PRELIMINARY RESULTS ON IN-BORE PROJECTILE ATTITUDE MEASUREMENTS BY INTEGRATED BALLISTIC SIMULATOR (PHASE1)

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The main objective of Integrated Ballistic Simulator (IBS) project is to establish the basic common building block for integrated ballistic simulation software covering interior, intermediate, external and terminal ballistics, and gun dynamics. In order to validate and improve the accuracy of simulation software, we have developed novel ballistic measurement devices, such as a bore centerline displacement (BCD) measurement device and an in-bore projectile attitude (IPA) measurement device. This paper presents preliminary results of simultaneous measurement of IPA and BCD. This study was undertaken to investigate the difference of projectile attitude measurements of APFSDS (Armor Piercing Fin-Stabilized Discarding Sabot) and blunt nose projectile during lunch process. Although the results of BCD are the same, the results of projectile attitude are quite different due to vibration of the rod.

INTRODUCTION

Ballisticians have endeavored to establish the numerical simulation technology on interior, intermediate, external, and terminal ballistics, and gun dynamics in order to accomplish the efficient research and development of fire arms. Recently, the integration of separately developed software and unified numerical simulation of entire ballistic phenomena are attracting a much attention, because integrated software is more effective to examine the analysis of firing dispersion.

TRDI prototyped the IBS (Phase1) [1] which consists of ballistic simulation software and hardware. The IBS software employs modular design, consisting of combustion, in-bore projectile motion, gun dynamics, intermediate ballistic, and exterior ballistic modules and their management module. The hardware structure was designed to improve the accuracy of software by means of comparing the numerical results with experimental results. The relationship between software structure and hardware structure is shown in Table 1.

For the purpose of comparing the numerical results with experimental ones, we have to design measurement hardware capable of unified space & time coordinate system and develop the new measurement devices for simultaneous IPA and BCD measurements. Although in-bore projectile-gun dynamics is supposed to have a significant effect on firing accuracy for direct firing weapon, the past works on this subject are very scarce. The investigation on the IPA was mainly done by numerical simulation, and their validation was conducted by comparing the experiment results of BCD and launched projectile [2], because the direct IPA measurement is difficult. Also, there are papers treating realistic numerical modeling [3], [4]. Considering these past works, we have to conclude that there is no numerical simulation on in-bore projectile motion compared with direct experimental measurement data, nor no direct measurement of IPA and BCD.

This paper, therefore, aims at presenting preliminary results on the simultaneous measurement of IPA and BCD for APFSDS projectile and blunt nose projectile.

Table 1. The Relationship Between Hardware Structure and Module Structure

<table>
<tr><th colspan="3">IBS Hardware (Phase 1)</th><th>Validated Module</th></tr>
<tr><td rowspan="8">Interior Ballistics Unit</td><td rowspan="5">Bore Centerline Displacement Measurement device</td><td>Magnetic Sensors</td><td rowspan="5">Gun Dynamics Module</td></tr>
<tr><td>Strain gauges</td></tr>
<tr><td>Thermocouple sheet</td></tr>
<tr><td>Laser and Position Sensing Device for Initial Centerline</td></tr>
<tr><td>Existing instruments (recoil displacement ...)</td></tr>
<tr><td rowspan="2">In-bore Projectile Attitude Measurement device</td><td>Laser and Position Sensing Device</td><td rowspan="2">In-Bore Projectile motion Module</td></tr>
<tr><td>Existing instruments (high speed video camera…)</td></tr>
<tr><td colspan="2">Existing instruments (Chamber pressure ...)</td><td>Combustion Module</td></tr>
<tr><td>Intermediate Ballistic Unit</td><td colspan="2">Digitalize 3D X-Ray device</td><td>Intermediate Ballistics Module</td></tr>
<tr><td rowspan="2">Instrumented projectile Unit</td><td colspan="2">APFSDS with reflect mirror</td><td rowspan="2">Combustion Sub-Module and In-Bore Projectile motion Module</td></tr>
<tr><td colspan="2">Blunt nose with reflect mirror…</td></tr>
<tr><td rowspan="2">Exterior Ballistics Unit</td><td colspan="2">Digitalized Spark Camera Stations</td><td rowspan="2">EB Module</td></tr>
<tr><td colspan="2">Existing instruments (High Speed Video Camera...)</td></tr>
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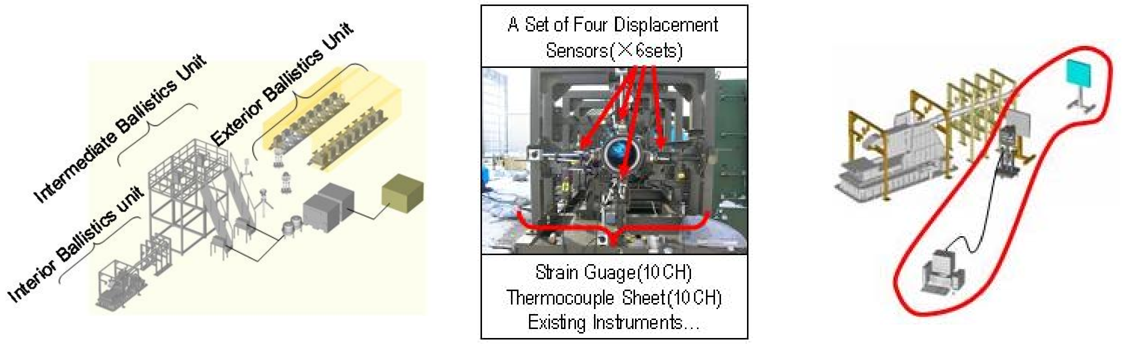
IBS HARDWARE

