analysis of two polarizations of the disturbing pulse: perpendicular and parallel. In the case of perpendicular polarization, the electric field intensity vector of the normally incident plane wave pulse is perpendicular to the largest walls (bottom and top) of the enclosure (and also to the longer edges of the aperture). In the case of parallel polarization, the electric field intensity vector of the normally incident plane wave pulse is parallel to the bottom and top walls of the enclosure (and also to the longer edges of the aperture). The author also conducted short test simulations for the case of a disturbing pulse with so-called twisted polarization. The tests showed that the CST Studio simulation environment can handle this case computationally. However, the results were difficult to interpret and of little substantive value.

The subject of the author's research is the temporal and spatial distribution of the electric and magnetic fields inside the shielding enclosure after the high-power electromagnetic disturbing pulse penetrates, as well as the shielding effectiveness of the enclosure's interior against this disturbance.

The dissertation consists of 11 chapters:

Chapter 1 introduces the research topic. It consists of 3 subsections.

Subsection 1.1 contains the classification of natural and intentional high-power electromagnetic disturbances, describes methods for shielding against EM radiation with a focus on shielding enclosures, and discusses parameters used to describe the shielding effectiveness of objects against EM radiation. This subsection also introduces and discusses the author's original definition of so-called global shielding effectiveness.

In Subsection 1.2, the research problem is presented, which involves analyzing the suitability of a small not high rectangular metallic enclosure with a technological perforation for shielding sensitive electronic devices (or components) from intentional EM pulse attacks. This subsection also specifies the research objective and hypothesis of the dissertation. The author decided to address the scientific problem using numerical simulation of the process of disturbing EM pulse penetration into the enclosure.

The next Subsection, 1.3, presents the structure of the dissertation.

Chapter 2 describes the chosen numerical simulation method. This method is based on the use of the commercial CST Studio Suite environment for simulating the interaction of electromagnetic radiation with three-dimensional (3D) objects.

In Chapter 3, the rectangular metallic shielding enclosure with a technological perforation in the shape of a rectangular aperture in the front wall of the enclosure, selected as the object for the simulated subnanosecond EM plane wave pulse attack, is presented.

Chapter 4 introduces the disturbing subnanosecond EM plane wave pulse, whose parameters, according to the literature, are close to those of the most probable intentional EM disturbances.

Chapter 5 serves as a brief introduction to the subsequent chapters of the dissertation. It presents the physical model of EM pulse interaction with metal surfaces, developed based on empirical knowledge from the literature. From this model, the author concluded that the primary effect of EM field interaction with metal surfaces is the redistribution of free electrons on these surfaces. The EM field-induced migration of free electrons results in the formation of regions with opposite electrical polarity on metal surfaces, which become secondary sources of the electric field, shaping the EM field inside and around the enclosure. The author hypothesized that tracking the migration of free electrons on the outer and inner surfaces of the metallic shielding enclosure may be crucial for analyzing other phenomena resulting from the interaction of the EM field with the metallic enclosure (e.g., for analyzing the current flow on the enclosure surfaces). Based on this hypothesis, the study of free electron migration on the shielding enclosure surfaces became an important aspect of this dissertation.

Chapter 6 consists of four subsections in which the author presents her own simulation results for the process of disturbing EM pulse penetration into the metallic enclosure and the development of the EM field within it, for the case of a disturbing pulse with perpendicular polarization.

