論文

적층 복합재 판을 이용한 전자기파 흡수 구조체의 설계

오정훈*, 오경섭**, 김천곤*+, 홍창선*, 이동민***

Design and Analysis of Electromagnetic Wave Absorbing Structure Using Layered Composite Plates

Jung-Hoon Oh*, Kyung-Sub Oh**, Chun-Gon Kim*+, Chang-Sun Hong*, and Dong-Min Lee***

ABSTRACT

The absorption and the interference shielding of the problems for both commercial and military purposes. In this study, the minimization of the electromagnetic wave reflections using composite layers with different dielectric properties was performed. Dielectric constants were measured for glass/epoxy composites containing conductive carbon blacks and carbon/epoxy fabric composites. Using the measured permittivities of the composites having various carbon black contents, the optimal electromagnetic wave absorbing structure in X-band(8.2GHz-12.4GHz) was determined. The optimal multi-layered composite plates have the thickness of 2.6mm. The maximum reflection loss is -30dB at 10GHz, and the bandwidth having the absorptivity lower than -10dB is about 2GHz.

초 록

군사적 목적뿐만 아니라 상업적 목적에서도 레이더나 기타 전자파를 방출하는 기기들로부터 생성되는 전자파의 흡수 또는 차폐는 매우 중요한 일이다. 본 연구에서는 다른 유전적 성질을 가지는 복합재층을 배열하여 전자기파의 반사를 최소화하는 연구를 수행하였다. Glass fabric/epoxy에 전도성을 가지는 카본블랙 분체를 혼합한 복합재와 Carbon fabric/epoxy 복합재 대한 유전성질을 측정하였고, 이를 이용하여 X-band(8.2 GHz-12.4GHz)에 대한 전자기파 반사의 최소화 구조를 구성 하였다. 두께2.6mm의 다층 구조로 최대 30dB 이상의 반사 손실과 최대 흡수 주파수로부터 2GHz 주파수 대역에 걸쳐 10dB이상의 반사손실을 일으킬 수 있었다.

1. Introduction

The absorption and the interference shielding of the electromagnetic wave problem become a very important issue for both commercial and military purposes. The interference shielding study is a matter of interest in the MHz frequency ranges generally used by commercial fields. The studies of higher frequency range are confidentially performed for military purposes. But in recent year electromagnetic wave studies in the high frequency range are becoming more

* 한국과학기술원 기계공학과 항공우주공학전공
*+ 한국과학기술원 기계공학과 항공우주공학전공, 교신저자(E-mail:cgkim@kaist.ac.kr)
** 한국과학기술원 전자공학과
*** 국방과학연구소

important because the commercially used frequencies are shifting to the higher frequencies.

Generally electromagnetic waves are absorbed by lossy coating materials which are composed of dielectric or magnetic lossy material mixed with flexible mediums such as rubber or epoxy etc. Coating materials can easily adhere to metal surfaces but need frequent repairs due to the poor structural strength. Recently the amount of composite materials used for aircrafts, ships and automobiles is rapidly increasing. Following this trend, adding lossy materials to composites in itself, we developed the electromagnetic wave absorbing structure having sufficient structural strength without an additional coating procedure.

Electromagnetic wave is composed of electric and magnetic fields. The electrical and the magnetic property of materials are represented by permittivity and permeability, respectively. The electromagnetic wave absorption is made possible by mixing various additives which can change the permittivity or the permeability of the composites. Of these two methods, the permeability control method uses magnetic additives such as ferrite. But general magnetic additives have the defect of weights and other bad characteristics. The resonance frequency producing magnetic losses exists in the MHz range and beyond this range, the loss efficiency rapidly decreases. So in X-band range, ferrite materials can not be used without special processing. The permittivity of a composite can be controlled by way of mixing carbon black or silver particles etc. which enhance the conductivity within the medium. There is a certain limit in the additive content which gives absorbing ability of electromagnetic waves. Beyond this limit, most of waves are reflected at the surface before absorption.

In this study, the minimization of the electromagnetic wave reflections in X-band with center frequency of 10GHz was performed. Glass/epoxy fabric having good transmission property is used as the front layer with the lossy material, carbon black. And the excellent reflector, carbon/epoxy fabric is used as the back layer. This layered structure functions as the absorption and the interference shielding of electromagnetic waves simultaneously. We designed the optimal electromagnetic wave absorbing structure using the muti-layers with various carbon black contents.

2. Manufacture of Composite Prepreg

Vulcan XC-72 conductive carbon black was supplied by Cabot Carbon Ltd, USA. The specific gravity is 1.8 and the particle diameter is 27nm. The composite Prepreges, carbon fabric/epoxy prepreg CF-3327EPC and glass fabric /epoxy prepreg K618 were supplied by HANKUK FIBER Co., Ltd.

