Design of Stealth Bulletproof Material Based on Sub-Wavelength Absorbing Structure

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Abstract. When stealth bulletproof materials achieve performance through simple superposition of layers and layers, there is a problem that the weight is heavier, and the coating or patch is easy to fall off, and the absorption rate is lower. In order to reduce the weight, broaden the frequency band, and increase the absorption rate, functional integrated design method based on absorbing sub-wavelength structure is adopted. According to the design principle of the absorbing sub-wavelength structure, a lightweight ballistic material is used as its dielectric substrate. Microstructure graphics are designed on the bulletproof medium. With the fusion of stealth and ballistic performance, the design of a new wide-band stealth ballistic material was completed. Test results show that the absorbing sub-wavelength structure based on the lightweight bulletproof material has an absorption rate of more than 90% in a wide frequency band of 4GHz to 18GHz and 27GHz to 40 GHz, which does not affect the ballistic performance of the ballistic material itself, and reduces the stealth material layer in the stealth ballistic material. The effect of reducing thickness and weight loss is achieved. The feasibility of this method is verified, which is of great significance for improving the combat capability of new functional vehicles.

1. Introduction

With the rapid development of high-tech combat equipment such as reconnaissance, precision guidance, and high-power microwave weapons, the threat of attack weapon systems to ground armored vehicles has become increasingly prominent. The new generation of ground armored vehicles needs to have good bulletproof, stealth, and lightweight performance [1]. Hengyang Taihao Communication Vehicle Co. Ltd. proposes a radar stealth bulletproof plate. It is made of low-areal density PVC structural foam wall panel and radar absorber. The absorber uses ultra-high molecular weight polyethylene fiber. Its reflectivity is 10dB-12dB, the radar cross-sectional area can be reduced by 9/10. It has strong anti-ballistic performance, lightweight and good rigidity [2, 3]. Huang Xiaozhong of Central South University proposes a lightweight stealth bulletproof plate. It consists of glass steel sheet layer, wave absorbing layer, aluminum plate, bulletproof layer, etc. When the areal density is 21.85 kg/m\textsuperscript{2}, it can defend 56-type rifles. 7.62 mm ordinary steel core bullet does not break through at 100m vertical shooting distance. Minimal RCS reduction greater than 7dB [4].

At present, the functional requirements of functional combat vehicles for lightweight, bulletproof, and stealth functions, the main method is to coat the surface of the metal shell with a stealth coating or an external absorbing patch. However, the stealth coating is easy to fall off, and the absorption band is
narrow, and the strong absorption is seriously insufficient, the external stealth patch has caused significant weight gain for combat vehicles. So in response to the above problems, dielectric substrate of the absorbing sub-wavelength structure uses the bulletproof material. A new algorithm of bulletproof/wave absorbing fusion design is established based on electromagnetic resonance sub-wavelength structure, the current shortage of stealth bulletproof materials is solved. Fusion design of absorbing sub-wavelength structure and light armor protection material is achieved. Under the premise of not sacrificing the bulletproof effect of the lightweight armor protective material and not significantly increasing the thickness, the goal of wideband wave absorption is achieved and functional integration is achieved.

2. Design Principles of Multi-Layer Absorbing Sub-Wavelength Structure

The broadband stealth bulletproof material is mainly based on the sub-wavelength structure of the absorption principle [5]. Absorbing sub-wavelength structure as one of the technical ways to realize the function of stealth materials, the artificial microstructure unit whose size is much smaller than the wavelength of the electromagnetic wave acts as an “atom” to form a uniform equivalent artificial structure. Its macroscopic properties are determined by the artificial microstructure unit [6]. The periodic structure of the absorbing sub wavelength structure is often made of copper film, silver film, ITO, carbon film, etc.; the dielectric layer is mostly foam, glass, composite materials, etc.; the bottom layer is good conductors such as metal films, conductive fiber reinforced composite materials. Schematic diagram of multi-layer impedance absorbing material structure is shown in figure 1.

According to transmission line theory, the first layer of material and metal can be regarded as a medium of input wave impedance $z_{in}^{(1)}$.

$$z_{in}^{(1)} = \eta_1 \tanh(jk_1d_1)$$  \hspace{1cm} (1)

The second layer of material and the medium of $z_{in}^{(1)}$ can be regarded as a medium of input impedance $z_{in}^{(2)}$.

$$z_{in}^{(2)} = \eta_2 \frac{z_{in}^{(1)} + \eta_2 \tanh(jk_2d_2)}{\eta_2 + z_{in}^{(1)} \tanh(jk_2d_2)}$$  \hspace{1cm} (2)

Substitute equation (1) into equation (2), then:

$$z_{in}^{(2)} = \frac{\eta_1 \tanh(jk_1d_1) + \eta_2 \tanh(jk_2d_2)}{1 + \frac{\eta_1 \tanh(jk_1d_1) \tanh(jk_2d_2)}{\eta_2}}$$  \hspace{1cm} (3)

