Construction and transmission mechanism of exterior ballistics of high-power microwave weapons

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Abstract
Booming technological advances and turbulent military reforms have promoted the continuous advancement of weapons and equipment. High-power microwave (HPM) weapons have changed the damage modes of traditional guns, missiles and other kinetic energy weapons, as well as having the huge advantage of “changing the rules of the game.” The study of exterior ballistics of high-power microwave weapons has theoretical support for the design and development of weapons and the verification of performance indicators and is also an important basis in the firing application of high-power microwave weapons. By studying the coupling mechanism between HPM weapons and targets, an exterior ballistics description of HPM weapons is given. According to the description of exterior ballistics, the differences between HPM and traditional weapons in definitions, accuracies, space trajectories, space descriptions, and “end points” are summarized, and the exterior ballistics space transmission is established. This study reveals the nine major transmission laws of the exterior ballistics of HPM weapons. The constructed model and related theories of the transmission laws for exterior ballistics lay a theoretical foundation for the in-depth study of key technologies of HPM weapons, such as fire control and damage assessment.

Keywords Exterior ballistics · High-power microwave weapons · Transmission laws · Transmission model

1 Introduction
High-power microwave (HPM) weapons refer to strong electromagnetic radiation weapons (also known as electromagnetic pulse or radio frequency weapons) with frequencies ranging from 0.1 to 300 GHz, a peak power above 100 MW, or an average power above 1 MW (Rentao et al. 2011; Haizhong 2009; Ni et al. 2005; Failed 2004; Ning and Xueyan 2018; Ming-dong and Tian-xiang 2014). High-power microwave (HPM) is an indefinite term utilized by a few networks. In the DoD, it relates basically to the era of high peak power explosions of narrowband (intelligent) electromagnetic radiation traversing the frequency range of around 1 GHz to 100 GHz. High-power microwave weapons have various unmistakable benefits over stringently active energy weapons. These benefits comprise: (1) speed of light conveyance, (2) exact commitment, (3) graduated impacts—up to framework execute, and (4) profound magazine. The present HPM weapons are huge and comprised of various segments.
As a new concept weapon that uses directional HPMs to disrupt and damage the opponent’s electronic information, if the opponent’s weaponry and equipment are more advanced, the electronic system is more complex, the degree of system networking is higher and it is more likely to attack and damage. Unlike traditional naval guns, missiles and other weapons, the HPM energy beam entering the electronic system does not physically destroy the electronic system like explosives, but instead damages or paralyzes it, making it unable to work normally. The degree of damage depends on the amount of power and energy entering the electronic system (Shangyong 2020; Xiongwei et al. 2016; Haiyun et al. 2018).

Simultaneously, HPM weapons also have unique advantages, such as all-weather work, low weather requirements, low launch costs, light speed propagation, simultaneous killing of multiple targets, and lack of trace evidence (Bao-liang 2015; Shi-li 2014; Kushwaha and Sharma 2008). Research on the transmission mechanism of exterior ballistics of HPM weapons has an important basis in their firing application and a theoretical support role in the design and development of weapons and the verification of performance indicators. Traditional ballistics theory states that “the exterior ballistics modeling of guns and other weapons focuses on the study of the law of movement of the center of mass and the law of movement around the center of mass under the influence of environmental factors after launching itself.” Criminological ballistics includes the assessment of proof from guns that may have been utilized in a wrongdoing. At the point when a shot is discharged from a weapon, the firearm leaves minute trajectories on the projectile as well as cartridge case. These trajectories resemble ballistic fingerprints. In contrast, the exterior ballistics modeling of HPM weapons needs to focus on the strong coupling effect of the microwave energy beam and target.

Traditional electronic warfare weapons adopt the “interference” damage mode, while kinetic energy weapons adopt the “collision” damage mode. The damage mechanism of HPM weapons is completely different from that of traditional conventional weapons. HPM weapons attack electronic systems, and the damage to an enemy target can be divided into two coupling modes, front door and back door, as shown in Fig. 1. Entering the electronic device through the antenna represents the front-door coupling method, while entering the electronic device through the slits and pores represents the back-door coupling method (Yan-bin et al. 2013). Front-door coupling is characterized as the passage of EM unsettling influence over accessible coupling ways besides ports arranged for the spread of alluring EM energy, either conducted else emanated, and intended to speak with the external climate, e.g., power attachments or radio wires.

Taking a missile as an example, front-door coupling mainly involves the HPM entering the missile through the antennas of various sensors on the missile (e.g. terminal guidance radar, radar altimeter, satellite positioning navigation system and data link devices). Its propagation path is consistent with the various echo signal transmission paths received/processed by the missile. Back-door coupling mainly involves the HPM entering the missile through various types of holes and slots existing in the missile (e.g. warhead, missile body, tail and front wing) and coupling induction voltage and current into the system through equivalent antennas (e.g. cables) inside the missile.