Subsection 6.1 concerns the 3D and 2D visualization of the penetration and development of the electromagnetic field inside the enclosure for the case of perpendicular polarization of the external disturbing pulse. It presents 3D and 2D maps of the electric and magnetic fields, which are coupled. The development of the EM field inside the enclosure proceeds in such a way that it can be divided into two phases: the wave phase and the interference phase. In the first, wave phase, (Fig. 6), primary and then secondary electromagnetic waves (e.g., after the primary waves reflect off the sidewalls of the enclosure) are generated inside the enclosure, consisting of coupled electric and magnetic waves in the shape of incomplete rings with a crescent-like longitudinal cross-section and a rectangular transverse cross-section (e.g., Figs. 6Ei, 6Hi and Figs. 7Ei, 7Hi). In the next interference phase, the EM field inside the enclosure, represented by the electric and magnetic field magnitudes, takes the form of complex spatial geometrical shapes that are difficult to visualize (Fig. 6). In such situations, it is convenient to describe the EM field inside the enclosure by presenting it on selected cross-sections (2D) of the enclosure interior. This yields two-dimensional distributions of the EM field inside the enclosure, referred to as interference mosaics of the electric and magnetic fields due to their typically unusual geometry (Fig. 7). The primary and secondary waves, along with the interference mosaics of the electric and magnetic fields, move from the front to the rear wall of the enclosure, experiencing successive reflections. Some of the energy of this oscillating EM field "leaks" out of the enclosure through the aperture during successive reflections off the front wall, resulting in a decrease in the electric and magnetic field strength inside the enclosure over time. In both phases of development, the distributions of the electric and magnetic fields inside the enclosure are symmetric with respect to the z-axis.

In Subsection 6.2, following the motivation presented in Chapter 5, the surface charge distributions on the inner walls of the enclosure are presented and analyzed, tracking the migration of free electrons on these surfaces. The surface charge densities on the walls of the enclosure were determined from the normal component of the electric field using the proportionality between these quantities. The analysis of the simulations indicates that, as a result of the migration of free electrons, pairs of regions ("islands") of positive and negative charge are locally formed on the inner walls of the enclosure. These pairs are referred to in this dissertation as "complementary charge islands." They, along with the part of the disturbing pulse that directly penetrates the enclosure through the aperture, become co-sources of the EM field inside the enclosure. In the early stage of disturbing pulse penetration into the enclosure, complementary charge island pairs appear in areas near the longer edges of the aperture on the inner side of the front wall of the enclosure. The islands forming the pairs are located on opposite sides of the aperture. As the disturbing pulse penetrates deeper into the enclosure, the surfaces of the existing complementary charge island pairs grow, covering the inner surfaces of the bottom and top walls of the enclosure. At the same time, new complementary charge island pairs form near the longer edges of the aperture on the inner side of the front wall of the enclosure. Both the existing and newly forming complementary charge island pairs migrate deeper into the enclosure (Figs. 11 and 12). The electric fields generated by the complementary charge island pairs, along with the portion of the disturbing pulse’s electric field that directly penetrates the enclosure, form characteristic electric wave structures with the geometry of incomplete rings. These rings have a crescent-like longitudinal cross-section and a rectangular transverse cross-section. The existence of such waves has already been noted and described earlier in Subsection 6.1, which concerns the 3D and 2D visualization of EM field development in the enclosure. Selected examples of characteristic electric field structures in the early stage of EM field development inside the enclosure are shown in Figs. 25 and 26. It is worth comparing them with the structures shown in Figs. 6Ed (or 6Ee) and 6Eg in Subsection 6.1. The explanation in Subsection 6.2 of the relationship between the electric charge on the inner walls of the enclosure and the EM field inside the enclosure confirms the importance of tracking the behavior of the electric charge on the inner surfaces of the enclosure, as predicted in Chapter 5.

In Subsection 6.3, the results of studies on the distributions of the normal electric field (Subsection 6.3.1), the tangential magnetic field (Subsection 6.3.2), as well as the surface charge and surface current (Subsection 6.3.3) on the external walls of the enclosure are presented. The motivation for studying these EM parameters on the external walls of the enclosure stemmed from the fruitful results of tracking the surface charge distributions on the inner walls of the enclosure (Subsection 6.2). It was expected that electromagnetic phenomena occurring on the external walls of the enclosure, especially on the surfaces adjacent to the aperture, could also influence the electromagnetic processes inside the enclosure.

