Some Features and Applications of Ballistic Science and Technology in China

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Introduction

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Prof. Hongzhi Li
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Introduction

China North Industries Group Corporation (NORINCO)
- Anti-terrorism mission
- Effective damage
- Precision strike
- Air defense and anti-missile
- Long-range suppression
- Armored assault

Nanjing University of Science and Technology (NUST)

Mission: NUST aims at developing itself into a major base in China for training high quality and creative personnel, high-tech research and transfer and academic and cultural exchanges as well as an indispensable force for China’s economic and social progress and national defense modernization.

Value: Unity, Dedication, Truth, Innovation.
China attaches great importance to innovative developments in defense technology. Since the beginning of the twenty-first century, the science and technology of China Ballistics has been developing rapidly and significant progress has been made in the fields of interior ballistics, intermediate ballistics, exterior ballistics and terminal ballistics. A lot of breakthrough has been achieved in theory, mechanism and focused technology.
Interior Ballistics

- Plasma Ignition Mechanism
- Non-Fourier Law Thermal Response
- Transient Burning Rate Model
- Interior Ballistic Optimization Design
- Interior Ballistic Potential Equilibrium Model
- Multi-Dimensional Multi-Phase Flow Simulation
- High Precision Measurement
- Launching tests

Electrothermal-Chemical Launch
Based on the MCM, a numerical model is established to simulate the plasma radiation process and discuss the mechanism of plasma ignition in ETC launchers. Because of the high power plasma and limited space characteristics of transient radiation, local solid propellant grains’ surface can quickly achieve ignition point by the early transient plasma radiation.
Interior Ballistics

Non-Fourier Law Thermal Response

\[
\frac{\partial^2 T}{\partial \tau^2} + \frac{\partial T}{\partial \tau} = a \frac{\partial^2 T}{\partial r^2} + \frac{2a}{r} \frac{\partial T}{\partial r} + \frac{ZQ}{\rho c} \exp\left(-\frac{E}{RT}\right)
\]

Plasma ignition model of non-Fourier law heat transfer effect due to thermal boundary layer. Because of the highly intense rapid plasma heat transfer, the propellant grain has not enough time to transfer the energy from the surface to the inner. This is a kind of unsteady non-Fourier law thermal response of the propellant grain.

Decrease of ignition delay with the increase of plasma energy

Non-Fourier effect is more remarkable for coated propellant
Closed bomb tests show that the plasma can enhance the burning rate of propellant especially under the condition of low and medium pressure, and the augmented combustion rate is strongly dependent on the electric discharging power, waveform and coupling with the propellant.

\[ u = u_1 p^{n_1} \left(1 + \beta_e P_e\right) \]  

**Vieille’s Law**

\[ u = u_1 p^{n_1} \]

**Electric Enhance Factor**

\[ u = u_1 p^{n_1} \left(1 + \alpha(t)n_1 \frac{dp}{dt}\right) \]

**Krier’s Law**

\[ u = u_1 p^{n_1} \left(1 + \frac{\alpha(t)n_1}{u_1^2 p^{2n_1+1}} \frac{dp}{dt}\right) \]

**Woodley’s Law**

\[ u = u_1 p^{n_1} \left(1 + \beta_e P_e\right) \]

**Pressure gradient**

Both electric power and pressure gradient are considered.
An interior ballistic optimization model is established to optimize the bore structure and loading parameters when the projectile mass, muzzle velocity and maximum pressure are specified.
The interior ballistic potential equilibrium theory is a phenomenological analysis method to characterize the combustion enhancement effect of propellant interacting with high power electrically discharging-supported plasma. This method based on the statistic thermodynamics, introduced the total pressure impulse instead of the burned propellant web size. The potential equilibrium point can be approximate as the burning end point of interior ballistic process.

Potential equilibrium point shift with the increase of plasma energy

$$
\pi_E = 0
$$

$$
\pi_\psi = f' \omega \beta' \psi
$$

$$
f' = f + E_{\text{plasma}} (K - 1) / \omega \psi
$$

$$
P \left( V + V_0 - \frac{\omega}{\rho} \left( \alpha - \frac{1}{\rho} \right) \omega \psi \right) = f \omega \psi + (K - 1) E_{\text{plasma}} - (K - 1) \int_0^{\psi'} P dV
$$
A multi-dimensional multi-phase flow dynamic model is established to simulate the ETC interior process, including the pressure, plasma temperature and velocity temporal-spatial distribution, etc.
Interior Ballistics