The energy transfer process of front-door coupling is that energy enters into the system containing the receiver or transmitter through the receiving or transmitting antenna of the target, thereby destroying the target’s electronic equipment. While the energy transfer process of back-door coupling is that energy enters the system through the target’s gaps and holes, interfering with the electronic equipment in the system makes it unable to function properly or even destroying and burning it.

In terms of distribution, the distribution of front-door coupling is that the induced current is generated and it enters the system along the electronic circuit and is distributed in the signal loop in the system. While the distribution of back-door coupling is that secondary radiation is generated and the radiation field is distributed throughout the system.

The coupling channel of front-door coupling is single and limited. The effect of coupling mainly depends on the gain and protection measures of antenna receiving and transmitting from the target electronic system. The damage efficiency is high and easy to determine. While back-door coupling has multiple channels, the effect mainly depends on the size and shape of the target electronic system’s aperture and gap, and cable connection method, size length, and protective measures. The level of damage is more difficult to predict for this coupling but is generally greater. It is difficult to protect, and the damage efficiency is difficult to determine.
Through analysis and comparison of the two coupling approaches, it is known that the damage from back-door coupling to the electronic system is difficult to predict and is not easy to protect from. In order to comprehensively analyze the transmission mechanism of the exterior ballistics of HPM weapons, the two coupling approaches are not distinguished.

2 Related work

The study of the transmission mechanism of the exterior ballistics of HPM weapons is based on the mutual coupling between HPM weapons and targets. Generally speaking, the literature on ballistics research of HPM weapons is relatively limited.

Using the SCI (Science Citation Index), EI (Engineering Index) and other databases, with “high-power microwave weapon” as the search keyword, the literature data of the last 15 years are summarized and shown in Table 1.

It can be concluded from Table 1 that the number of papers and data on HPM weapons is relatively small. The research mainly focuses on the research status, but the research on the key technology of HPM weapons is very limited. The reason for this is mainly due to military secrecy and technical blockades.

References (Rui et al. 2015; Dailiang et al. 2012) analyzed the damage mechanism of HPM weapons and proposed a calculation method for the microwave energy and power density of HPM ballistic attack on enemy targets. These studies therefore provide a theoretical basis and technical support for research of HPM weapons against targets. Reference (Jian et al. 2008) established the operational model of HPM weapons and calculated and simulated the damage distance of the exterior ballistics of HPM weapons on electronic equipment and controllers. In addition, the authors verified the effectiveness of HPM weapons in executing the attack target mission. Reference (Jinshi et al. 2010) calculated the operational area of HPM weapons against air targets and simulated the radiation power required to damage the target considering transmission attenuation. This provides a theoretical basis for HPM weapons to effectively damage the target.

Table 1 Literature data for “high-power microwave weapon” in the last 15 years

| Database       | 2006–2010 | 2011–2015 | 2016–2020 |
|----------------|-----------|-----------|-----------|
| SCI            | 24        | 24        | 17        |
| EI             | 37        | 20        | 22        |
| Other databases| 46        | 38        | 30        |

Reference (Xin et al. 2016) studied the factors that influence the exterior ballistics transmission of HPM weapons and constructed the HPM weapon electronic damage level and damage probability evaluation model. They also calculated the damage probability with the corresponding damage level, which has a certain reference value for quantitative research on the electronic damage of HPM weapons. Reference (Haishan 2011) established an evaluation index system that affects HPM weapon effectiveness. They also designed an analytic hierarchy model for HPM weapon attacks on electronic systems, with the goal of improving their effectiveness. The importance of factors affecting HPM weapon killing effectiveness was also explored.

Based on the above research, the study presented here provides a definition of exterior ballistics for HPM weapons. According to the HPM weapon coupling mechanism, in this study, the HPM weapon exterior ballistics space and energy transmission models are established, and the transmission laws of HPM weapon exterior ballistics are revealed, which can provide a theoretical basis for future research on HPM weapon fire control and damage assessment technology.

3 Construction of exterior ballistics of HPM weapons

The definition of ballistics is the science of studying the law of movement and the overall performance of projectiles and rockets during the launch process. With reference to the definition of traditional weapon exterior ballistics, combined with the coupling mechanism of HPM weapons and targets, this study puts forward a definition of the exterior ballistics of HPM weapons.

3.1 Exterior ballistics of traditional weapons

The definition of the exterior ballistics of traditional weapons is the behavior and movement of projectiles or missiles after they leave the barrel. The focus is on the position of the center of mass of the projectiles or missiles and their flight attitude. The law of motion in the air is almost the same as that of a free rigid body, which contains two major parts: the law of the center of mass motion and the law of motion around the center of mass (Hangyu et al. 2006; Zhiming et al. 2011).

3.2 Exterior ballistics of HPM weapons

In space, the coverage of the HPM beam emitted by HPM weapons when attacking the target increases significantly as a “V” shape. In this study, the effective killing range of
its energy is taken as the exterior ballistics of HPM weapons. Without considering the influence of attenuation and tail erosion in the atmospheric transmission of HPM weapons, by using the HPM weapon, we can able to emanate HPM beam energy and that energy will be considered as an immeasurable cone.

