An Optimized Microwave Absorber Geometry Based on Wedge Absorber

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Abstract **—** Low reflectivity of microwave absorbers is important to improve the performance of anechoic chamber measurements. The shape of the absorber as well as the material used are among the main components to provide desired low reflection performance. Pyramidal and wedge-shaped absorbers are two of the most well-known microwave absorber types. We discuss the effect of a convex shape on reflection performance of microwave absorbers and show that convex shape structure has significantly performance by absorbing most of the electromagnetic energy of the incident wave. We used a concavity theorem based design method to obtain a function for a convex shape. Absorbing structures have been analyzed by using the periodic moment method (PMM). An optimization method is employed to find coefficients of the convex function, which provides better absorption performance than the wedge type absorber. Reflection performances of the wedge and convex absorbers for the 2-12 GHz frequency band are compared. Their reflection performances at 2 GHz for different angles of incidence are presented. An important implication of this study is that the alternative absorber shapes other than the wedge shape are demonstrated by using simple mathematical methods to have the optimal reflection characteristics.

Index Terms **—** Anechoic chamber, electromagnetic scattering, electromagnetic wave absorption, microwave absorber, periodic moment method, periodic structures wedge diffraction.

I. INTRODUCTION

Unwanted or stray electromagnetic signal radiation such as electromagnetic interference (EMI), which usually radiate from electronic devices, can be a serious threat to living beings and cause faults on other electronics devices located nearby when radiation is strong [1-3]. Therefore, detection of them is very important. Microwave absorbers are used to eliminate these signals in microwave applications [4]. Many electronic systems are evaluated by using absorbers [5]. They are essential components for performing electromagnetic compatibility (EMC), EMI, radar cross section and antenna radiation pattern measurements accurately in a chamber instead of open field [1,4,6-10]. This chamber is called an “anechoic chamber” and is used to simulate a free space environment [4,11]. Microwave absorbers have dielectric or magnetic losses to absorb electromagnetic waves. The absorption capability of an absorber is depended on permittivity and permeability properties of the absorber material [12]. Absorbed electromagnetic waves are attenuated and their energy transformed into heat energy [4,13]. The two main categories of absorbers according to the working mechanism are resonating and graded (non-resonating) absorber structures [14]. Absorbers are used inside anechoic chamber surfaces (wall, ceiling, floor) to minimize reflection of incident electromagnetic waves and to perform measurements [14-18]. Absorbers having low reflectivity are preferable to trap most of the incident electromagnetic waves. Thus, almost perfect free space conditions are obtained in a chamber [6,19]. Various factors such as the electrical properties of the absorber material have an essential role in absorption performance of microwave absorbers [16]. The relative permittivity (dielectric constant) of the material used in an absorber is one of the most important factors [20]. It is a measure of the electrostatic energy stored in the material and affects the propagation speed of electromagnetic wave in the material [15,21].

The shape of the absorber used in the chamber also has significant importance on absorption performance in addition to other factors [22]. There are many types of absorber having different shapes, such as pyramidal, wedge, convoluted, among many others. The wedge-shaped absorber is one of the most well-known type which is also commonly used for EMC/EMI measurements [23,24]. Its wedge shape provides a suitable impedance match from free space to the base of the absorber [16].

Submitted On: November 24, 2016
Accepted On: February 1, 2017

Gradually impedance transition acts as an impedance matching network in order to have minimum amount of reflected EM wave [25]. On the other hand, while wedges are larger compared to a wavelength, incident EM waves are reflected numerous times between the sides of adjacent wedges before being reflected back [16]. Thus, a significant portion of its energy is absorbed upon each reflection due to the wedge-shape [26]. At higher frequencies, diffraction due to edges of wedge absorber contribute electric field significantly, which effects absorption performance of the absorber [27]. Therefore, numerical analysis of such structures need to take diffraction into account and Method of Moments (MoM) is one of techniques that can effectively incorporate such effects as well [28-30].

