Applied Mechanics and Materials Vols 300-301 (2013) pp 1448-1453 *Online: 2013-02-13*
© (2013) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/AMM.300-301.1448

Physical Modeling of Magneto Hydrodynamic Explosive Munition and Detonation Control

Yun Lei Shi [a], Shao Jie Ma [b], He Zhang [c] and Lin Gu [d]

Ministerial Key Laboratory of ZNDY, NUST, Nanjing 210094, China

[a]13770562272@163.com, [b]438729185@qq.com, [c]hezhangz@mail.njust.edu.cn, [d]438714995@qq.com

Keywords: MAHEM; Primary source; Physical model; Detonation control

Abstract. Definition of magneto hydrodynamic explosive munition is introduced. The technology that magneto hydrodynamic loaded EFP is presented. The magneto hydrodynamic power is generated by MFCG. The physical model of magneto hydrodynamic explosive munition using ferroelectric ceramics as primary source is established. The equivalent circuit of primary source, MFCG and magneto hydrodynamic accelerating model is analyzed by current transfer process. The security system is designed for the new ammunition, and its initiation timing is analyzed. A microsecond detonation control method is also given.

Introduction

Magneto Hydrodynamic Explosive Munition (MAHEM) is a new type of ammunition. It's proposed by Mr. Stephen M Waller of DARPA (U.S. Defense Advanced Research Projects Agency) in recent years and listed as a U.S. weapon research project [1]. In order to destroy target, MAHEM uses magneto-hydrodynamic motive power loading on the kill element to form metal jet or self forging fragment. Compared to the traditional Explosively Formed Penetrator (EFP), MAHEM is more controllable and efficient. Because of the orientable and higher-velocity mental jet, its performance on the accuracy and lethality has an enormous promotion [2].

In this paper, by the analysis of the internal current three-stage transfer process, physical models of MAHEM using ferroelectric ceramics as primary source are established, and the calculation formula of the kill element jet velocity is derived. On the basis, a kind of safety and arming system is proposed for this new ammunition, and its initiation timing is analyzed. A detonation control method is also given.

MAHEM

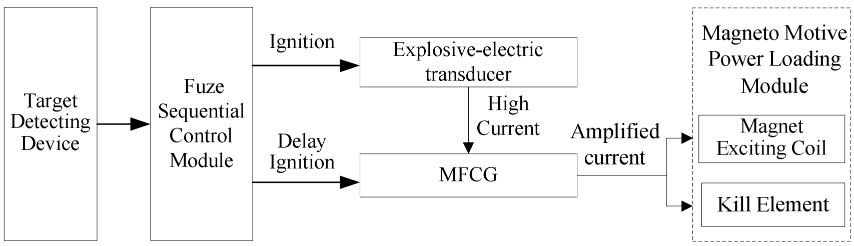


Fig.1 Principle block diagram of MAHEM

The principle of MAHEM is as shown in Fig.1. MAHEM is generally composed of magnetic flux compression generator (MFCG), fuze control module, magneto motive power loading module, etc. Among them, the fuze control module includes primary source which supplies seed current to MFCG, safety and arming system, target detecting device, etc. The primary source of missile-borne MFCG generally has two ways: storage battery or ferroelectric explosive-electric transducer [3]. This research takes ferroelectric explosive-electric transducer as the primary source.

After the launch of MAHEM, the fuze control module arms the safety mechanism according to the predetermined program. Then the detonators in the primary source and MFCG stay in arming condition. While MAHEM goes into the target area, the fuze receives ignition signal from the target detecting device. The detonator in the primary source initiates first to provide seed electric current for MFCG. After the precision delay by the fuze high-precision sequential control module, the detonator in MFCG initiates. This precision delay can make sure the initiation time of the detonator in MFCG is synchronous with the maximum of the seed current supplied by the primary source.