First, we explain the outline of IBS hardware. The hardware consists of three units, Interior Ballistics Unit, Intermediate Ballistics Unit, and Exterior Ballistics Unit, which are shown in Figure 1 (a). Each measurement Unit has a unified space & time coordinate system. The Interior Ballistics Unit is divided into two devices and existing instruments. These two devices are shown in Figure 1 (b) and (c).



(a) The Over View of Hardware Structure (b) BCD Measurement Device (c) IPA Measurement Device

Figure 1. Schematic Diagram of IBS (Hardware)

BCD measurement device

The BCD measurement device consists of strain gauges for the measurement of projectile travel and magnetic displacement sensors (displacement resolution:6 μ m, sampling frequency:10kHz) for the measurement tube outer surface displacement.

An initial bore centerline was measured by optical method in 50 μ m displacement accuracy. The four magnetic displacement sensors located top, bottom, left and right measure the gun tube surface displacement in order to calculate its bore centerline relative to the initial bore center line during launch process. Strain gauges are used for validating the result of calculated centerline curvature of gun tube, too.

During the preliminary tests, it was found that there are three factors affecting the accuracy of calculating the BCD from gun tube surface displacement, they are tube outer surface expansion, tube surface taper, and curvature effects. We will explain these effects and the procedures to circumvent these difficulties.

It is well known that the gun tube outer surface expands slightly by passing the projectile. Fortunately the magnitude of expansion of outer surface is symmetric, thus, simple addition and division of a pair of sensors, such as top and bottom, and left and right sensors, work for compensating the effects of tube outer surface expansion.

The gun tube outer diameter is made to decrease from breech to muzzle. The measured signal of outer surface displacement contains the effects of tube surface taper depending on the recoil length. Gun tube surface shape can be measure before the launch, and recoil motion is measured during the BCD measurement. Thus measurement of outer surface displacement is compensated by considering the geometry of the surface taper thoroughly.

The curvature effect is depicted in Figure 2, for example, the displacements of vertical distance from tube outer surface measured by the top and bottom sensors are different depending on the change of the curvature of gun tube surface. Although these distances are the same geometrically, the outputs of the magnetic displacement sensors are different, since they are designed to measure distance of a flat surface. In order to overcome this difficulty, we examined the relationship between gun tube surface displacement and the output of each sensor, and found out that the gun tube surface displacement is successfully recovered by the following empirical relations (1) with reasonable accuracy.