Here, we discuss obtaining an absorber shape by using a methodology that provides better impedance matching. Alternatively, obtaining a shape that will provide many bounces of an EM wave between sides of wedges before reflecting back.

Impedance transition of the wedge-shape absorber varies linearly from free space to the base of the absorber. For better impedance transition and multiple reflections between the sides of wedges, increasing of height of the wedge absorber is required. However, absorber height limits usable measurement space of the chamber and restricts usage of absorbers in small and semi-anechoic chambers [31,32]. Increasing available measurement space of the anechoic chamber is possible by using different absorber shapes that have the same or better absorption performance with lower height. Using nonlinear (curved) absorber shapes instead of a wedge type helps to improve the performance of the EMI/EMC measurements and available space in the chamber [32]. In addition, nonlinear absorber shapes provide smoother nonlinear impedance transition and/or many more reflections between the wedge sides [32].

Within this framework, the contribution of this study is proposing a method to obtain surface functions for absorbers that have better absorption performance than a wedge-shape absorber. Scattered electric fields from absorber structures have been analyzed by using the PMM. Reflection values of the plane electromagnetic wave that is E-field polarized along the axes of the absorber structure (TM case) are calculated. Since the TM case reflection performances are worse than the TE case performances, the scope of the study is limited for the TM case only [27].

Organization of the paper is as follows: Analyzing periodic absorber structures by using PMM is briefly explained to provide a background, followed by a discussion of the reflection performance and impedance transition relation. Then, a general method is proposed to obtain surface functions of the periodic structure by using the concavity theorem. Obtaining second order convex polynomial functions is demonstrated as a simple example. Numerical results of the wedge and convex absorber structures are presented in the results section, and finally conclusions given in the following section.

II. METHODS

A. Analyzing periodic absorber structures

Reflection performances of periodic absorber structures illuminated by a plane wave can be obtained by employing the PMM. Assuming that a TM polarized plane electromagnetic wave which has $e^{j\omega t}$ time dependency is incident upon singly-periodic structure having a period "L". Spectral domain expression of scattered E-field from structure is given by a well-known equation [33]:

$$\boldsymbol{E}^s(\boldsymbol{x},\boldsymbol{y}) = -(j\frac{k^2}{2L})\sum_{p=-\infty}^{\infty}\iint(\varepsilon_r - 1)E_0(\boldsymbol{x}',\boldsymbol{y}')\frac{e^{-j(x-x')\beta_{1p}}.e^{-j|y-y'|\gamma_{1p}}}{\gamma_{1p}}dx'dy', \tag{1}$$

where

$$\beta_1 = ks_x,\ \beta_{1p} = \beta_1 + p\frac{2\pi}{L},\ \gamma_{1p} = \sqrt{k^2 - \beta_{1p}^2}. \tag{2}$$

Since the vector sum of the scattered and incident electric field vectors is equal to the total electric field at any point as given in expression (3), the scattered field can be calculated by using PMM:

$$\boldsymbol{E} = \boldsymbol{E}^i + \boldsymbol{E}^s. \tag{3}$$

PMM is based on dividing a cross section of the reference element into small size cells and calculating the scattered field by solving linear independent algebraic equations. The size of cells is selected in order to be small enough to consider dielectric constant and electric field density in each cell to be constant. A detailed explanation of the PMM is given in study [32].

MATLAB code is developed based on PMM in order to obtain reflection performances. Since MATLAB performs vector and matrix operations efficiently, complex matrix operations are calculated rapidly.