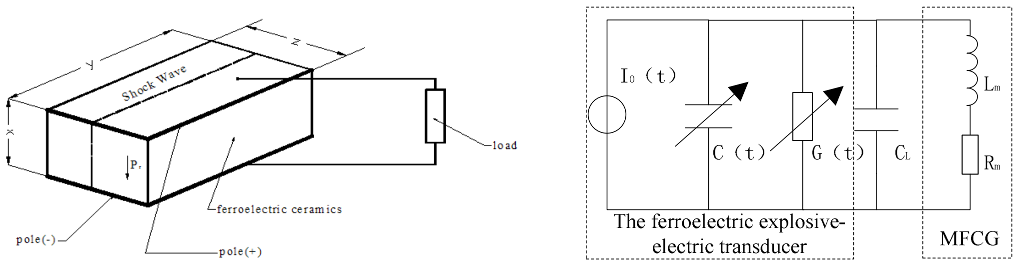
The amplified current by MFCG then goes into the magneto motive power loading module. The magneto motive power loading module makes use of the magnet exciting coil to generate high-intensity internal magnetic field distributing in a certain range. The pulsed magnetic power will overwhelm and accelerate the kill element to form fragments or jet to damage the target.

Physical Model

According to the current transfer, MAHEM can be divided into three stages: Primary Source (Seed Current), MFCG and Magneto Motive Power Loading Module. The relationship between any two of the three modules is pre-stage and later-stage or power supply and load. However, these three modules also work relatively independently. Therefore, this paper respectively builds physical model of the three stages to make an analysis of the equivalent circuit and magnetic field.

Ferroelectric Explosive-electric Transducer Model. The ferroelectric ceramics (usually PZT95/5) subjected to vertical load of the explosive shock wave can release hundreds to thousands amperes of current on the microsecond inductive load. It has relatively simple structure, light weight and large energy density. Its anti-interference ability is also strong. It meets the requirements of MAHEM to the primary source very well [3].

The vertical shock load on the ferroelectric ceramics refers to shock wave loading direction perpendicular to the ferroelectric polarization direction P_r. Yuan-ji He, Jin-mei Du et al in China have studied the discharge characteristic of ferroelectric while its load is short out and capacitive [4, 5]. In this paper, the discharge load is MFCG and its characteristic of electrical parameter is inductive and resistive.



(a) (b)

Fig.2 The schematic diagram of the ferroelectric explosive-electric transducer and its equivalent circuit

The ferroelectric explosive-electric transducer is as shown in Fig.2 (a), its equivalent circuit diagram is as shown in Fig.2 (b). Firstly, the ferroelectric ceramics is equivalent to a constant-value current source, a constant-value capacitance and a constant-value conductance being in parallel. During the shock wave propagation process, due to the ferroelectric ceramics' area changes between the wave front interface and the wave back interface, the values of the equivalent capacitance and conductance will also change [4,7]. So in the equivalent circuit model, the ferroelectric ceramics is equivalent to a time-dependent current source $I(t)$, a time-dependent capacitance $C(t)$ and a time-dependent conductance $G(t)$ being in parallel. In consideration of dielectric relaxation effect, the $I(t)$ function derivation formula is as follow, t_{sc} is the relaxation time.

$$I_0(t)=\begin{cases} P_r A\left[1-\exp(-t/t_{sc})\right]/t_0 & t\le t_0 \\ P_r A\exp\left(-(t-t_0)/t_{sc}\right)\left[1-\exp(-t/t_{sc})\right]/t_0 & t>t_0 \end{cases} \quad (1)$$

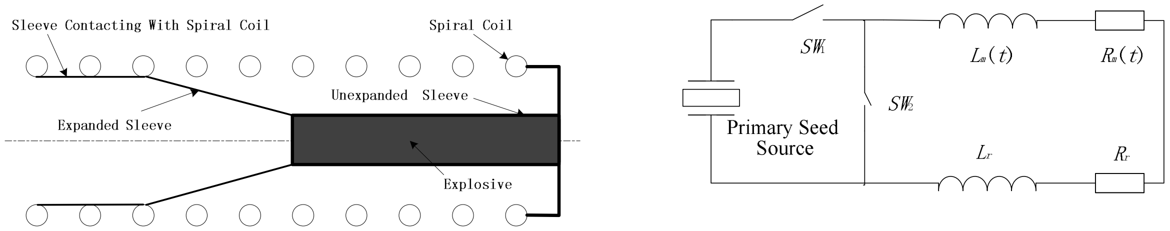
Where A is the load area, and $A= yz$. The detailed derivation about the calculation of $C(t)$ and $G(t)$ is in 4,7 references. The differential equation of the equivalent circuit which primary source discharges on the load MFCG is as follow.