From the presented distributions of the electric field on the external surfaces of the enclosure in Subsection 6.3.1, it follows that the disturbing pulse induces a normal component of the electric field on the external surfaces of the top and bottom walls of the enclosure. The vectors of the normal component of the electric field on these surfaces form a narrow "belt" of electric field vectors with a Gaussian profile in cross-section. This belt extends from the left to the right sidewall of the enclosure and moves along the top and bottom walls of the enclosure in the −z direction, in line with the disturbing pulse. In addition to the characteristic electric field belt, it is worth noting the relatively high values of the normal electric field component, particularly in the early stage of the disturbing pulse's interaction with the enclosure, at the bottom and top edges of the front wall of the enclosure, the bottom and top edges of the aperture, and the corners of the front wall. The intensity of the normal electric field component in these areas increases as the maximum of the disturbing pulse approaches the plane of the front wall and decreases as the maximum of the disturbing pulse moves away from the front wall of the enclosure.

In Subsection 6.3.2, the distributions of the tangential magnetic field on the surface of the enclosure, which accompanies the electric field described in the previous subsection, are presented. The primary form of the tangential magnetic field on the external surfaces of the enclosure is, like the electric field, a narrow Gaussian-shaped belt extending from the left to the right sidewall, which moves in the −z direction, in line with the disturbing pulse. Similar to the electric field, the strongest tangential magnetic field occurs on the surface of the front wall near the aperture when the disturbing pulse passes through the plane of the front wall. The tangential magnetic field persists in this area even after the disturbing pulse moves away from the front wall at a distance equal to half the length of the enclosure.

In Subsection 6.3.3, the distributions of electric charges and surface current on the external surfaces of the enclosure are presented. These, together with the distributions of the electric and magnetic fields described in the previous subsections 6.3.1 and 6.3.2, allow for a more complete understanding of the correlation between the electric field, magnetic field, surface charge density, and surface current on the external surfaces of the enclosure.

Using the results obtained in the previous subsections, Subsection 6.4 presents an original model of the penetration of a perpendicularly polarized electromagnetic pulse into the enclosure. According to this model, part of the disturbing pulse penetrates through the aperture into the interior of the enclosure, initiating the formation and development of complementary charge island pairs on the inner surfaces of the enclosure, which generate the electric field inside the enclosure. In the early stage of disturbing pulse penetration, the electric field penetrating the enclosure through the aperture and the electric field generated by the complementary charge island pairs create characteristic electric wave structures with the geometry of an incomplete ring with a crescent-like longitudinal cross-section and a rectangular transverse cross-section inside the enclosure. The bases of this ring are the complementary charge island pairs (Figs. 25 and 26). These waves move deeper into the enclosure. The analysis of free electron migration on the enclosure surfaces played a fruitful role in formulating this model.

Chapter 7 presents the author’s own simulation results for the process of disturbing EM pulse penetration and EM field development within the enclosure with an aperture, for the case of a disturbing pulse with parallel polarization. This chapter consists of four subsections.

Subsection 7.1 concerns the 3D and 2D visualization of the penetration and development of the EM field inside the enclosure. From the presented 3D and 2D maps of the electric and magnetic field distributions, it is evident that, similar to the case of perpendicular polarization, the development of the EM field inside the enclosure can be divided into two phases: wave and interference. In the wave phase, the disturbing pulse penetrating through the aperture into the enclosure initiates primary and secondary EM field waves with the geometry of U-shaped cylinders with an oval cross-section, with the bases of the cylinder starting and ending on the inner surface of the front wall of the enclosure (e.g., Figs. 27Ei, 27Hi, and Figs. 28Ei, 28Hi). These waves differ in spatial shape from those generated in the case of perpendicular polarization (Subsection 6.1). In the interference phase, as with perpendicular polarization, the EM field takes the form of complex spatial geometrical shapes (Fig. 27), which are difficult to visualize. In this case, an easier-to-perceive image of the EM field inside the enclosure can be obtained by presenting two-dimensional EM field distributions in selected cross-sections of the enclosure. The EM field distributions presented in these cross-sections are referred to as interference mosaics of the electric and magnetic fields due to their unusual geometry (Fig. 28). The primary and secondary waves, along with the interference mosaics of the electric and magnetic fields, move between the front and rear walls of the enclosure, undergoing successive reflections from these walls as well as from the sidewalls of the enclosure. These fields experience energy losses at the aperture during successive reflections from the front wall. The EM field inside the enclosure exhibits axial symmetry with respect to the z-axis.