Table 1 Specimen denotations of glass fabric/epoxy composite

Denotation	CB0	CB5	CB6	CB7
Contents of carbon black	0%	5%	6%	7%
Denotation	CB8	CB10	CB15	CB20
Contents of carbon black	8%	10%	15%	20%

The carbon black contents by weight percentage of the specimen are denoted for each type of specimen as shown in Table 1. The specimens of the glass fabric are impregnated by epoxy with carbon black. At first, the mixing of epoxy and carbon black was accomplished and uniformly applied to glass fabrics. For the specimens of carbon black content over CB15, the viscosity increased rapidly and it was hard for the specimen to keep the uniformity in carbon content.

S-parameters in the frequency range of 8.2-12.4GHz were measured using network analyzer and X-band wave-guide as sample holder. Sample size is 10.1mm×22.9mm and thickness is different for each case. Permittivity was calculated based on the measured s-parameters.

3. Permittivity

The permittivity, ε, μ and the permeability, , representing electromagnetic characteristic are complex values and defined by the follow equations:

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \qquad \mu_r = \mu_r' - j\mu_r'' \tag{1}$$

The subscript r means the relative value to the permittivity or permeability of air. The permeability of the specimens is expressed as 1(real term)-j0(imaginary term) because glass/epoxy and carbon black are inert in the magnetic property. Therefore the specimens have only dielectric property and the permittivity values are shown in Fig. 1 and Fig. 2.

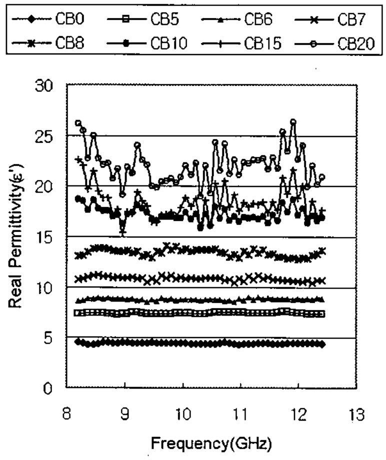

Fig. 1 Real part of permittivity vs carbon black content.

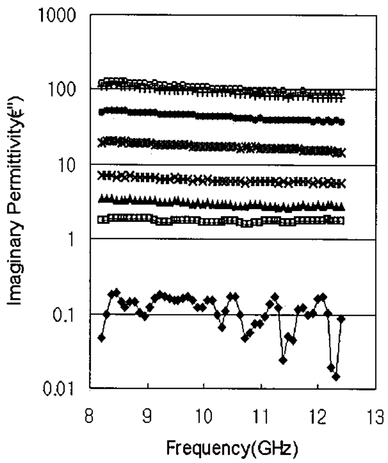

Fig. 2 Imaginary part of permittivity vs carbon black content.

Real part of permittivity for the specimen above CB10 shows variation along the frequency range. This is thought to be caused by uneven distribution due to excessive carbon black content in mixing process and wave leaks between specimen and wave-guide. The more additives are added, the smaller the amount of transmitted waves(S_{12}) used in calculation of permittivity is. If S_{12} approaches leaks, we can not distinguish between the real value and the experimental errors. When measuring the electromagnetic characteristics of lossy material, we must pay attention to the sealing between the specimen and wave-guide. In this measurement we used silver coating at the sides of specimens and minimized the gap between the specimen and wave-guide. For the specimen with carbon content above CB10, the measured value of the imaginary permittivity rapidly increased over 40. As increasing carbon black contents, dielectric properties show conductive characteristic. This critical threshold value exists nearby CB10. If the imaginary part of permittivity has high value, almost electromagnetic waves are reflected at a surface like metal. Then it is possible to shield electromagnetic waves but impossible to minimize reflection of incident waves. Thus, CB5, CB6, CB7 and CB8 having proper loss values could be the candidates of absorbing material that is used for front layers of the electromagnetic absorbing structure. And the permittivity of carbon/epoxy fabric hard to be measured because S_{12} value is near 0. Their electric resistance is $10^{-4}\Omega$m and reflection coefficient calculated from the electric resistance is 0.9895. These values are almost same as those of metal.

4. Eletromagnetic Wave Absorbing Structure

For the minimization of reflection waves, required is the impedance-matching condition. When the single-layered matching-type absorbing structure with a metal back-surface receives a plain wave, the incident impedance Z_{in} normalized by that of free air, Z_0, is

$$Z_{in}= Z_0\sqrt{\frac{\mu_r}{\varepsilon_r}}\tanh\left[j2\pi df\sqrt{\mu_r\varepsilon_r}\right] \qquad (2)$$

In this case, $Z_0=Z_{in}$ satisfies the zero-reflection condition. Eq.(2) has six variables such as $\mu_r', \mu_r'', \varepsilon_r', \varepsilon_r'', f, d$. The meaning of Eq. (2) is that if electromagnetic waves with frequency f enter to an absorbing material with electromagnetic properties of $\mu_r', \mu_r'', \varepsilon_r', \varepsilon_r''$, the material has a matching thickness d. In terms of design, minimization of matching thickness is the main objective by controlling the permittivity and permeability for a given working frequency. Reflection coefficient and reflection loss are defined by the follow equations

$$R = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} = \frac{\frac{Z_{in}}{Z_0} - 1}{\frac{Z_{in}}{Z_0} + 1} \qquad (3)$$

Reflection loss (dB)= 20 log | R|I

The finite element code that is able to calculate reflection losses of multi-layered composites plates was developed and the multi-layered absorbing structure with maximum reflection loss was analyzed using the code.