For different typical targets, HPM weapons have different damage distances. For a certain type of target, suppose the maximum effective range of the HPM weapon’s exterior ballistics is \( R_{\text{max}} \); then, the range of the HPM weapon in space is a hemisphere with the HPM weapon launcher as the center and the maximum range \( R_{\text{max}} \) as the radius, as shown in Fig. 2 (Yanbin et al. 2013; Benford et al. 2015).

### 3.3 Exterior ballistics description of HPM weapons

HPMs are transmitted in the atmosphere. Atmospheric-free electrons in the propagation path are heated rapidly because they absorb the energy of the HPM pulse. As a result, intense interactions between electrons, molecules and atoms result in an unbalanced energy distribution of electrons in space. The distribution function of electrons in an unbalanced state can be expressed by the Boltzmann equation (Ying et al. 2006). For the Maxwell–Boltzmann conveyance, the Boltzmann appropriation ought not to be mistaken. The previous provides possibility that a framework will be in a specific state as a component of that state’s energy; interestingly, the last is utilized to portray molecule speeds in glorified gases.

\[
\left( \frac{\partial f}{\partial t} \right) = \left( \frac{\partial f}{\partial t} \right)_d + \left( \frac{\partial f}{\partial t} \right)_c
\]  

(1)

Among them, \( \left( \frac{\partial f}{\partial t} \right)_d \) is known as the drift term, which is caused by motion, while \( \left( \frac{\partial f}{\partial t} \right)_c \) is a collision term. Equation (1) can be expressed specifically as follows (Woo and DeGroot 1984):

\[
\frac{\partial f}{\partial t} + u \cdot \nabla f + a \cdot \nabla' f = C. 
\]  

(2)

In Eq. (2), \( u \) and \( a \) are the velocities and accelerations of electrons, respectively, \( \nabla \) is the derivation of coordinate components, \( \nabla' \) is the derivation of velocity components and \( C \) is the collision term and is the distribution change caused by elastic and inelastic collisions. Elastic collisions are caused by the transfer of momentum, and inelastic collisions are caused by electron excitation, ionization and adhesion.

In the atmosphere, the mass of electrons is much smaller than the mass of heavy particles, so it can be considered that heavy particles are stationary relative to electrons, and there is no need to calculate the motion of heavy particles in the calculation process. The Boltzmann equation can be greatly simplified, and the electrohydrodynamic equations in the atmosphere can be derived from Eq. (2). Simultaneously, the Maxwell equations can be used to describe the propagation of electromagnetic waves in space. Therefore, the atmospheric propagation model of HPM weapons, that is, the construction of exterior ballistic of HPM weapons, can be obtained by combining the electrohydrodynamic equations with the Maxwell equations (Tao et al. 2010). Maxwell’s conditions portray how electric charges as well as electric flows make electric and attractive fields. They portray how an electric field can create an attractive field, and inversely. Electromagnetic hypothesis is depicted by Maxwell’s conditions. The primary clue that light is electromagnetic radiation came from electromagnetic analyses not including noticeable light. From relativity hypothesis, we realize that the speed \( c \) of light is a key consistent and a definitive restriction of speed.

Maxwell previously utilized the conditions to recommend that light is an electromagnetic wonder. A significant outcome of Maxwell’s conditions is that they show how fluctuating electric and attractive fields spread at a consistent speed \( c \) in a vacuum.

\[
\frac{\partial E_x}{\partial t} = -\frac{1}{\varepsilon_0} \frac{\partial H_y}{\partial z} - \frac{e \cdot n \cdot u_x}{\varepsilon_0} 
\]  

(3)

\[
\frac{\partial E_y}{\partial t} = -\frac{e \cdot n \cdot u_z}{\varepsilon_0} 
\]  

(4)

\[
\frac{\partial H_y}{\partial t} = -\frac{1}{\mu_0} \frac{\partial E_z}{\partial z} 
\]  

(5)
\[
\frac{\partial n}{\partial t} = (v_i - v_a) \cdot n - \nabla_z \cdot (n \cdot u) \tag{6}
\]
\[
m \frac{\partial (nu)}{\partial t} = e \cdot n(E + u \times B) \cdot n - n \cdot m \cdot v_e \cdot u - \nabla_z \cdot (n \cdot v_e) \tag{7}
\]
\[
\frac{\partial (n \cdot v_e)}{\partial t} = e \cdot n(u \cdot E) - n \cdot v_i \cdot v_e - n \cdot v_w \cdot v_e. \tag{8}
\]

Equations (3)–(5) show the Maxwell equations describing HPMs, and Eqs. (6)–(8) give the electrohydrodynamic equations. Equation (6) describes the continuity of changes in the density of electrons in the atmosphere. Equations (7) and (8) are the momentum and energy equations of electrons, respectively. In the above equations,

- \(e, m\) and \(c\)—the charge of electrons, the mass of electrons and the velocity of light, respectively.
- \(\varepsilon_0\) and \(\mu_0\)—the dielectric constant in vacuum and permeability in vacuum, respectively.
- \(n, u\) and \(v_e\)—the density, velocity, and energy of electronic fluids, respectively.
- \(v_i, v_a, v_c\) and \(v_w\)—the ionization rate, adhesion rate, collision rate and energy transfer rate of the interaction between electrons and atmospheric neutral particles, respectively.