B. Reflection performance and impedance transition relation

Microwave absorbers need a smooth transition from air into the absorber in order to enhance impedance matching and complete absorption of the wave inside the absorber in order to achieve the desired low reflectivity properties [34,35]. Wedge or pyramidal-shaped absorbers have linear surfaces and they have good reflection performances because of linear impedance matching between air and absorber. Reflection performances of absorbers that have non-linear surfaces and impedance matching properties are different. Comparison of the reflection performances of the absorbers that have wedge, concave and convex surfaces are shown in Fig. 1 to specify the differences between them. The reflection performance of a wedge-shaped absorber is better than a concave-shaped one, and a convex-shaped absorber has the best reflection performance. A convex-shaped absorber also has smoother impedance transition than both of concave-shaped and wedge-shaped absorbers. It is possible to obtain better impedance transitions by changing parameters of the related convex surface function such as polynomial functions, power function, exponential function etc.

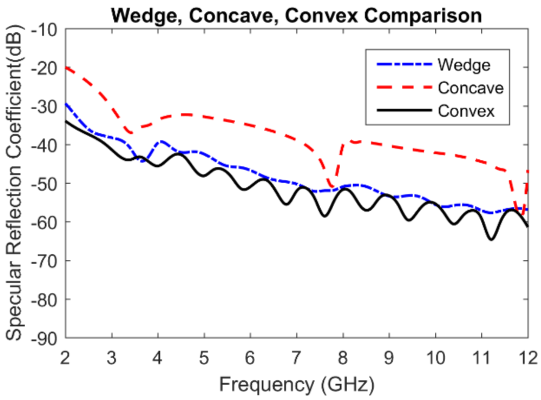


Fig. 1. Comparison of the reflection performances of absorbers that have wedge, concave and convex surfaces.

C. Design of convex shape 1-D microwave absorber function

Assume that the cross-section of the reference element of any lossy structure at the origin of the *x-y* plane, which has period “*L*”. It consists of two symmetrical half parts in the interval [*-L/2,L/2*]. Finding the function for the half in the interval [*0,L/2*] as a function of “*x*” defines the symmetrical half of the reference element in the interval [*-L/2,0*].

Any function *f(x)*, which has a second derivative at each point in the interval [*0,L/2*] and meets the $f'''(x)>0$ condition in this interval, is a convex (or concave upward) function according to the concavity theorem. Boundary values of the function are $f(0)=h$ and $(L/2)\geq 0$. Where “*h*” is height of the reference element. Several convex functions such as polynomial functions, power function, exponential function etc… could be observed to satisfy conditions of the concavity theorem. Second order convex polynomial functions, as an example, are one of the simplest such functions for which determine coefficients.

A second order convex polynomial function *f(x)* which has a constant positive second derivative value, $f'''(x)=a$ in the interval [*0,L/2*] is shown in the expression below:

$$f\ (x)\ =\ \frac{a}{2}x^2+bx+h. \tag{4}$$

A convex function with a local minimum point outside the interval [*0,L/2*], is shown in expression (5) and satisfies the $f(0)=h$ and $f(L/2)=0$ boundary conditions. It is a decreasing function. The condition for the first order derivative at the point *(L/2,0)* is $-2h/L\leq f'(L/2)\leq 0$. Thus, the condition for “*a*” values is $0\leq a\leq 8h/L^2$,

$$f\ (x)\ =\ \frac{a}{2}x^2+\left(-\frac{aL}{4}-\frac{2h}{L}\right)x+h. \tag{5}$$

For a convex function, which has its local minimum point (x_m,y_m) inside the interval [*0,L/2*], is shown in expression (6). It satisfies $f(x_m)=0$ and $f'(x_m)=0$ conditions. Thus, $a\geq 8h/L^2$ for “*a*” values are obtained by using these conditions,

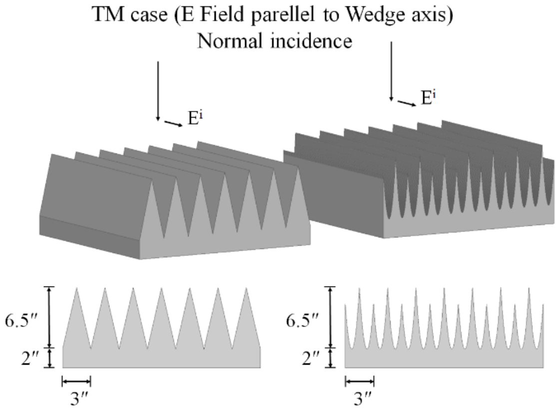
$$f(x)=\frac{a}{2}x^2-\sqrt{2ah}x+h. \tag{6}$$

Various convex periodic surface functions with different absorption performances satisfying the concavity theorem can be derived by using different second derivative functions.