In Subsection 7.2, the formation of electric charge and its distribution on the inner walls of the enclosure due to the portion of the disturbing pulse with parallel polarization that penetrates through the aperture into the enclosure is presented and described. In the early stage of disturbing pulse penetration into the enclosure, electric charges on the inner surface of the front wall of the enclosure accumulate primarily in areas near the shorter edges of the aperture. Similar to the case of perpendicular polarization, the resulting electric charge regions form complementary charge island pairs. The islands forming a pair are located on opposite sides of the aperture, near its shorter edges. As the disturbing pulse penetrates deeper into the enclosure, the islands forming the complementary charge island pairs "detach" from the shorter edges of the aperture and migrate along the inner surface of the front wall of the enclosure toward the sidewalls. In their place, on both sides of the aperture, near its shorter edges, new islands form, creating new complementary charge island pairs. These islands have the opposite electrical polarity to the islands they neighbor. On both sides of the aperture, on the inner surfaces of the front wall, and then on the sidewalls, an alternating chain of complementary electric charge islands forms (Figs. 29 and 30). Each of these islands has its complementary partner on the opposite side of the aperture. Over time, the distance between the complementary island pairs on the front wall increases. The complementary charge island pairs are sources of the EM field inside the enclosure. Together with the EM field that penetrated through the aperture into the enclosure, they form wave electric structures with the geometry of U-shaped cylinders. These structures move deeper into the enclosure. The U-shaped cylinder waves have already been noted and discussed in Subsection 7.1, which concerns the 3D and 2D visualization of EM field development inside the enclosure. Selected examples of characteristic electric structures in the early stage of EM field development inside the enclosure are presented in Fig. 45. It is worth comparing them with the structures shown in Figs. 27Eg and 28Eg in Subsection 7.1. From this, it follows that the study of the behavior of electric charge on the inner walls of the enclosure, as suggested by the author in Chapter 5, contributed to a deeper explanation of the origin and nature of the EM field inside the enclosure.

In Subsection 7.3, the results of studies on the distributions of the normal electric field (Subsection 7.3.1), electric charge density (Subsection 7.3.2), surface current (Subsection 7.3.3), and the tangential magnetic field (Subsection 7.3.4) on the external walls of the enclosure are presented.

From the presented electric field distributions on the external surfaces of the enclosure in Subsection 7.3.1, it follows that the disturbing pulse induces an electric charge on the external surfaces of the enclosure, as evidenced by the appearance of a normal component of the electric field on these surfaces. In the early stage of the disturbing pulse’s interaction with the enclosure, the highest values of the normal electric field component occur at the left and right front corners of the enclosure and at the left and right shorter edges of the aperture. Over time, as the disturbing pulse moves away from the front wall of the enclosure, the electric fields at the left and right front corners of the enclosure decrease, "expanding" onto the adjacent surfaces of the enclosure walls (Fig. 31). The electric field around the edges of the aperture also decreases. The highest values of the normal electric field component occur on the sidewalls of the enclosure, at the location of the disturbing pulse. Outside this location, the electric field is relatively weak. Unlike in the case of perpendicular polarization, no electric field is present on the top and bottom walls of the enclosure at the location of the disturbing pulse. This is because the electric charges generated by the disturbing pulse on the left and right sidewalls generate an electric field that compensates for the electric field of the disturbing pulse, causing the tangential electric field component on the top and bottom surfaces of the enclosure to be zero.