The Nth layer of material and the medium of $z_{in}^{(n-1)}$ can be regarded as a medium of input impedance $z_{in}^{(n)}$.

$$z_{in}^{(n)} = \eta_n \frac{z_{in}^{(n-1)} + \eta_n \tanh(jk_nd_n)}{\eta_n + z_{in}^{(n-1)} \tanh(jk_nd_n)}$$  \hspace{1cm} (4)

![Figure 1. Schematic diagram of multi-layer impedance absorbing material structure.](image-url)
Reflection coefficient on the first boundary:

\[ R = \left| \frac{z_{in}^{(2)} - 1}{z_{in}^{(2)} + 1} \right| \] (5)

According to the above formula, it can be concluded that the multilayer impedance allosteric absorbing material has significant microwave absorption performance, because there are multiple parameters that can be adjusted. By adjusting the shape and size of the periodic unit structure, the thickness of each layer, the relative complex permittivity and relative complex permeability to control its effective permittivity and permeability, to achieve impedance matching with free space, so that the reflectance approaches zero, and it has the best absorbing performance.

3. Design of Bulletproof Materials

High-strength fibers are widely used in the field of protection due to their low density, high tensile strength, and high elastic modulus. They are mainly glass fibers, aramid fibers, ultra-high molecular weight polyethylene fibers, and PBO fibers. The performance parameters of the fiber are shown in table 1. Compared with other types of fiber, glass fiber has high density and low modulus. Aramid fibers have lower density, higher tensile strength and modulus [7]. Ultra-high molecular weight polyethylene fibers have the lowest density and higher tensile strength. The tensile strength of PBO fiber is the largest, but the current market price is higher.

Based on comprehensive density, modulus, tensile strength, and price factors, the fibers most currently used as bulletproof materials are aramid fibers and ultra-high molecular weight polyethylene fibers. This study mainly focused on the anti-elastic properties of ultra-high molecular weight polyethylene fibers.

| Material | Density (g·cm⁻³) | Tensile modulus (GPa) | Tensile strength (GPa) | Elongation at break (%) |
|----------|------------------|-----------------------|------------------------|-------------------------|
| S-2Glass | 2.5              | 87                    | 4.8                    | 5                       |
| Kevlar 29| 1.44             | 70                    | 2.9                    | 4                       |
| Kevlar 49| 1.45             | 135                   | 2.9                    | 2.8                     |
| PE       | 0.97             | 110                   | 3.5                    | 3.5                     |
| Tcarbon fiber 300 | 1.76 | 230                   | 3.6                    | 1.5                     |
| PBO AS   | 1.54             | 180                   | 5.8                    | 3.5                     |

Ultra-high molecular weight polyethylene unidirectional cloth is used [8]. The fiber direction is 0°/90°, the areal density is 22.5 kg/m², and the thickness of the sample is 25 mm. The failure cross-sectional view and residual bomb figure after testing are as follows. The front part of the target plate is mainly damaged by shear, and there are some insignificant delamination phenomena. The fiber tip has traces of high temperature melting. The second half of the target plate mainly absorbs the energy of the projectile in a stretched form and presents it in the form of a back convex. The unpenetrated thickness is 13.7 mm, and the hump height is 16 mm. Visible delamination appeared on the back of the target. It can be seen that the main energy consumption forms of the target plate are: shear failure energy consumption, delamination energy consumption, fiber melting energy consumption, and fiber stretching energy consumption. The original core weight was 4.84 g, and the measured mass of the recovered core was 4.60 g. It shows that the missile core has almost no mass loss during the penetration of the projectile. PE laminated board anti-53-type 7.62 mm ordinary bomb failure cross section and residual bomb body diagram are shown in figure 2.

Based on the test results, a simulation model of a 53-type 7.62 mm ordinary bullet penetrating the PE (polyethylene) laminated was established [9]. The simulation results show that the critical thickness of the PE board protection 53-type 7.62 mm ordinary bomb is 16mm. As shown in figure 3...
below, the penetration depth is 15 mm, serious delamination occurs inside, and the back deforms greatly.

Figure 2. PE laminated board anti-53-type 7.62 mm ordinary bomb failure cross section and residual bomb body diagram.

Figure 3. Section view of the penetration of ordinary steel core bullets into 16 mm PE laminated.

4. Design of Absorbing Sub-Wavelength Structure

The absorbing sub-wavelength structure designed in this paper is a multilayer periodic structure. Each periodic structural unit is formed by stacking four layers of resistance film and five layers of PE fiber laminated. The surface resistance of each layer of resistance film is different. According to the equivalent model of the transmission line, it can be known that the periodically arranged resistance film of each layer can be equivalent to an effective impedance, which contains the resistance component and the reactance component. Together with the PE laminated board, it can be equivalent to a resonant circuit loaded with resistance. When the surface resistance of the resistance film is appropriate, resonance can occur at the resonance frequency point, and because the distance between each layer of the resistance film and the bottom surface of the conductor is different, more resonance frequency points can be obtained to achieve ultra-wideband absorption performance [10]. Aiming at the multi-layer absorbing sub-wavelength structure, an improved genetic algorithm is used for simulation. The convergence speed is faster and the optimization ability is stronger, which can effectively solve the optimization problem of the multi-layer absorbing sub-wavelength structure [11].