$$
\begin{aligned}
D_{top} &= a_{top} V_{top} + b_1 (V_{left} - V_{right})^2 + c_1 (V_{left} - V_{right}) + d_1 \\
D_{bottom} &= a_{bottom} V_{bottom} + b_2 (V_{left} - V_{right})^2 + c_2 (V_{left} - V_{right}) + d_2 \\
D_{left} &= a_{left} V_{left} + b_3 (V_{top} - V_{bottom})^2 + c_3 (V_{top} - V_{bottom}) + d_3 \\
D_{right} &= a_{right} V_{right} + b_4 (V_{top} - V_{bottom})^2 + c_4 (V_{top} - V_{bottom}) + d_4
\end{aligned}
\qquad (1)
$$

where D_{top}, D_{bottom}, D_{left}, D_{right} = Gun tube surface displacements [μm]
a_{top}, a_{bottom}, a_{left}, a_{right} = Calibration constants [μm /V]
b_i, c_i, d_i = Experimental constants $(i = 1,2,3,4)$
V_{top}, V_{bottom}, V_{left}, V_{right} = Sensor Outputs [V]

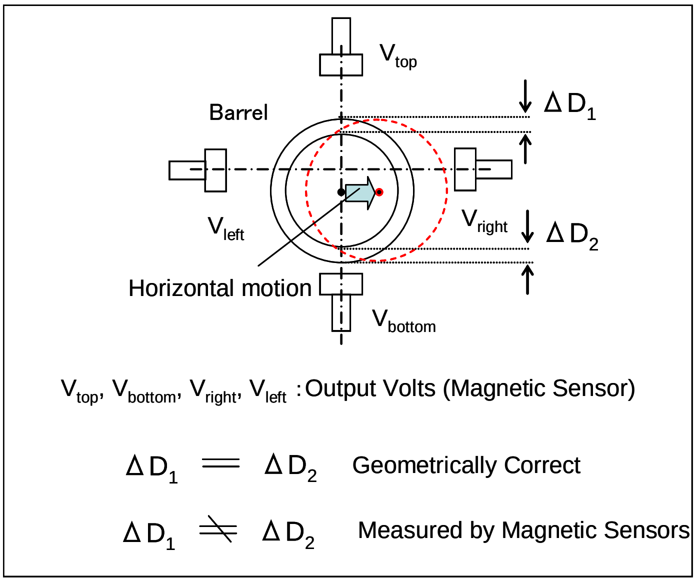
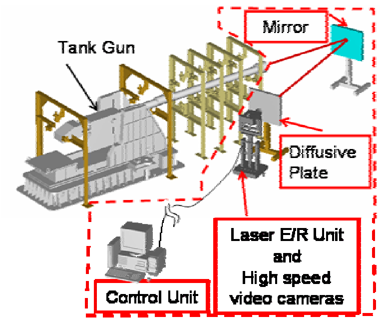


Figure 2. Curvature Effects of Gun Tube Surface

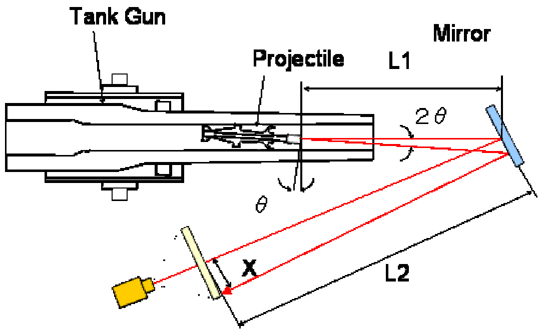
IPA Measurement device and Instrumented Projectile

The IPA measurement device consists of reference laser beam, reflection mirror, projectile-mount mirror, diffusive plate and PSD (Position Sensing Device) or high speed video camera. Its principle is that the reference laser beam is deflected by the mirror at the head of the projectile. The deflection of laser beam is proportional to the projectile attitude. The deflection of the laser beam is measured as the vertical and horizontal displacement at the diffusive plate by PSD (sampling rate:20 μ sec) or high speed video camera (flaming rate:10,000fps). The PSD resolution of attitude measurement is less than 0.08 degree at longest light path. In addition, in-bore phenomena are taken by a high speed video camera. Figure 3 shows the experimental set-up of IPA measurement device.

Figure 4 shows a sketch of instrumented projectile and APFSDS. The Blunt nose projectile has the same physical properties as those of APFSDS such as projectile weight, the center of mass, and band location, except rigid structure without sabot, and nose shape. Both projectiles have also a head-mounted mirror to reflect laser beam and the same charge system.