In Subsection 7.3.2, the distributions of electric charge density on the external walls of the enclosure are presented. These distributions are shown in Figs. 33 and 34. These distributions correlate with the distributions of the normal electric field component on the external walls of the enclosure. This is due to the proportionality between surface charge density and the normal electric field component. Thus, in accordance with the behavior of the normal electric field component described in Subsection 7.3.1, in the early stage of the disturbing pulse’s interaction with the enclosure, the largest electric charge accumulates on the left (negative electric charge) and right (positive electric charge) corners of the enclosure and on the left and right shorter edges of the aperture. As the disturbing pulse moves away from the front wall of the enclosure, the surface charge density on the left and right front corners of the enclosure decreases. Simultaneously, a low surface density electric charge develops on the top, bottom, and sidewalls of the enclosure, adjacent to the left and right front corners. The surface charge densities around the aperture also decrease. The disturbing pulse moving toward the rear wall of the enclosure induces on the sidewalls of the enclosure narrow areas of significant electric charge of opposite polarity. On the left sidewall, a region of negative electric charge forms, while on the right sidewall, a region of positive electric charge forms. These regions move with the disturbing pulse toward the rear wall of the enclosure. This is accompanied by the flow of electric current and, consequently, a magnetic field on the enclosure surfaces, which are described in the following subsections.

In Subsection 7.3.3, the flow of electric current on the external surfaces of the enclosure is discussed (Figs. 35-37). In the early stage of the disturbing pulse's interaction with the front wall of the enclosure, the electric field of the disturbing pulse forces the very intense migration of free electrons across the front wall from the right corner of the enclosure to the left corner so that the resulting system of electric charges of opposite polarity (negative charge on the left corner, positive charge on the right corner) on the surfaces of the front wall of the enclosure creates an electric field that compensates for the electric field of the disturbing pulse. This migration is impeded by the aperture in the front wall, where areas of opposite-polarity electric charges (negative charge on the right edge, positive charge on the left edge) also form at its shorter edges. Near the aperture, free electron migration also occurs along its longer edges. (It is important to note that the direction of electric current flow in Figs. 35-37 is the conventional direction used in electromagnetism. The free electrons forming the actual electric current move in the opposite direction to the conventional current. In other words, the direction of electron current is opposite to the direction of conventional current.) As noted in the previous subsection (7.3.2), as the disturbing pulse moves away from the front wall of the enclosure, the electric charge densities on the front corners of the enclosure decrease. This results in a reduction in the intensity of electron migration on the front wall of the enclosure. Simultaneously, the disturbing pulse moving toward the rear wall of the enclosure induces on the sidewalls of the enclosure a narrow paired region of opposite-polarity electric charges. Free electrons accumulate in the region formed on the left side of the enclosure, which, under the influence of the electric field of the disturbing pulse, have migrated along the surfaces of the top and bottom walls from the paired region on the right side of the enclosure. This migration is illustrated in Figs. 35d-35h and 36. After the disturbing pulse moves away from the front wall of the enclosure, the surface current on the top and bottom walls of the enclosure takes the form of a narrow belt in the plane defined by the disturbing pulse. This belt moves toward the rear wall of the enclosure along with the disturbing pulse.

The tangential magnetic field on the external surfaces of the enclosure is described in Subsection 7.3.4. In the early stage of the disturbing pulse's interaction with the front wall of the enclosure, there is the well-known phenomenon of EM wave reflection from the metal surface. In the case of a disturbing pulse with parallel polarization, the intensity of the tangential magnetic field on the "continuous" surface of the front wall of the enclosure is uniform and twice as high as the intensity of the magnetic field of the disturbing pulse. The uniformity of the tangential magnetic field is disrupted near the aperture. After the disturbing pulse moves away from the front wall of the enclosure, the tangential magnetic field on the surface of the enclosure results from the existence of a narrow belt of surface current in the plane of the disturbing pulse (Subsection 7.3.3). The tangential magnetic field also takes the form of a narrow belt on the top and bottom walls of the enclosure. This belt moves toward the rear wall of the enclosure along with the disturbing pulse (Figs. 38 and 39).