The absorbing sub wavelength structure is shown in figure 4a, and the side view is shown in figure 4b. The structure contains four layers of the same resistance film, the support layer is epoxy, and five layers of PE laminated. The relative permittivity of PE laminated was measured [12], the ε is 2.55 and tanδ is 0.01. The thickness of the PE laminated is 4.2 mm, the thickness of the resistance film is 0.05 mm, and the thickness of the epoxy resin film is 0.15 mm. The microstructure pattern of the resistance film is square ring and square, that is, a square ring structure with a width of 0.4 mm, an outer ring length of 5.0 mm and an inner ring length of 4.2 mm is etched on the resistance film layer, and the side length is 3.0 mm The square structure is the shaded part shown in figure 4, and the rest is the microstructure pattern of the resistive film. The bulk conductivity of Ohmic sheet1 is 50 S/m (square resistance is 400 Ω), the bulk conductivity of Ohmic sheet2 is 55.6 S/m (square resistance is 360 Ω), the bulk conductivity of Ohmic sheet3 is 200 S/m (square resistance is 100 Ω), the bulk conductivity of Ohmic sheet4 is 667 S/m (square resistance is 30 Ω). Ground plate is metal Cu, its bulk conductivity is 5.8 × 107 S/m.
5. Performance Verification of Broadband Stealth Bulletproof Material

Preparation of absorbing sub-wavelength structure patterns by laser etching [13]. Preparation of PE laminated by moulding process [14]. The whole is prepared by structural glue bonding and vacuum bag pressing process, during which the alignment accuracy and process parameters are guaranteed.

The bow-shaped method was used to measure the reflectance of the structure. The reflection coefficient curve is shown in figure 5 under the normal incidence of electromagnetic waves. It can be seen from the figure that the absorbing sub-wavelength structure is less than equal to -10 dB in 4 GHz to 18 GHz and 27 GHz to 40 GHz, covering four bands of C, X, Ku, and Ka to achieve wide-band absorption.

![Reflection coefficient curve of broadband stealth material.](image)

In the actual test, a 600 mm × 600 mm × 23 mm sample was prepared, which could prevent 5 rounds of ordinary bullets with a target distance of 100 meters and a firing angle of 0°. Sample after shooting is shown in figure 6. The hump height is 14 mm. Except for the penetration of the projectile at the edge, which led to the delamination of the absorber layer and the PE layer, the other missiles did not affect the combination of the absorber layer and the PE layer. Anti-ballistic performance data sheet is shown in table 2.

![Sample after shooting.](image)
Table 2. Anti-ballistic performance data sheet.

| Sample serial number | Sample specifications (mm) | Sample weight (kg) | Sample thickness (mm) | Shooting distance (m) | Shooting angle | Firing order | Warhead speed (m/s) | Shot | Hump height (mm) |
|----------------------|---------------------------|-------------------|----------------------|----------------------|----------------|-------------|--------------------|------|------------------|
| YP191017-4           | 600.0×600.0               | 8.36              | 23.62                | 100                  | 0°             | 1           | 827                | Unpenet-rated | 13.0             |
|                      |                           |                   |                      |                      |                | 2           | 821                | Unpenet-rated | 14.2             |
|                      |                           |                   |                      |                      |                | 3           | 824                | Unpenet-rated | 13.0             |
|                      |                           |                   |                      |                      |                | 4           | 830                | Unpenet-rated | 18.2             |
|                      |                           |                   |                      |                      |                | 5           | 824                | Unpenet-rated | 13.6             |

6. Conclusion

Based on the absorbing sub-wavelength structure and the aramid bulletproof composite material as the dielectric substrate, this paper designs the integrated material structure of stealth bulletproof function. The reflectivity of this material is less than -10 dB at 4 GHz to 18 GHz and 27 GHz to 40 GHz, and the absorption rate is more than 90%. Through the simulation of ballistic performance, it is verified that the structure does not affect the anti-ballistic performance of the material. Under the condition of the same length and width, the quality of the structure is 1/7 lighter than that of the steel plate under the same protective conditions [15], and the weight is reduced design requirements for broadband stealth performance. The broadband stealth bulletproof material based on the absorbing sub-wavelength structure is a combination of the absorbing sub-wavelength structure design and the bulletproof material, so that the stealth bulletproof material is no longer a simple functional overlay, but an integrated fusion design of structure and function. It solves the shortage of traditional stealth bulletproof materials, and it is of great significance to improve the protection capabilities of the new generation of ground armored vehicles and functional combat vehicles and enhance the battlefield penetration ability.

Acknowledgments

Thanks to colleagues in the department for their help and administrative department’s support in resources.

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