D. Periodic structure based on second order convex polynomial function

Absorber structure configuration based on second order convex polynomial function is designed as an example by adding 2 inches of base thickness. Constrained nonlinear optimization method is used to obtain the “*a*” value indicated in expressions (5) and (6). Optimized convex functions provide the best reflection result. Reflection values of several frequencies along 2-12 GHz frequency band are calculated. Reflection values at these frequencies are limited to be better than a predetermined limit value. This limit value is determined to satisfy the stated condition. The average value of them is considered as the objective function for optimization.

The absorption performance of the structure with the obtained “*a*” value by using optimization as shown in the Fig. 2 (b).



(a) (b)

Fig. 2. Dimensions of the compared periodic structures: (a) wedge structure, and (b) second order convex polynomial function based structure.

The “*a*” value indicated in expressions (5) and (6) is obtained as $a=20.7439$ for the analyzed structure. The local minimum of the function is inside the interval [*0,L/2*] which is seen in Fig. 2 (b). This “*a*” value provides the best absorption performance for TM mode plane electromagnetic wave normal incident case.

Total calculation time of the PMM is an important factor while performing optimization and reflection calculations. The Conjugate Gradients Squared Method with precondition is used in MATLAB PMM code to enhance calculation time while calculating matrix inverses.

III. RESULTS & DISCUSSION

Reflection coefficients of the wedge type and designed convex absorber structures are calculated by using PMM. Interpolation is used before plotting graphs of the reflection performances to obtain smooth curves. The base width of the periodic structures is three inches, base thickness is two inches and wedge height is 8.5 inches. The dielectric constant of the black wedge material shown in studies [27,32] has been used for PMM calculations.

Dimensions (base widths, base thicknesses and wedge heights) based on the black wedge absorber in studies [27,32] are used for analysis of the wedge type absorber in this study to validate developed MATLAB PMM code. The specular reflection coefficient versus frequency plot of the black wedge absorber shown in Fig. 73 on page 117 in study [27] is obtained with extended frequency band (2-12 GHz frequency band instead of 2-8 GHz). Same base widths, base thicknesses and wedge heights with the wedge type absorber are used for analysis of the designed absorber to compare their reflection performances.

Comparison of the reflection performances are shown in Fig. 3. Absorber structures are illuminated by normally incident TM mode plane electromagnetic wave at the 2-12 GHz frequency range with a step of 0.1 GHz. By comparing the wedge type and convex absorber structures, the results in the figure show a significant improvement in performance for the designed convex absorber structure relative to the wedge type. It has almost 17 dB better reflection performance, which is -46 dB, at 2 GHz. It also provides better reflection more than 14 dB at several frequencies such as 2.4 GHz, 6.6 GHz and 10 GHz. Its reflection values at 3.7 GHz, 8.1 GHz and 12 GHz frequencies are not more than reflection values of the wedge absorber.

It is clear that the proposed absorber has a sharper geometry than conventional wedge absorbers. It also has more edges. Therefore, edge diffraction has much more dominant effects on the absorption performance of the proposed absorber. On the other hand, for arbitrary shaped parametric surfaces, it is not straightforward to formulate absorption performance which includes diffraction effects. In this context, the basis of this research is optimizing absorption performance through incorporating diffraction effects numerically.

