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Numerical investigation of radar reflection reduction of quadratic surfaces and conical sections made of aluminum in the X-band frequency range: A study based on electromagnetic permittivity and permeability

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Abstract

This research investigates the reduction of radar cross-section and electromagnetic signal loss in various geometric cross-sections, including conical sections and quadratic surfaces made of aluminum. Numerical solution was performed in the finite element software COMSOL and the cross-sections were coated with a layer of electromagnetic absorbers including carbon nanotubes, silica magnetite in an epoxy resin matrix. Simulations were performed in the X-band frequency range (8 to 12 GHz) considering environmental conditions similar to the incident electromagnetic wave. The results from the S11 element of the dispersion matrix indicate that the elliptical parabolic cross-section with a loss of -8.2 dB at 10 GHz has a significant loss of 84.6 percent of the energy. In addition, this cross-section offers an optimal impedance match in the range of 0.05 to 1 ohm, which helps improve the loss and propagation of electromagnetic waves. The elliptical geometry also achieves a loss of -8 dB at 9 GHz, which clearly demonstrates its importance in the design of stealth systems. In contrast, the spherical cross-section with an average loss of -0.08 dB, due to its surface uniformity, provides a significant performance for optimal antenna performance in detection. In general, the selection of appropriate geometry and absorbing materials has a significant impact on improving the efficiency and reducing the radar cross-section of defense systems. These results can help develop effective solutions to increase stealth capabilities in future designs.

Keywords: Radar cross-section, conical sections, aluminum, X-band, electromagnetic loss, absorbent materials

1. Introduction

Stealth technology is one of the common methods in the field of military surveillance, during which several techniques are used to conceal a structure from enemy radar. Today, the use of electromagnetic wave absorbing materials with low thickness and very high effectiveness in energy dissipation from antenna source signals is very important. Carbon-based materials with nanometer thickness, high electrical and magnetic conductivity, and unique morphological properties form the basis of radar evasive structures [1]. The most important frequency bands studied for long-range surveillance radars are the X-band (8-12) GHz and the Ku-band (12-18) GHz, where electromagnetic waves behave nonlinearly in these frequency ranges depending on the type and material of the cross-section, the distance of the wave to the antenna origin, the size of the cross-section area, etc. [2, 3]. Changing the geometry of the cross-section can be effective in scattering the radiated waves to the target surface. Changing the shape and creating structural complexities in the design, in addition to reducing the radar cross-section, can cause aerodynamic drag from the surface of the structure; therefore, one of the most common methods of reducing wave scattering fields is to modify the cross-section shape [4-5]. The use of two-element hyper surface arrays, which create a random distribution in the cross-section structure, can waste part of the received wave energy and convert it into thermal energy, causing a decrease in the reflection of electromagnetic waves from the surface of the structure. Figure 2 shows the antenna environment test setup for samples with two-element arrays, so that the electromagnetic scattering characteristics in the antenna environment with a transmitting antenna and a receiving antenna can be observed [6].

Given that numerous studies have been presented on the reduction of the radar cross-section of various geometric shapes, this study has specifically examined specific surfaces of geometric shapes, including quadratic surfaces and conical sections. In addition to the effect of the geometric parameters of the surfaces on reducing radar reflection, the effects of absorption, permittivity, and electromagnetic permeability of surfaces covered with nano-absorbent materials used in this industry have been numerically solved to depict the effects of electromagnetic scattering and loss using the analysis of S-matrix parameters. In general, choosing the right geometry along with electromagnetic absorbent materials can have a significant impact on reducing the radar cross-section and improving the efficiency of cloaking systems.

2. Numerical Method

In the definition of the experiment to be solved numerically in the COMSOL software, an electromagnetic network is designed in the electromagnetic conduction space with two input and output ports in such a way that the aluminum surfaces are located in the middle part of the waveguide. In such a way that, to increase the efficiency of the dissipation of the incoming electromagnetic energy, a one-millimeter layer in the form of a homogeneous mixture of multi-walled carbon nanotube dielectric and silica magnetite in an epoxy resin matrix is assigned to the cross-section surfaces as an average mass fraction, considering the mechanical properties of the materials. The input power equivalent to one watt is defined in the X-band frequency domain. Figure 1 shows the general scheme of the designed experiment in such a way that all cross-section surfaces in the middle part of this test are the target of oblique electromagnetic wave radiation.