$$\frac{d^2 I_1(t)}{dt^2}+\frac{1}{C}\left(G(t)+\frac{dC}{dt}\right)\frac{dI_1(t)}{dt}+\frac{I_1(t)}{L_m(0)C}=\frac{I_0}{L_m(0)C} \quad . \tag{2}$$

Where $I_1(t)$ is the discharge current, C=$C(t)$+C_L, C_L is the matched capacitance, $L_m(0)$ is the inductance of MFCG before it works. The circuit's random inductance and resistance are ignored.

Physical Model of MFCG. MFCG is a high-power explosive-driving pulse energy, which can convert the explosive energy into the electrical energy. It can generate high voltage, strong current and high energy [6]. There are several design types of MFCG, such as Coaxial MFCG, Spiral MFCG, Plate MFCG, Loop MFCG, Disk MFCG, Shock Wave MFCG, etc. Among them, the Spiral MFCG is appropriate for missile-borne, and its research is more mature. So MAHEM generally selects the Spiral MFCG [6, 7].

The action process of MFCG is as shown in Fig.3 (a). Firstly the primary source provides seed current for MFCG to produce axial magnetic field between metal sleeve and spiral coil. After a precise delay, the explosive in MFCG detonates. Then the metal sleeve starts to expand and contacts with the spiral coil under the influence of detonation wave. So shorted coils in the spiral coil increase, and the magnetic field is compressed to generate induction current. As a result, the current is amplified.



(a) (b)

Fig.3 Action process of MFCG and its equivalent circuit

The equivalent circuit is as shown in Fig.3 (b). As the switch SW_1 is being closed, primary source starts to provide seed current for MFCG. While the current reaches its maximum, closing the switch SW_2 to ignite the detonator, then MFCG starts to compress. $L_m(t)$, $R_m(t)$ are the equivalent inductance and equivalent resistance of MFCG at time t. L_r, R_r are the inductance and resistance of the loop circuit cable. After closing the switch SW_2, according to the KCL, the differential equations of the equivalent circuit are as follows.

$$d\left\{\ln[(L_m(t)+L_r)I_2(t)]\right\}=-\frac{(R_m(t)+R_r)}{(L_m(t)+L_r)}dt \quad . \tag{3}$$

$$I_2\left(0\right)=I_{1\max} \quad . \tag{4}$$

By integrating, the calculation formula of the current $I_2(t)$ which MFCG provides for magneto motive power loading module is as follow.

$$I_2\left(t\right)=\frac{L_m(0)+L_r}{L_m(t)+L_r}\exp\left[-\int_0^t\left(\frac{(R_m(t)+R_r)}{(L_m(t)+L_r)}\right)dt\right]I_{1\max} \quad . \tag{5}$$

Where I_{1max} is the peak current of the ferroelectric ceramics discharging, $L_m(0)$ is the initial inductance of MFCG.

Physical Model of Magneto Motive Power Loading Module. Magneto motive power loading module includes the processes of kill element's formation and acceleration. These two processes exist at the same time. This paper mainly takes the theoretical derivation of the kill element's velocity in the acceleration process.

In the process of magneto-hydrodynamic motive power accelerating kill element, the change of electromagnetism is very complex, and there are lots of influencing factors. In order to study easily, the simplification is as follow.