Based on the results presented in Subsections 7.1-7.3, an original model of the penetration of a parallel-polarized electromagnetic pulse into the enclosure is presented in Subsection 7.4. According to this model, part of the disturbing pulse penetrates through the aperture into the enclosure, causing the formation and development of complementary charge island pairs on the inner surfaces of the enclosure. The complementary charge island pairs generate the electric field inside the enclosure. In the early stage of disturbing pulse penetration, the electric field that penetrates the enclosure through the aperture and the electric field generated by the complementary charge island pairs create characteristic electric wave structures with the geometry of a U-shaped cylinder with an oval cross-section, with the bases of the cylinder starting and ending on the inner surface of the front wall of the enclosure (Fig. 45). The bases of the U-shaped cylinder are the complementary charge island pairs. The crests of the U-shaped electric waves move deeper into the enclosure. Simultaneously, the bases of these waves, i.e., the complementary charge island pairs, move along the sidewalls in such a way that the arms of the U-shaped waves become more open. The U-shaped electric waves are accompanied by coupled magnetic waves. The analysis of free electron migration on the enclosure surfaces played a fruitful role in formulating this model, as it did in the case of the perpendicularly polarized disturbing pulse.

Chapter 8 presents the author’s own test simulation results for the case of a disturbing pulse with so-called twisted polarization. The conducted tests showed that the CST Studio simulation environment handled the case of twisted polarization computationally. However, as expected, the results obtained for twisted polarization were difficult to interpret and of little substantive value. Therefore, more detailed studies of this case were abandoned. Moreover, if necessary, the complex case of twisted polarization can be analyzed as a linear combination of perpendicular and parallel polarizations, which are described in Chapters 6 and 7, respectively.

Chapter 9 presents the analysis of the shielding effectiveness of the enclosure with an aperture. This chapter consists of four subsections.

Subsection 9.1 contains time characteristics of the electric and magnetic field intensities at selected points A and B inside the enclosure for both polarization cases of the disturbing pulse: perpendicular and parallel. Point A (0, 0, 0) is located at the geometric center of the enclosure, i.e., the most commonly chosen point for numerical analysis of shielding effectiveness quality. Point B (0; 0; −211.5) is located on the z-axis, near the rear wall of the enclosure, where the most local constructive interferences of the EM field occur (Subsections 6.1 and 7.1). Point B was selected to highlight the differences in the shielding effectiveness values (presented in Subsection 9.3) resulting from the selection of different points inside the enclosure. For both polarization cases (perpendicular and parallel), in the wave phase (described in Subsections 6.1 and 7.1), the time characteristics of the electric and magnetic fields passing through points A and B take the form of repeating pulses. The pulses on the characteristics correspond to the characteristic electric wave structures passing through points A and B, described in Subsections 6.2 and 7.2. The amplitudes of these internal pulses are smaller than the maximum amplitude of the disturbing pulse and decrease over time.

In Subsection 9.2, the change in the nature of electromagnetic interference in the enclosure with an aperture is described for two cases: without the use of protection in the form of an enclosure with an aperture and for the case of placing point A in the enclosure with an aperture. The interaction of the external disturbing pulse with the selected point A in space in the case without the use of protection in the form of an enclosure with an aperture is of a one-time nature. However, in the case of placing point A in the enclosure with an aperture, as a result of the disturbing pulse penetrating through the aperture, a series of internal pulses is generated inside the enclosure, which oscillate between the front and rear walls of the enclosure and repeatedly pass through point A. From these two examples, it follows that the nature of electromagnetic interference experienced by point A after placing it in the enclosure with an aperture changes compared to the case without the use of the enclosure.

Subsections 9.3 and 9.4 present two views on the shielding effectiveness (SE) of the enclosure interior with an aperture: local and global.