High Precision Measurement

- Pulsed Current
- Pulsed Voltage
- Barrel Pressure
- Muzzle Velocity

Electrothermal-Chemical Launch

ETC System
- Pulse Power Supply
  - Rogowski Current Transformer
  - High Voltage Probe
- Launcher System
  - Velocity Test Screens
  - Pressure Sensor
  - Pressure Transient Recorder
- HBM GEN5i DAQ
- Computer
Small and medium caliber ETC launching tests show that the bore pressure history has the high precision ignition, good consistency and platform effects in controlled fashion.
Interior Ballistics

- 3D Transient Multi-Physical Fields Simulation
- Impact Dynamics Simulation
- Multi-Physical Fields Measurement

Electromagnetic Launch
We have developed a 3D multi-physical fields coupling model to simulate the EML process. Calculations include the electromagnetic, thermal and stress fields.
Interior Ballistics

3D Transient Multi-Physical Fields Simulation

Velocity Skin Effect

A (V_{\text{max}}=2000\text{m/s})

J (V_{\text{max}}=2000\text{m/s})
Ohmic heat: The rapid heat deposition will increase the temperature in the interface between rails and armature, which will lead to the happening of contact transition.
High speed movement and swing of the armature may induce the gouging damage in the surface of rails.
Interior Ballistics

Multi-Physical Fields Measurement

Signals measurements subsystem
- Current Transformer
- Fiber Bragg Grating Strain Transient Test System
- High Voltage Probe
- Instant Multi-Spectral Temperature Measurement System

Pulsed Current
Pulsed Voltage
Transient Plasma Temperature
Transient Structure Strain
Armature Surface Topography

Image diagnosis subsystem
- High Speed Camera
- Flash X-ray System
- Velocity Test Screens
- CR Scanner

Dynamic deformation and stress waves in railgun

- Breech
- Muzzle
- Dynamic strain

Pulsed Current
Pulsed Voltage
Transient Plasma Temperature
Transient Structure Strain
Armature Surface Topography
A pulse laser grating imaging system was developed to recover the armature shape when it is leaving the muzzle. Armature surface topography is reconstructed by the image processing algorithm.

The transient arc plasma thermal temperature in bore was measured using the Boltzmann plot method to characterize the contact transition.
Intermediate Ballistics

Muzzle Flow Field
A numerical simulation program of muzzle flow has been developed by using large eddy simulation method and high accuracy hybrid numerical scheme.
Intermediate Ballistics

Muzzle Flow Fields of Barrel Weapon

Considering the ground influence

Considering the Air-inlet influence

Main Battle Tank

Aircraft Gun

Recoilless Gun
Exterior Ballistics

- Pulse Detonation Engine
- Range Extension Technique
- Flight Control Technology
In recent years, it was the first time that the liquid-fuel continuous rotating detonation engine was successfully initiated in China, which was a major breakthrough.

- The maximum peak value of rotating detonation wave pressure reached 3MPa, and the average value was 1.2MPa.
- Detonation wave velocity: 1022.2~1171.8 m/s.
- Detonation wave frequency: 2.1~2.4kHz.
The optimal trajectory of gliding flight extended range projectile which has limited control variable was obtained by using Pontryagin maximum principle and conjugate gradient methods. The longitudinal channel control structure and control parameters are obtained. Due to the effect of atmosphere and other uncertain factors, robust control of pitching movement is so critical for the flight control.
Exterior Ballistics

Flight Control Technology

Comparison of three guidance laws

<table>
<thead>
<tr>
<th>Guidance law</th>
<th>Landing angle (degree)</th>
<th>Control energy consumption</th>
<th>Miss distance (meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal guidance law</td>
<td>84.85</td>
<td>26.27</td>
<td>0.04</td>
</tr>
<tr>
<td>Suboptimal guidance law</td>
<td>80.74</td>
<td>34.42</td>
<td>0.07</td>
</tr>
<tr>
<td>Proportional navigation</td>
<td>38.94</td>
<td>12.47</td>
<td>0.28</td>
</tr>
</tbody>
</table>

A design method of optimal guidance law is presented combining optimal control theory and piecewise function method. Compared to the proportional navigation law, the optimal guidance law is able to more than double the landing angle. Because of the steep terminal trajectory, the strike accuracy and damage effects are increased.
Exterior Ballistics