The whole process of HPM atmospheric propagation, that is, the construction of exterior ballistics of HPM weapons, can be described by solving the equations composed of Eqs. (3)–(8). It should be noted that the movement of electrons in the atmosphere is complex and uncertain. The four parameters \(v_i, v_a, v_c\) and \(v_w\) cannot be obtained by theoretical equations and can generally be represented by fitting experimental data.

### 3.4 Difference between traditional and HPM weapons

Exterior ballistics is a science that arrangements with the variables influencing the conduct of a shot after the shot leaves the gag of the shooting weapon (like the underlying speed of the shot, the power of gravity, and environmental conditions)—think about inside ballistics. There are different branches of ballistics, and it is given as,

1. Inside ballistics is the part of the science that arrangements with the shot while it is as yet in the weapon.
2. Temporary ballistics is the part of the science that arrangements with the movement of the shot from the time it leaves the gag until the lone powers following up on it are because of outside ballistics.

Inner ballistics is the investigation of what occurs inside the barrel of a weapon from the second the discharging pin hits the groundwork to the time the slugs exit from the barrel. Outside ballistics manages the trip of the slug from the gag of the weapon to the objective.

#### 3.4.1 Different definitions of exterior ballistics

The exterior ballistics of traditional weapons mainly refer to the movement laws of projectiles or missiles after they leave the barrel, and the focus is on studying whether their ballistics “collide” with the target. In contrast, the exterior ballistics of HPM weapons are the effective killing range of the HPM beam energy, and the focus is on whether the weapon’s exterior ballistics “radiate” the target and the coupling between the weapon’s exterior ballistics energy and the target, as shown in Fig. 3(a).

#### 3.4.2 Different accuracies of exterior ballistics

The exterior ballistics of traditional weapons form a ballistics dispersion after the projectile or missile leaves the barrel due to error, the environment, or other factors. In contrast, the exterior ballistics of HPM weapons are the energy of the HPM beam, which is only weakly affected by error, the environment, or other factors, and there is no issue regarding ballistics dispersion as shown in Fig. 3(b).

![Fig. 3 Differences between traditional and HPM weapons](image-url)
3.4.3 Different space trajectories of exterior ballistics

The exterior ballistics of traditional weapons represent a moving track in space. During the time from the launch of the projectile or missile to the end of the strike, the projectile or missile is in a certain position on a trajectory in space at any time, so its exterior ballistics are not persistent. However, once the launching device of a HPM weapon is started and the weapon does not cease fire, the exterior ballistics of the weapon can continue to exist in space, and within the effective killing range of its energy, the targets will be radiated at any time, as shown in Fig. 3c.

3.4.4 Different space descriptions of exterior ballistics

The exterior ballistics description of traditional weapons is based on the equation of motion of the center of mass and the equation of motion around the center of mass under the influence of environmental factors. In contrast, the exterior ballistics of HPM weapons are essentially a strong electromagnetic pulse. By combining electrohydrodynamics and the Maxwell equations, the atmospheric propagation model of HPM weapons, that is, an exterior ballistics description, can be obtained. By fitting and expressing the ionization rate and other parameters through the experimental data and solving the equations, the whole process of atmospheric transmission of HPM weapon exterior ballistics can be described.

3.4.5 Different “end points” of exterior ballistics

The end point of the exterior ballistics of traditional weapons is the impact point, which is the first intersection point of the projectile or missile with the target, the ground or water. The determination of the end point of exterior ballistics is independent of the target type. The end point of the exterior ballistics of HPM weapons is the maximum effective range. For different types of typical targets, the effective range is different. Therefore, the end point of the exterior ballistics of HPM weapon will change according to different target types, but for the same type of target, the end point is always the maximum effective range for that type of target, as shown in Fig. 3d. Significance of exterior ballistics: it is significant from the percept of forensic. It is troubled about shooting of police to scatter the group, utilization of enhanced guns (country-made weapons) utilized in criminal cases including man’s laughter as well as murders. It contributes a lot at the time of war.

4 Basic model of space transmission for exterior ballistics of HPM weapons

4.1 Space model for exterior ballistics of HPM weapons

In general, HPM weapons attack an air attack target at a certain inclination. We take the horizontal flight of an air attack target as an example. As shown in Fig. 4, the collision area between the target and the exterior ballistics of the HPM is an elliptical damage cross section known as the damage ellipse. The angle between the elliptical damage cross section and the energy center line (also known as the launch inclination) of the HPM exterior ballistics beam is $\varphi$, the vertical distance of the air attack target is $h$, the exterior ballistics beam angle of the HPM weapon is $\theta$, and the distance between the HPM weapon and the attacked target is $R$, so the relationship between $h$ and $R$ is:

$$h = R \sin \varphi.$$  \hfill (9)