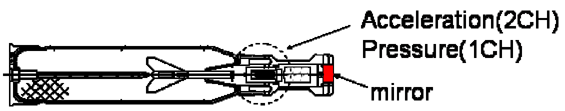


(a) Experimental Setup for IPA

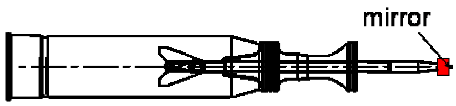


(b) Measurement Principle of the IPA

Figure 3. Experimental Setup of the IPA Measurement Device



(a) Blunt Nose Projectile (Mirror Mounted)



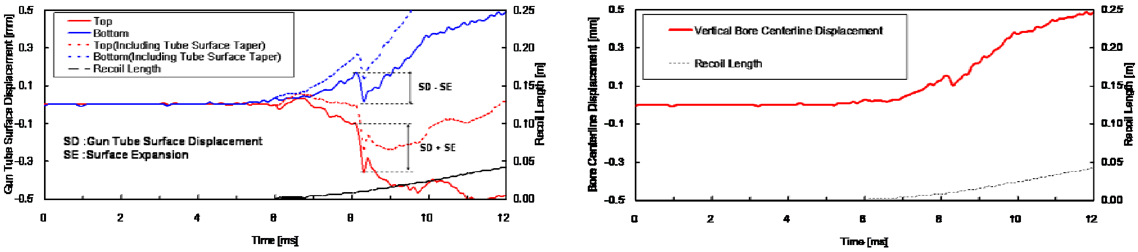
(b) APFSDS (Mirror Mounted)

Figure 4. Sketch of the Instrumented Projectiles

RESULTS AND DISCUSSION

Tube Motion and BCD Measurement

Figure 5 shows that the result of gun tube surface displacement of vertical direction by adopting the equation (1) and BCD. It can be seen form Figure 5 (a) the influences of gun tube outer surface taper and its surface expansion. The BCD calculated by adding and dividing of top and bottom was shown in Figure 5 (b). Figure 6 shows the displacement of gun tube centreline with time. This result clearly shows that the cradle side displacement propagates to the muzzle. Also, it was founded that the vibration mode of gun tube centreline is similar regardless of the type of projectile. This fact implies that the difference between separating and non-separating sabot has insignificant effect on the BCD.



(a) Surface Displacement of Top and Bottom (b) Vertical Displacement of Centerline

Figure 5. Gun Tube Displacement

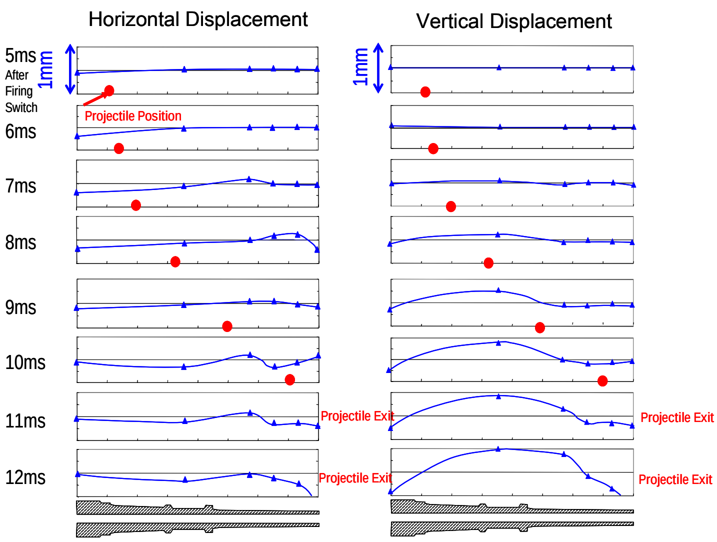
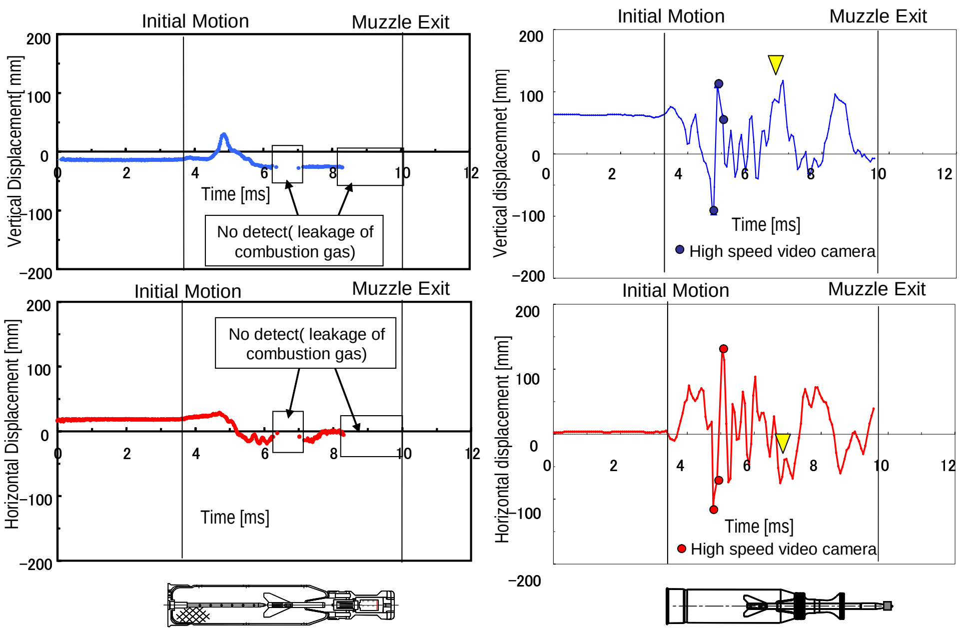