Figure 4 shows the reflection coefficient versus the angle of incidence for the wedge type and convex absorber structures at 2 GHz. The convex absorber structure provides reflection performance of -46 dB for normal incidence case. Its performance is almost 17 dB better than the wedge absorber, which has approximate -29 dB reflection performance. The convex absorber structure also provides better reflection performance values for the oblique incidence case than the wedge type. For a 70 degrees angle of incidence, while the wedge type provides approximately a -7 dB reflection value, the convex absorber structure gives -9.3 dB reflection performances. It has almost a 2 dB better value than the wedge type. The convex absorber has almost a 10 dB better reflection performance for angles of incidence of less than 30 degrees.

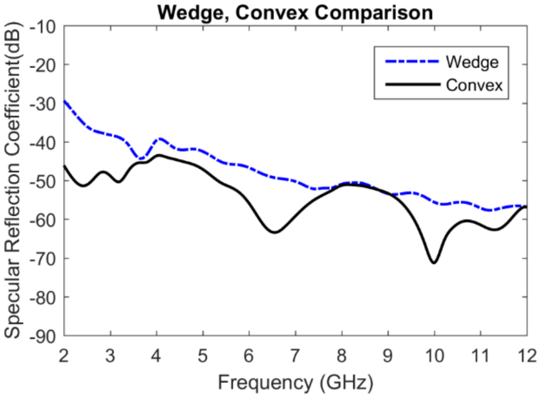


Fig. 3. Comparison between the wedge type and convex absorber structures for the 2-12 GHz frequency range.

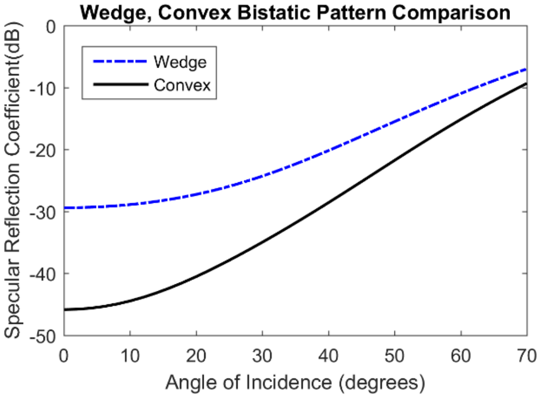


Fig. 4. Comparison of the bistatic pattern performances for the wedge type and convex absorber structure.

IV. SUMMARY & CONCLUSIONS

A design method for obtaining absorber geometry for better reflection performance, among the wedge types has been explained in this study. The concavity theorem is used to obtain convex function for determining absorber geometry. Absorber structure configuration based on second order convex polynomial function is designed as an example. The range of the unknown parameters of the function are calculated by using boundary conditions. Optimization is used to obtain specific values of the parameters of the function which give optimum results. By considering the optimized parameters of the function associated with the boundary conditions of the periodic structure, absorption performance values for the total frequency range have been calculated. Also, reflection values versus angle of incidence are obtained. Comparison of the reflection performances of the absorber structures have been presented.

A designed convex absorber structure has significantly better absorption performance and it is an ideal absorber to enhance measurements at low signal levels. It can be used to increase the available measurement space of the chamber. For a wide frequency range, a designed absorber structure has better performance than the wedge type for both, the normal and oblique incidence cases.

In terms of manufacturing of absorbers, non-wedge shape of absorbers as design in this study can be produced with CNC controlled foam cutting equipment for smaller quantities. They can be produced with mould fabrication for mass production. However, a single cut through a foam block with foam cutting technique and obtaining two similar absorber panel to maximize factory production cannot be performed because of non-complementary geometry of non-wedge shapes. Thus, small amount of unused material is wasted during production.

The results of experimental works based on theoretical studies presented in this work are planned to be verified as future studies. Calculation of unknown parameters of the higher order functions and design of absorber structures will be discussed in a future study as well.

ACKNOWLEDGEMENT

This research has been supported by the Istanbul Technical University BAP Foundation, project number 36033.

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