The center point of the damage ellipse is defined as $T$, the minor axis is the segment AB, and the long axis is the segment CD. A spatial connection indicates how some article is situated in space corresponding to some reference object. At the point when the reference object is a lot greater than the item to find, the last is frequently addressed by $a$. Normally utilized kinds of spatial relations are: topological, directional as well as distance relations. According to the spatial geometric relationship, the lengths of the long and short semi-axes of the power ellipse are $a$ and $b$, respectively (Guo et al. 2012; Jin-shi and Wen-hua 2008; Jin-shi et al. 2013):
\[
a = R \sin \varphi \cdot \left[ \cot \left( \frac{\varphi - \theta}{2} \right) - \cot \left( \frac{\varphi + \theta}{2} \right) \right]
\]
\[
b = R \tan \frac{\theta}{2} = h \tan \frac{\theta}{2} \sin \varphi.
\] (10) (11)

Therefore, the relationship between the area \( S_M \) of the damage cross section and the target distance \( R \) is:
\[
S_M = \pi a b = \pi R^2 \sin \varphi \tan \frac{\theta}{2}
\times \left[ \cot \left( \frac{\varphi - \theta}{2} \right) - \cot \left( \frac{\varphi + \theta}{2} \right) \right] \left( \varphi - \frac{\theta}{2} \geq 0 \right).
\] (12)

The relationship between the area \( S_M \) of the damage cross section and the vertical distance \( h \) is:
\[
S_M = \pi a b
= \pi h^2 \tan \frac{\theta}{2} \left[ \cot \left( \frac{\varphi - \theta}{2} \right) - \cot \left( \frac{\varphi + \theta}{2} \right) \right] / \sin \varphi \left( \varphi - \frac{\theta}{2} \geq 0 \right).
\] (13)

Equation (13) shows that the area \( S_M \) of the elliptical damage cross section is related to the vertical distance \( h \) of the target, the exterior ballistics beam angle \( \theta \) of the HPM weapon, and the firing inclination \( \varphi \). The area \( S_M \) of the elliptical damage cross section increases parabolically with increasing vertical distance \( h \) of the target. Theoretically, the range of the exterior ballistics beam angle \( \theta \) of the HPM weapon is \( \theta \in [0, \pi] \) and the range of launch inclination \( \varphi \) is \( \varphi \in [0, \pi] \).

In the special case of \( \varphi = \frac{\pi}{2} \), when the target is directly above the HPM weapon launcher, the area of the damage cross section is:
\[
S_M\left( \varphi = \frac{\pi}{2}, \theta \right) = \pi h^2 \tan^2 \frac{\theta}{2}.
\] (14)

Equation (14) shows that when the launch inclination \( \varphi \) is \( 90^\circ \), the area \( S_M \) of the elliptical damage cross section increases with increasing \( \theta \).

4.2 Energy transmission model for exterior ballistics of HPM weapons

Power density is an important index to measure whether HPM weapons can effectively kill targets. The measure of force (time rate of energy transfer) per unit volume is termed as power density. The following factors are contained in energy transformers such as energy components, batteries, engines and so on. Furthermore, power supply units or comparable, power thickness alludes to a volume.

It is then likewise called volume power thickness, which is denoted as \( \text{W/m}^3 \).

Within a certain range, the greater the power density, the greater the damage effect on targets. According to the “4D” (Dailiang et al. 2012) concept of HPM weapon operational effectiveness for electronic systems proposed by the US Army, the relationship between the range of power density and the damage effect of HPM weapons on targets is shown in Table 2.

The exterior ballistics microwave beam emitted by HPM weapons can transmit energy in the atmosphere in accordance with the law of energy propagation of electromagnetic waves in space. Therefore, the power density is inversely proportional to the square of the operating distance, meaning that the power density of the exterior ballistics of a HPM weapon at the target is (Sabath et al. 2004; Ren-de and Bing-fa 2012):
\[
S = \frac{P_t G_t}{4 \pi R^2} = \frac{P_t G_t \sin^2 \varphi}{4 \pi h^2}
\] (15)

where \( S \) is the power density at the target, \( P_t \) is the transmission power of the HPM weapon, and \( G_t \) is the gain of the transmission antenna. The essential part of radio innovation is said to be as transmission antenna. This kind of receiving wire is made out of a conveyor that conveys an electric flow whose power changes after some time and converts it into radiofrequency radiation that proliferates in space. The receiving wire at the transmitter creates the radio wave. The voltage across the receiving wire components and the flow through them make the electric and attractive waves, separately. At the beneficiary, the electromagnetic wave disregarding the radio wire prompts a little voltage. The gain \( G_t \) of the transmitting antenna is given by:
\[
G_t = \frac{4 \pi A_e}{\lambda^2}
\] (16)

where \( A_e \) is the antenna area and \( \lambda \) is the wavelength of the HPM.