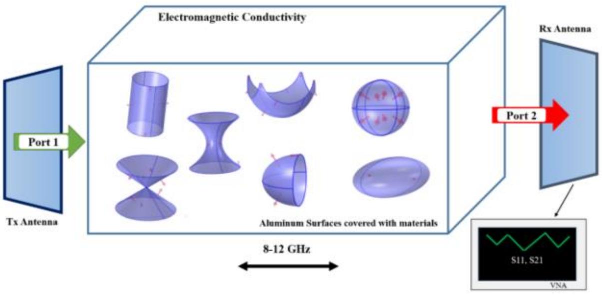

Figure 1. Electromagnetic waveguide test schematic designed in COMSOL software

Since the definition of the coating on the cross-sectional area in the numerical solution is defined as 22% by mass of carbon nanotubes, 16% nano-silica, and 62% epoxy resin matrix, Table 4 shows the dielectric ratio and surface conductivity of the materials used in the electromagnetic absorber coating.

Table 1. Electrical properties of surface coating materials

Material Name	Dielectric %	Coating conductivity (S/m)
Aluminium	1	3.8×10^{7}
MWCNT	5	1×10^{4}
Silica	4	1×10^{-10}
Epoxy Resin	3/5	1×10^{-12}

3. Reflection reduction results from the numerical solution

In this section, the results of the numerical study in the software are examined in the form of numerical values of absorption and transmission, electromagnetic graphs and absorption contours in the X-band frequency range, with an oblique angle of incidence. In Figure 2, the amount of radar signal loss for all cross-sections is given. The results indicate that, in the ranges between 8 and 10 GHz, the greatest changes in signal loss are observed, but in the range between 10 and 12 GHz, the signal loss values approach zero and even remain absolute zero in some cases, and include the least changes. For the elliptical parabolic geometry, the highest S_{11} value, which is in its most negative state, is in the 10 GHz frequency range, which includes a significant amount of electromagnetic dispersion and loss. In the next category, the elliptical cross-section, as a cross-section with significant curvature that is predicted to have the highest scattering of the incident wave, is recorded in the 9 GHz frequency range, equivalent to -8 dB, and for the integrated hyperbola in the same frequency range, the value is recorded as -7.8 dB.

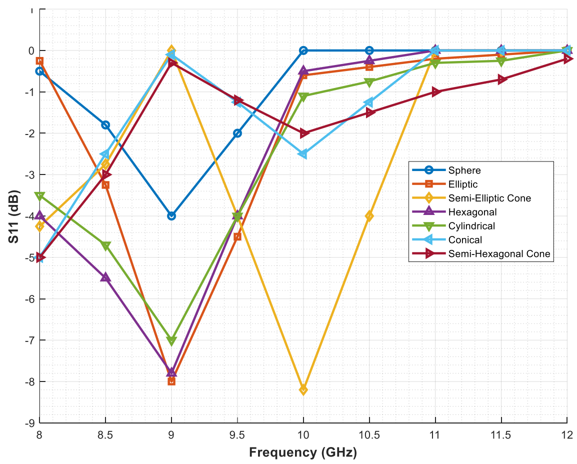

Figure 2. Plot of S_{11} values in decibels for all geometries in the frequency range

S_{21} means the transfer from port 1 to port 2, which depends on the permittivity and permeability of the material and the surface. If the type of material changes between the two ports, for example, from vacuum to dielectric, or if the surface and geometry of the structure change the distance between the two ports, this change can amplify or block the continuous wave passage and change the coupling angle. In general, materials with high conductivity coefficients can increase S_{21}. for the elliptical parabolic surface that had the highest signal loss, the transmitted energy value, unlike the reflection, reaches zero in the frequency range of 10 GHz and experiences its most positive state. For the hyperbolic, elliptical and cylindrical cross-sections that had the most negative reflection state in the 10 GHz range in the S_{11} diagram, the value of the S_{21} function approaches zero and is considered positive. As can be seen, in the final frequency ranges, assuming that the signal loss reaches zero, the transmission is at its most negative, up to a maximum of -120 dB, which indicates the highest reflection to the source and the lowest transmission, proving the inverse relationship between the values of S_{21} and S_{11}.