The local view of shielding effectiveness described in Subsection 9.3 is based on determining the quantitative time dependencies of SE at selected points A and B inside the enclosure. This local approach (determining the time dependencies of SE in the geometric center of the enclosure) is the most commonly used method for determining the shielding effectiveness of enclosure interiors. The obtained SE characteristics indicate that in both considered points (A and B) in the enclosure, the shielding effectiveness of the disturbing pulse is at least 8 dB in the case of perpendicular polarization and 12 dB in the case of parallel polarization. In both polarization cases (perpendicular and parallel), the shielding effectiveness of the enclosure interior increases over time (analyzed over 30 ns). This applies not only to points A and B but also to other points in the enclosure. This trend results from a more even distribution of the EM field throughout the volume of the enclosure and the leakage of part of the energy from the enclosure through the aperture during successive reflections of the EM field from the front wall.

Subsection 9.4 presents a new, global approach to determining the shielding effectiveness of the enclosure interior. The new approach proposed in this dissertation involves determining global, two-dimensional (2D) maps of instantaneous shielding effectiveness values for the entire xy plane (z = const.) inside the tested shielding enclosure at time t = const. The obtained global SE maps in the 2D plane enable a detailed assessment of shielding effectiveness in the selected plane of the interior of the tested enclosure. From the determined global shielding effectiveness maps, it is possible to quickly identify the most vulnerable points in the enclosure.

Chapter 10 contains remarks on the validation of the numerical simulation results. Since sources of subnanosecond pulses for EM attack purposes are available to a narrow, essentially anonymous group, and conducting experimental studies in the scope presented in this dissertation is an extreme challenge, it was practically impossible to perform experimental validation. For these reasons, particular attention is paid in this dissertation to the consistency of the obtained results with the principles of physics, especially Maxwell's laws. No objections were raised by the reviewers of the articles in which the results obtained in this dissertation were published (listed at the end of the work as the author's publication list) or by the discussants of scientific posters related to the topic of this dissertation presented at scientific conferences.

Chapter 11 provides a summary and final conclusions leading to the proof of the dissertation hypothesis.

The most important of these are:

1. 3D and 2D visualizations of the morphology of the electric and magnetic fields during the process of EM field penetration and development inside the shielding enclosure,
2. The discovery of two phases of EM field development in a small not high metallic shielding enclosure with an aperture: the wave phase and the interference phase,
3. Electric charge distributions on the inner surfaces of the enclosure,
4. Electric and magnetic field distributions, electric charge, and surface current on the external surfaces of the enclosure,
5. An explanation of the origin and nature of the EM field inside the enclosure for two polarization cases of the disturbing pulse,

6. Original models of electromagnetic pulse penetration into the enclosure interior for two polarization cases of the disturbing pulse,
7. Time characteristics of electric and magnetic field intensity at selected points inside the enclosure,
8. The discovery and description of the change in the nature of electromagnetic interference inside the shielding enclosure with an aperture, consisting of the generation of a series of so-called subnanosecond internal EM pulses inside the enclosure,
9. Local time characteristics of electric and magnetic field shielding effectiveness,
10. Two-dimensional global maps of electric and magnetic field shielding effectiveness for selected times,
11. The relationship between the shielding effectiveness of the enclosure interior and physical processes (including the migration of free electrons) occurring on the metal surfaces of the enclosure with an aperture during the processes of EM field penetration and development inside the enclosure with an aperture.

Thus, the analysis of disturbing pulse penetration processes for two polarization cases (perpendicular and parallel) conducted in this dissertation demonstrated that it is possible to determine the electromagnetic shielding effectiveness of a small not high metallic enclosure with a technological perforation based on the analysis of the subnanosecond high-power EM pulse penetration simulation process into its interior. Therefore, the hypothesis posed in this dissertation has been confirmed.

The dissertation concludes with a list of references and a list of the author’s publications. The list of the author’s publications contains 10 items related to the topic of the dissertation (including 3 scientific articles published in journals from the JCR list) and 11 other scientific publications on different research topics (including 5 scientific articles published in journals from the JCR list). The list of references includes 63 items.