5 Transmission laws for exterior ballistics of HPM weapons

By establishing the basic model of the space transmission for the exterior ballistics of HPM weapons, it can be seen that there are obvious differences between the exterior ballistics of HPM weapons and traditional electronic warfare and kinetic energy weapons. In addition, there are many differences between HPM weapons and other directional energy weapons, such as high-energy lasers and particle beams. Dependent on lasers, a laser weapon is a coordinated energy weapon and it is prepared to do
straightforwardly harming else annihilating an objective in battle are as yet in the exploratory stage. The overall thought of laser-shaft weaponry is to hit an objective with a train of short pulses of luminescence. While a HPM weapon is considered to have a peak force of in excess of 100 MW, else energies over 1 J. By using RF ways, the energy can arrive, for instance, target radio wires (front entryway), or accidental ways, like cavities, circuit wires (indirect access) and lodging joints. HPM gadgets can deliver impacts that range from preventing the utilization from getting electronic-based hardware to upsetting, harming, or obliterating such gear. The following factors are benefits of HPM weapon such as climate capacity, low accuracy pointing prerequisites, and impacts ingenuity after the transmitted EM energy “beam” has been killed.

Based on the exterior ballistics model of HPM weapons, the exterior ballistics transmission laws of HPM weapons are sorted and summarized as follows (Failed2012; Chong et al. 2020; Yue-wei and Min 2016):

5.1 Law 1: the exterior ballistics of HPM weapons have “high fire energy”

The exterior ballistics of HPM weapons can be regarded as a strong electromagnetic pulse interference, but their equivalent radiation power level is increased by more than three to four orders of magnitude compared with conventional electronic countermeasures, as shown in Fig. 5.

Mathematical model: Mathematical models are an interaction of encoding as well as disentangling of the real world, wherein a characteristic marvel is decreased to a formal mathematical articulation by an easy-going design. Numerical models can assist understudies with comprehension and investigate the importance of conditions or practical connections.

The relationship between the equivalent radiation power of the HPM weapon \( P_{\text{HPM}} \) and the equivalent radiation power \( P_{\text{C}} \) of conventional electronic countermeasure weapons can be described as:

\[
\frac{P_{\text{HPM}}}{P_{\text{C}}} \geq 10^3.
\]  

5.2 Law 2: the exterior ballistics of HPM weapons have “fire continuity”

Traditional kinetic weapons destroy targets by “collision,” while the damage from a HPM weapon to the target requires the target to be radiated by exterior ballistics for a period of time. Equal energy needs to reach the target’s damage threshold to destroy the target.

Mathematical model: If we set \( T_e \) as the duration of radiation to the exterior ballistics of a HPM weapon and \( Q_t \) as the damage threshold of the target electronic system, then:

\[
P_{\text{HPM}} \cdot T_e \geq Q_t.
\]  

The relationship curve between the duration of radiation and the radiation energy of a HPM weapon is shown in Fig. 6. When the accumulated energy of radiation is greater than \( Q_t \), the target can be damaged.
5.3 Law 3: the exterior ballistics of HPM weapons have a “fire step”

According to the energy transmission model of HPM weapons, the effectiveness of a HPM weapon in killing its targets can be divided into four levels: deny, degrade, damage and destroy. The relationship between the effectiveness of a HPM weapon and the power density is shown in Fig. 7 with a “step” feature.

Mathematical model: When the power density $S$ satisfies $S \in [1 \times 10^{-6}, 0.01]$, the effectiveness of the HPM weapon is “deny,” when $S \in (0.01, 1]$, the effectiveness of the HPM weapon is “degrade,” when $S \in [10, 10^2]$, the effectiveness of the HPM weapon is “damage” and when $S \in [10^3, 10^5]$, the effectiveness of the HPM weapon is “destroy”:

$$
effectiveness = \begin{cases} 
\text{deny} & 1 \times 10^{-6} \leq S \leq 0.01 \\
\text{degrade} & 0.01 < S \leq 1 \\
\text{damage} & 10 \leq S \leq 10^2 \\
\text{destroy} & 10^3 \leq S \leq 10^5 
\end{cases}$$  \quad (19)

5.4 Law 4: the exterior ballistics of HPM weapons have “fire time variation”

As can be seen from Law 2, the exterior ballistics of a HPM weapon are required to continuously radiate the target for a period of time and to then move with the target. Therefore, the exterior ballistics of a HPM weapon constantly change in space, as shown in Fig. 8.

Mathematical model: If we set $V_T$ as the target’s current moving speed, then the HPM weapon launcher’s current angular velocity $w_{\text{HPM}}$ is:

$$w_{\text{HPM}} = \frac{V_T}{R}$$ \quad (20)

It can be seen from Eq. (20) that the angular velocity of the HPM weapon launcher changes with the moving speed of the target and has a linear relationship.

5.5 Law 5: the exterior ballistics of HPM weapons have “light speed and directivity”

For traditional kinetic weapons, we need to calculate the current target distance, target movement and the vector equation of ballistic movement, i.e., solve the hit triangle. However, the exterior ballistics of a HPM weapon has the advantages of light speed attack and 100% shoot accuracy when aiming at the target, so it is no longer necessary to calculate the advance of a target movement, as shown in Fig. 9.