The skin effect in the magneto motive power driving coil is ignored, and the current in the coil wires is regarded as rectangular distribution. Due to the deformation of motive power driving coil under the influence of some stress, the internal magnetic field will change, and this influence is ignored. The inductive method is adopted to calculate the accelerating force on the kill element. The force is equal to the rate of change of the stored energy in the motion course, or the energy gradient in the direction of motion. The magnetic energy W stored in current-carrying conductor (kill element) is related to the inductance $L(x)$ of the system. The inductance $L(x)$ is the flux of per unit current coupling in the circuit. In the ideal condition, the total stored energy of the kill element induction coil is as follow.

$$W = \frac{1}{2} L(x) I_2^2(t) \quad . \tag{6}$$

According to the virtual work principle, the electromagnetic force Fp applying on the kill element is the range of change of the energy W in the infinitesimal displacement course. To the magneto motive power loading module, in the short time of the infinitesimal displacement of the kill element, the current is regarded as a constant value.

$$F_p = \frac{dW}{dx} = \frac{1}{2} I_2^2(t) \frac{dL(x)}{dx} \quad . \tag{7}$$

In the acceleration course of kill element, the resistance mainly includes friction and air resistance. The frictional resistance F_m between kill element and the inner wall of magneto motive power loading module is as follow, k_f is the friction factor.

$$F_m = k_f mg \quad . \tag{8}$$

The air resistance is the exponential function of the damage velocity.

$$F_k = f_k \left(\frac{dx}{dt}\right)^{\alpha} \quad . \tag{9}$$

Where f_k is the coefficient of air resistance, α is the exponential of the air resistance.

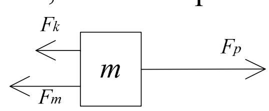


Fig.4 Force diagram in the acceleration course of kill element

According to Newton's Second Law of Motion, the kinematics differential equations of kill element are as follows.

$$m\frac{d^2 x}{dt^2} = \frac{1}{2} I_2^2(t) \frac{dL(x)}{dx} - k_f g - f_k \left(\frac{dx}{dt}\right)^{\alpha} \quad . \tag{10}$$

$$a(t) = \frac{1}{2m} I_2^2(t) \frac{dL(x)}{dx} - \frac{k_f g}{m} - \frac{f_k}{m} (\frac{dx}{dt})^{\alpha} \quad . \tag{11}$$

$$v(t) = \int_0^t a(t)dt + v_0 \quad . \tag{12}$$

Where m is the quality of single kill element, $a(t)$ is the acceleration at time t, $v(t)$ is the velocity at time t, v_0 is the projectile velocity at the time of MAHEM detonating or the primary velocity of kill element.

Detonating Control of MAHEM

Initiation Timing Analysis and Detonation Control. The action process of MAHEM taking ferroelectric ceramics as the primary source is as follow. While MAHEM goes into the target predetermined orientation, the detonator of primary source detonates first, the booster detonates after that. Then the detonation wave goes through the plane wave generator. In the next moment, the wave is decompressed at the effect of attenuation layer to get a suitable force to change the ferroelectric phase, and the phase change can generate seed current for MFCG. After a time delay, the MFCG detonator detonates, the booster detonates, and then the explosive in the metal sleeve detonates to make the sleeve expand. In the expanding process, the sleeve contacts with the lever switch and open it, and then the MFCG starts to run [7]. In order to get the maximum Magneto-hydrodynamic motive power, there is an optimum detonating time sequence. When the current which the ferroelectric ceramics supply to MFCG reaches its maximum, the expanding sleeve is just having opened the lever switch. Therefore, there is a retardation time T_{ys} from the primary source detonator detonating to the MFCG detonator detonating.

$$T_{ys} = T_1 - T_2 \quad . \tag{13}$$

T_1: The time from the primary source detonator detonating to the current reaching its maximum

T_2: The time from the MFCG detonator detonating to MFCG starting to run

It can take the microsecond detonator and high-precision time-delay circuit to achieve the microsecond-precision detonating control of MAHEM. The flow chart of detonating time sequence is as shown in Fig.5.

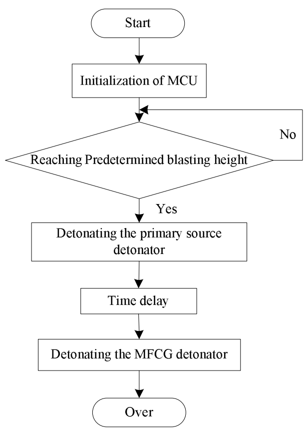


Fig.5 The flow chart of detonating time sequence

Safety and Arming System. There are detonators both in the primary source and MFCG. Therefore, the fuze of MAHEM has to supply safety and arming mechanism to two explosive trains. These two trains don't detonate synchronously but micro-time difference detonation output. A kind of micro-time Bidirectional safety and arming system is as shown in Fig.7. The system can ensure the normal safety and the timely arming of the two explosive trains.