Flight Control Technology

Mortar

Rocket

2-D Correction Flight
Flow separation induced by shock wave/boundary layer interaction (SWBLI) is a ubiquitous phenomenon encountered in supersonic or hypersonic inlet. Based on large-eddy simulations, combined with high order numerical scheme, ghost fluid method and adaptive mesh refinement technique, the flow separation induced by the supersonic flow past an Micro-vertex generator (MVG) and the interaction of shock wave with boundary layer were investigated numerically. And their flow separation control mechanisms were obtained.
Terminal Ballistics

- New Penetrating Technology
- Penetration Effect of Various Targets
- Target Vulnerability and Assessment of Damage Effects
- Simulation of Explosion and Penetration
We have conducted researches on the composite material formula, preparation technology of the micro/nano-crystalline penetrator core, and the self-sharpening effect of the micro/nano-crystalline penetrators, and shaped charge liner made of nano-crystalline and energetic materials.

- New materials
- New structures
- New principles
Experimental research were carried out for penetration effect of high velocity projectile above 2000 m/s.

(a) $v_0 = 2497 \text{ m/s}$  $\theta = 0^\circ$
(b) $v_0 = 2755 \text{ m/s}$  $\theta = 30^\circ$
(c) $v_0 = 2542 \text{ m/s}$  $\theta = 0^\circ$

Steel Front  Steel Back  Al Front  Al Back

(d) $v_0 = 2790 \text{ m/s}$  $\theta = 30^\circ$
(e) $v_0 = 2572 \text{ m/s}$  $\theta = 30^\circ$

Steel Front  Steel Back  Steel Front  Steel Back
Terminal Ballistics

Target Vulnerability and Assessment of Damage Effects

Aircraft

Tank

Missile
A special software which is named EP3D was established. The finite element method (FEM), finite volume method (FVM), meshless method such as smooth particle hydrodynamic (SPH) were selected and applied in the EP3D. This software can play a great role for the development of high-efficient lethal technology.
Future Development

- Interior Ballistics
- Intermediate Ballistics
- Exterior Ballistics
- Terminal Ballistics
Future Development of Interior Ballistics

ETC Launch
- Plasma enhanced control mechanism in the new propellant charge
- High efficiency coupling technology between the electric energy waveform and plasma
- Structure optimization design of plasma generator
- Plasma enhanced control of the high loading density propellants
- Develop the high precision measurement technology
- ...

EM Launch
- High velocity guided projectile
- Extreme phenomena of multi-physical complex structural barrel
- Repetitive stable launching Technology
- Muzzle arc management
- ...

HFR Launch
- In order to cope with the threat of hypervelocity air-raid weapons, firing rate, range and caliber must be further increased in the future.
- Information-based ammunition also should be developed to improve the lethal capability.
- ...

In order to cope with the threat of hypervelocity air-raid weapons, firing rate, range and caliber must be further increased in the future. Information-based ammunition also should be developed to improve the lethal capability.
Future Development of Intermediate Ballistics

- Improvement of muzzle flow simulation program
- Turbulent combustion model of transient high-pressure flows with intensive blast
- Formation process of secondary blast
- Generation mechanism and suppression method of muzzle flash
- Devices for high precision measurement of muzzle flow temperature, muzzle pulse noise
- Experimental simulation system for high altitude environment

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<table>
<thead>
<tr>
<th>Pulse Detonation Engine</th>
<th>Range Extension Technique</th>
<th>Flight Control Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>■ High frequency</td>
<td>■ Intelligence</td>
<td>■ Broad-airspace (over 30km height) and hypervelocity (over 5Ma) projectile of railgun, high-precision satellite or inertial guidance flight ballistics control technology used for autonomous precise guided cannonball, etc.</td>
</tr>
<tr>
<td>■ High specific impulse</td>
<td>■ Networking</td>
<td>■ Multi-barrel coordination</td>
</tr>
<tr>
<td>■ Multi-barrel coordination</td>
<td>■ High efficiency</td>
<td>■ Intellectualized flight control</td>
</tr>
<tr>
<td>■ Intellectualized flight control</td>
<td>■ Increase of range and stability</td>
<td>■ … …</td>
</tr>
<tr>
<td>■ Increase of range and stability</td>
<td>■ … …</td>
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Future Development of Terminal Ballistics

Terminal effects of new defense structures and materials will be studied such as long rods and inhomogeneous complex long rod.

Multi-modes damage, smart mutilation, laser and microwave damage technique, etc. will be focused.

Terminal ballistics of hypervelocity (about 2500m/s) impact will be researched to improve penetration efficiency.

Develop new theoretical model and simulation method for the assessment of target vulnerability and damage.

Simulation will be focused on constitutive relations and physical parameters under high pressure of materials.
THANK YOU
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