5. Single-Layered Absorbing Structure

The single-layered absorbing structure is consisted of a front layer of CB5 or CB6 etc. and a back layer of carbon fabric/epoxy. Because the layer of carbon fabric/epoxy functions only as a reflector like a metal surface, it is termed not to be a double layer but single layer. For the specimens with carbon black contents over CB10, the maximum reflection loss is only -2.5dB owing to high reflection on the surface. And a matching status can be found at CB5, CB6 and CB7. The best simulated case has the matching thickness of 2.7mm in CB6 with a working frequency of 10GHz. The variation of the reflection loss with thickness is shown in Fig. 3 for the specimen of CB6.

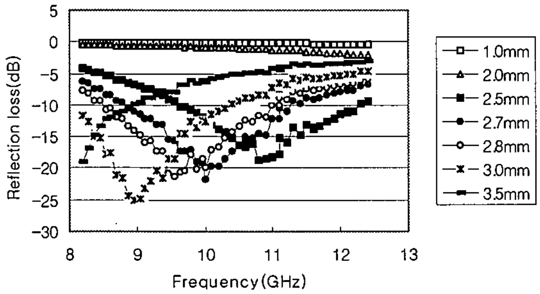

Fig. 3 Simulated reflection loss of glass fabric/epoxy composites with 6w% carbon black (CB6).

A matching status is not observed for the thickness below 2.0mm. As the thickness increases, matching frequency shifts to the lower frequency. The specimen with 2.7mm thickness shows maximum loss(about -20dB) at working frequency of10 GHz and -10 dB absorption is predicted from 9GHz to 11GHz. This bandwidth remains unchanged with the thickness variation. Generally speaking, the reflection loss of -20dB corresponds to an excellent performance.

6. Multi-Layered Absorbing Structure

The reflection loss was simulated for the multi-layered plate composed of laminate, CB5, CB6, CB7 and CB8. All cases were simulated with 0.1mm thickness steps. The best double-layered structure is the combination of CB5 1.9mm and CB7 0.7mm. And the best triple-layered structure is the combination of CB5 1.4mm, CB6 0.7mm, CB7 0.5mm. Fig. 4 shows the comparison of absorbing performance among a single-layered structure and multi-layered ones.

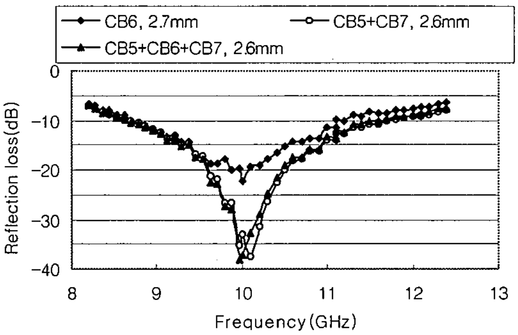

Fig. 4 Reflection loss of single and multi-layered absorbing structures.

The multi-layered structure shows improved performance in both thickness and the reflection loss. The matching thickness of the multi-layered structure is smaller than that of single-layered one by 0.1 mm. The maximum reflection loss and -20dB bandwidth significantly are improved. But improvement in the performance is not obvious between the double and triple-layered structures. Thus we selected the double-layered structure for the optimal electromagnetic absorbing structure.

7. Experimental Results

The selected optimal structure was tested and compared with the calculated result. The specimen is composed of CB5 1.9 mm, CB7 0.7 mm and carbon fabric/epoxy of thickness

1.75 mm in series. The result of reflection loss is shown in Fig. 5.

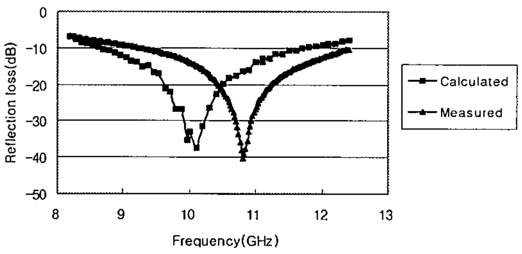

Fig. 5 Measured and calculated reflection loss of the optimal absorbing structure.

The two cases have almost the same value in the absorbing bandwidth and maximum loss. But the measured central frequency shifted by 0.8 GHz to the higher frequency. There are two possible reasons. One is the experimental problem of wave-guide in which the TM(Transverse Magnetic) mode of plain wave in wave-guide didn't have a perpendicular incident angle to the surface of the specimen. The other is the measurement error in the permittivity which was used in the calculation of the reflection loss.

8. Conclusion

Structures absorbing electromagnetic wave of X-band region have been designed and fabricated using fiber-reinforced composites and dielectric loss material, carbon black. Multi-layered structures showed improved performance in the electromagnetic wave absorption compared to the single layered ones. The selected optimal double layered structure is composed of CB5 1.9mm and CB7 0.7mm. Maximum reflection loss is about -40dB at 10GHz and the bandwidth having the absorptivity -10dB is about 2GHz .

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