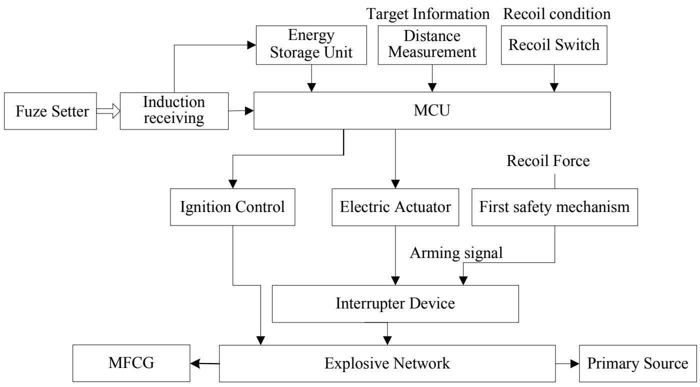


Fig.6 Principle block diagram of safety and arming system

When the MAHEM projectile is being launched, the safety and arming system uses the recoil force as the first environmental force to arm the first safety mechanism. After a period of precise delay, MPU will remotely arm the second safety mechanism by controlling the electrical actuator. Then the interrupter device acts to make the two explosive trains respectively be in line. After that, the detonators of the primary source and MFCG stay in armed state to wait for the detonating signals from MCU. The two explosive trains are armed at the same time, but they can detonate reliably and independently due the enough space interval.

Summary

Recently MAHEM is at the pre-feasibility study stage in the world. In this paper, ferroelectric ceramics is chosen as the primary source of MAHEM, relevant physical models are established to analyze the current's three-stage transfer process, a safety and arming system is proposed to ensure the normal safety and the timely arming of MAHEM and its action timing sequence is analyzed. This paper provides reference for the development of the theory and detonation control technology of MAHEM.

References

[1] Information on http://www.darpa.mil/Our Work/TTO/Programs/MAHEM

[2] Ming Xia. Study on the magnetic field of high field magnet powered by flux compression generator. Chinese journal of high pressure physics, 2012, 26(4): 433-441(in Chinese)

[3] Xing-gen Gong, Qi-zhi Sun. Available portable primary source of MFCG. Detonation and shock waves, 2002, (3): 93-98(in Chinese)

[4] Yuan-ji He, Ya-zhou Zhang. Chuan-lu Li, Hong-Gang Wang. The numerical simulation of electric response of PZT95/5 ferroelectric ceramics subjected to shock loading. Chinese journal of high pressure physics, 2000, 14(3): 189-194(in Chinese)

[5] Jin-mei Du, Yi Zhang, Fu-ping Zhang, Hong-liang He, Hai-Yan Wang. Large current out-put of PZT 95/5 ferroelectric ceramics under shock loading. ACTA PHYSICA SINICA, 2006, 55(5): 2584-2589(in Chinese)

[6] L.L.Altgilbers, Mark D.J. Brown, Igor Grishnaev, Bucur M. Novac, Ivor R. Smith, Yuriy Tkach, Iaroslav Tkach. Magnetocumulative Generators (Shock Wave and High Pressure Phenomena). Cheng-wei Sun, Zhou Zhi-kui. Bei Jing: National Defense Industry Press, 2008: 33-34

[7] Xiu-li Shi.Key technology research on magnetic flux compression generator. Ms D Thesis. Nanjing: Nanjing University of Science and Technology, 2011: 1-5(in Chinese)

Mechatronics and Applied Mechanics II
10.4028/www.scientific.net/AMM.300-301

Physical Modeling of Magneto Hydrodynamic Explosive Munition and Detonation Control
10.4028/www.scientific.net/AMM.300-301.1448