Mathematical model: The velocity $V_{\text{HPM}}$ of the exterior ballistics of the HPM weapon is:

$$V_{\text{HPM}} = c$$ \quad (21)

where $c$ is the speed of light.

Fig. 6 Exterior ballistics of HPM weapons with “fire continuity”

Fig. 7 Exterior ballistics of HPM weapons with a “fire step”

Fig. 8 Exterior ballistics of HPM weapons with “fire time variation”
5.6 Law 6: the exterior ballistics of HPM weapons have “wide damage”

HPM weapons are regionally lethal and their exterior ballistics can cover multiple targets in a depth range in space. When attacking a group of targets in the same batch, the area $S_M$ of the elliptical damage cross section of a HPM weapon is greater than the elliptical area $S_T$ of enveloping the group targets of this batch, so the group targets of this batch can be effectively destroyed, as shown in Fig. 10.

Mathematical model: The condition that a HPM weapon can effectively damage group targets is as follows:

$$S_M \geq S_T.$$  \hspace{1cm} (22)

5.7 Law 7: the exterior ballistics of HPM weapons have “variable distance damage”

The damage capability of a traditional weapon warhead does not change with distance. As long as it is within the effective damage distance, its damage energy to the target is the same. Equation (15) shows that the hitting energy of the exterior ballistic electromagnetic beam of a HPM weapon decreases inversely as a square with increasing distance from the target, and the energy decreases rapidly from the center of the beam to all sides. As shown in Fig. 11, $R_{\text{max}}$ is the maximum operating distance of the exterior ballistics of a HPM weapon, and $r_{\text{max}}$ and $r_{\text{min}}$ are the maximum and minimum killing distance of a conventional weapon, respectively.

Mathematical model: The target hitting damage energy of HPM weapons is inversely proportional to the square of the damage distance $r_k$. The target damage energy of traditional weapons is independent of the damage distance, namely

$$Q_{\text{HPM}} = \frac{k_{\text{HPM}}}{r_k^2} \left( 0 \leq r_k \leq R_{\text{max}} \right)$$  \hspace{1cm} (23)

$$Q_{\text{traditional}} = k_{\text{traditional}} \left( r_{\text{min}} \leq r_k \leq r_{\text{max}} \right)$$  \hspace{1cm} (24)

where $Q_{\text{HPM}}$ and $Q_{\text{traditional}}$ are the target hitting damage energy of HPM and traditional weapons, respectively, and $k_{\text{HPM}}$ and $k_{\text{traditional}}$ are constants.

5.8 Law 8: the exterior ballistics of HPM weapons have “variable range coverage”

The coverage of the exterior ballistics of the electromagnetic beam of HPM weapons increases significantly in a “V” shape with increasing distance. This is different from another directed energy weapon, high-energy laser
weapons, whose damage beam diameter does not change with distance. This phenomenon will lead to the problem that the same target can be completely covered in the distance and that only part of the target can be radiated at short distance and at the end, as shown in Fig. 12.

Mathematical model: Eqs. (12) and (13) show that the area $S_M$ of the damage cross section of a HPM weapon is proportional to the square of target distance $R$. With increasing target distance $R$, the exterior ballistics fire of the HPM weapon can completely cover the target. With decreasing target distance $R$, the exterior ballistics fire of the HPM weapon can only radiate the target partially, while the area $S'_M$ of the damage cross section of a laser weapon is a fixed value and will not change with target distance $R$, namely

$$\begin{align*}
\text{HPM weapon} & \quad \left\{ \begin{array}{l}
S_M = k_M \cdot R^2 \geq S_{\text{critical}} \Rightarrow \text{completely cover} \\
S_M = k_M \cdot R^2 < S_{\text{critical}} \Rightarrow \text{local radiation}
\end{array} \right. \\
\text{laser weapon} & \quad S'_M = c_M
\end{align*}$$

(25)

where $k_M$ and $c_M$ are constants, respectively, and $S_{\text{critical}}$ represents the critical value for a HPM weapon to completely cover the target in the cross section of damage.

5.9 Law 9: the exterior ballistics of HPM weapons have “continuous operation”

Compared with conventional ammunition, HPM weapons have a lower launch cost and the ability to repeatedly engage in long-term operation. The exterior ballistics of HPM weapons can fight with a target continuously without cease fire when making multi-batch target cease-fire and turn-fire decisions, as shown in Fig. 13.

Mathematical model: Suppose $t_1$ and $t_2$ are the moments when target 1 and target 2 are destroyed, respectively, then the launch power of HPM weapon meets:

$$P_t = p(t_1 \leq T \leq t_2)$$

(27)

where $p$ is the power of the HPM weapon when it attacks the target, which is a constant value. Equation (27) shows that when the time $T \in [t_1, t_2]$, that is, during the turning time of HPM weapons, HPM weapons always maintain a certain launch power and can directly attack the next target without stopping fire.