4. Results of Absorption

The contour of Figure 3 shows the electromagnetic loss and absorption in percentage. The elliptical parabolic geometry with an electromagnetic loss of 84.86% at 10 GHz shows the highest absorption among all shapes. This phenomenon is probably due to the special geometric structure of this shape that traps electromagnetic waves and converts them into heat. The spherical shape with an average absorption of 15.77% has the weakest performance, which is due to the higher reflection of waves from the regular and symmetrical surface of the sphere. High reflection in spherical structures is a well-known property in electromagnetics. The cylinder with an average absorption and loss of 34.69% and the elliptical parabolic with 34.95% show similar performance, indicating the importance of edges and angles in wave absorption. It is observed that most of the shapes have the highest absorption in the frequency range of 9 to 10 GHz, which can be related to the properties of the composite coating with a relative permeability of 3.91. The significant difference between the electrical conductivity of aluminum (38000000 S/m) and the composite coating (2200 S/m) indicates the use of materials with dielectric losses designed to absorb waves. The ellipse with an average absorption of 26.16% has an average performance, which indicates that the mere non-sphericality is not enough for high loss and that other geometric parameters are also involved. Although this geometry includes the most optimal loss mode in the 9 GHz range. In general, a frequency-dependent behavior is observed in all shapes, which is suitable for frequency-selective applications such as electromagnetic filtering. The conical surface with an average absorption of 23.13% has a relatively poor performance, probably due to the higher reflection of waves from its inclined surface. More complex shapes, such as a hyperbolic parabola with an average absorption of 28.35%, have moderate to high performance, indicating the effect of multiple curvatures on wave absorption. According to the results, it can be concluded that designing surfaces with complex curvatures is more effective for electromagnetic absorbers in the X-band than simple geometric shapes.

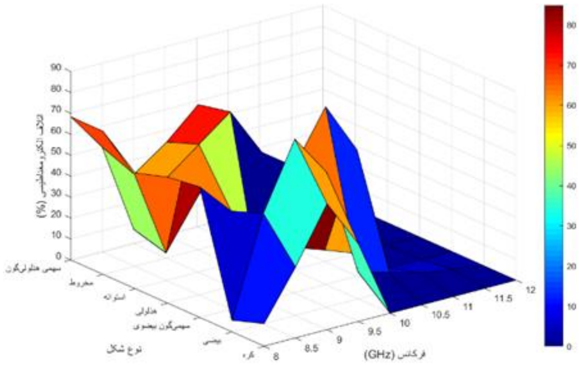

Figure 3. 3D contour diagram of electromagnetic absorption and loss in percentage for different geometries

5. Conclusions

In this study, a specialized study of the electromagnetic effect on conical sections and quadratic surfaces was conducted, which, unlike previous studies, focused mainly on specific geometric surfaces, including conical sections, and their effect on reducing the radar cross-section. This study not only investigated the effect of geometric parameters of surfaces on reducing radar reflection, but also analyzed the electromagnetic absorption, permittivity, and permeability of surfaces covered with absorbent nanomaterials through a numerical method and depicted the effects of electromagnetic scattering and loss using the analysis of S-matrix parameters. The results show that the elliptical parabolic section has the highest signal loss in the 10 GHz range, equivalent to -8.2 dB, which recorded the highest impedance match in the Smith reflectance chart in the range between 0.5 and 1 ohm; Also, for this surface, the highest peak of the graph in the 10 GHz range, which includes the highest variations in reflection loss, is known as the most optimal geometry in electromagnetic wave loss. In addition, based on the results of the admittance contours that define the inverse values of impedance, the elliptical parabolic cross-section with the highest input admittance of 6.5 Siemens in the 10 GHz range has the highest contribution and has shown the highest electrical permittivity close to that of vacuum and the highest magnetic permeability. This geometry, due to the inflection points and one-way curvature in the direction of the transmitted wave, can cause nonlinear distribution of the electromagnetic field and create more compact areas at certain frequencies. In contrast, the spherical surface recorded the lowest average reflection loss with a value of -0.8 dB in all frequency ranges, which indicates a very low impedance match and very high reflection among all the geometric shapes studied. This has led to the highest efficiency of the antenna in detecting radar waves. This result can be due to the uniformity of the surface and the geometric structure of the sphere, which shows a more optimal performance in wave reflection than sections with an elliptical surface. This study, with a special focus on quadratic procedures and conical sections, has opened new horizons in the field of designing surfaces with optimal electromagnetic properties for radar applications and can be the basis for future research in the field of developing smart materials and surfaces with the ability to control the reflection of electromagnetic waves.

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