Figure 6. Gun Tube Centerline Displacement

In-Bore Attitude Measurement

Figure 7 shows the difference of in-bore attitude between the blunt nose projectile and the APFSDS projectile. Although both of them had the same results of BCD, the results of in-bore attitude are quite different. The fact that the frequency of the APFSDS projectile was higher than that of the blunt nose projectile indicates that the vibration of the rod has significant effect on in-bore attitude.

Close examination of the date of APFSDS in-bore attitude, one finds the frequency change around at 7ms, indicating as a triangle on figure 7(b). This implies that the dynamics of APFSDS attitude changes around 7ms. Figure 8 shows the snapshot of high speed video of in-bore projectile, and indicates that three-piece sabot which binds around the rod slightly opens. Therefore, the in-bore attitude of APFSDS is mainly due to the vibration of the rod, and its dynamics changes according to the configuration of the sabot and the rod. Before 7ms, the rod is supported by the all of the grooved region of sabot, and after 7ms, the rod is supported by only the rear part of the grooved region of sabot (figure 9). The change of support condition would result in the change of frequency of vibration of the rod. For our best knowledge, there is no simulation considering this effect. This knowledge can be used for the enhancement of IBS software modeling.



(a) Blunt Nose Projectile (b) APFSDS Projectile

Figure 7. In-bore Attitude with Regard to the Top of Projectile

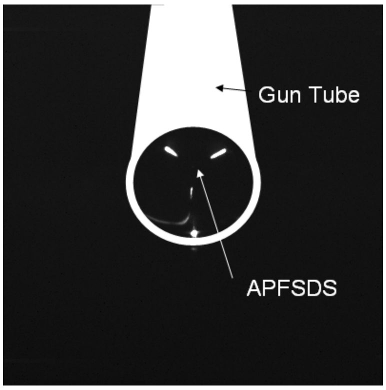


Figure 8. Openings of Three-piece Sabot (7ms)

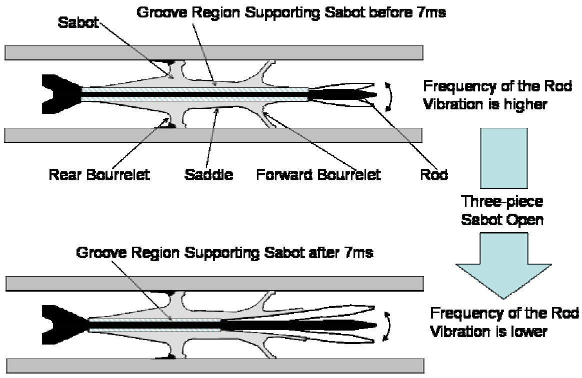


Figure9. Change of the Rod Support Condition

CONCLUSIONS

The preliminary results of the simultaneous measurement of bore centerline displacement and in-bore projectile attitude during the projectile launch, are presented. The three difficulties of the measurement of bore centerline displacement are pointed out and their remedies are demonstrated. Comparison of in-bore attitude of blunt-nose and APFSDS projectiles revealed the significance of configuration of the rod and the sabot. Obtained data of bore centreline displacement and in-bore projectile attitude would provide a valuable knowledge for enhancing the modelling of ballistic simulation.

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