6 Simulation and conclusion

6.1 Simulation and conclusion of space model for exterior ballistics of HPM Weapons

From the space model for exterior ballistics of HPM weapons, it can be seen that the value of the area $S_M$ of the damage cross section is related to three variables, namely the vertical distance $h$, beam angle $\theta$ and launch inclination $\phi$. By setting different $h$ and $\phi$ values, the relationship between the area $S_M$ of the damage cross section and the beam angle $\theta$ can be obtained, as shown in Fig. 14.

The title of the vertical axis is the area $S_M$ of the damage cross section, and the title of horizontal axis is the exterior ballistics beam angle $\theta$ of the HPM weapon. Four colored curves are drawn according to the function relationship to show the area $S_M$ of the damage cross section and beam angle $\theta$.

Beam angle refers to the angle at which the light is circulated; else discharged. Lights like halogens (a few LEDs) arrive in an assortment of angles from $4^\circ$ to $60^\circ$ with a portion of the bigger incandescent lights up to $120^\circ$. These are average bar angles spread shortenings.
Launch inclination is the point among north course as well as the projection of the underlying orbital plane onto the dispatch area. The orbital tendency is the point betwixt the orbital plane as well as divine body’s reference plane. Assuming the body turns, this is typically the central plane.

Taking Fig. 14(a) as an example, when $h = 500$ m, the red curve represents the relationship between the area $S_M$ of the damage cross section and beam angle $\theta$ when the value of launch inclination $\phi$ is $30^\circ$. The green curve represents the relationship between the area $S_M$ of the damage cross section and beam angle $\theta$ when the value of launch inclination $\phi$ is $45^\circ$. The blue curve represents the relationship between the area $S_M$ of the damage cross section and beam angle $\theta$ when the value of launch inclination $\phi$ is $60^\circ$. The black curve represents the relationship between the area $S_M$ of the damage cross section and beam angle $\theta$ when the value of launch inclination $\phi$ is $90^\circ$. The four curves all show the same law, that is, within the defined domain of the beam angle, the area $S_M$ of the damage cross section increases markedly as the beam angle $\theta$ increases. The same result can be obtained in Figs. 14 (b-d), which will not be repeated here.

Therefore, we can draw the following conclusion: when the values of the vertical distance $h$ and launch inclination $\phi$ are fixed, the area $S_M$ of the damage cross section increases markedly as the beam angle $\theta$ increases within the defined domain of the beam angle.

6.2 Simulation and conclusion of energy transmission model for exterior ballistics of HPM weapons

By setting the initial values $P_t = 1$ GW, $G_t = 10$ dB and $\phi = \pi/4$, the relationship between the power density at the target and the vertical distance of the target can be obtained, as shown in Fig. 15.

It can be concluded from Fig. 15 and the energy transmission model for exterior ballistics of HPM weapons that the power density $S$ at the target is inversely proportional to the square of the vertical distance $h$ when the values of the transmission power $P_t$ of the HPM weapon, the gain $G_t$ of the transmission antenna and launch inclination $\phi$ are fixed.

The measure of force (time rate of energy transfer) per unit volume is termed as power density. The following factors are contained in energy transformers such as energy components, batteries, engines and so on. Furthermore, power supply units or comparable, power thickness alludes to a volume. It is then likewise called volume power thickness, which is denoted as W/m$^3$.

Power transmission is the development of energy from its location of era to an area where it is useful to achieve valuable work. Meanwhile, the improvement of innovation, transmission as well as capacity frameworks have been of tremendous interest toward technologies as well as innovation clients.

Gain of transmission antenna is also said to be as antenna gain. It acquires the capacity of radio wire to emanate much toward any path contrasted with a hypothetical radio wire. On the off chance that a receiving wire could be made as an ideal circle, it would transmit similarly in entire way. Directional radios can be designed with gains up to in excess of 20 dB.
7 Summary and prospects

HPM weapons have excellent advantages and have potential to “change the rules of the game.” The construction of exterior ballistics and the study of their transmission mechanism have theoretical support for key technologies of HPM weapons, such as fire control and damage assessment, weapon design and development, and verification of weapon performance indicators.

According to the definition and coupling mechanism of a HPM weapon’s exterior ballistics, the model of space transmission and energy transmission has been established, and a simulation analysis was carried out in combination with examples. The nine laws of HPM weapon’s exterior ballistics transmission have been sorted out and revealed. The main conclusions are as follows: (1) Within the defined domain of beam angle, the damage cross-sectional area increases significantly as the beam angle increases. (2) According to the energy transmission model, the power density of HPM weapons at the target is inversely proportional to the square of the vertical distance. (3) The exterior ballistics of HPM weapons have nine transmission laws that are “high fire energy,” “fire continuity,” “fire step,” “fire time variation,” “light speed and directivity,” “wide damage,” “variable distance damage,” “variable range coverage,” and “continuous operation.”

In the subsequent research, atmospheric transmission, energy loss, tail erosion, and other effects can also be considered in the transmission model. The nine laws summarized can be further analyzed and key technologies such as target positioning and tracking technology of HPM weapons, target damage technology of HPM weapons group, and damage assessment of HPM weapons can be designed and developed.

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