DEVELOPMENT OF INTEGRATED BALLISTIC SIMULATOR (PHASE 1)

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The Integrated Ballistic Simulator (IBS) is on-going project to establish the basic common building block for the integrated ballistic simulation software from interior, intermediate, and exterior and terminal ballistics, and gun dynamics. Unique feature of IBS is the architecture harmonizing the simulation software and hardware to obtain the validation data and improving mathematical modelling. IBS consists of IBS software and hardware, including ballistic data measurement unit, and instrumented projectiles. The main target of IBS (Phase 1) is smooth bore tank gun and its ammunition. The basic concept and current status of IBS project is briefly described.

INTRODUCTION

Numerical simulation has become one of major pillars for design of guns and ammunitions. For example, multidimensional, multi-phase flow simulation is indispensable tool for gun charge and primer design. Numerical simulation helps us to reduce the risk of anomalous combustion and to obtain the (sub-)optimal design in cost effective way. Also numerical simulation can be used for obtaining the understandings of complex ballistic phenomena, which cannot be observed by the ordinary instruments. It is desirable to have a common design tool to simulate the entire ballistic phenomena.

Integrated ballistic simulator (IBS) project has started to meet these requirements. Figure 1 shows the concept of integrated ballistic simulator. The development process of guns and ammunitions using IBS would be as follows. First, a base-line gun and ammunition by assembling their components, if necessary original components can be designed, are assembled in the IBS environment. Second, the ballistic simulation is conducted on the interested ballistic region: interior, intermediate, and/or exterior ballistics, and the design results are evaluated, and if necessary, the base-line design is modified until the design goal is met. Also integrated ballistic simulator could conduct the virtual firing, such as firing on the drive, firing under extremely severe condition, to evaluate the overall performance of the gun and ammunition. It may be possible to substitute some firing trial by well validated simulations.

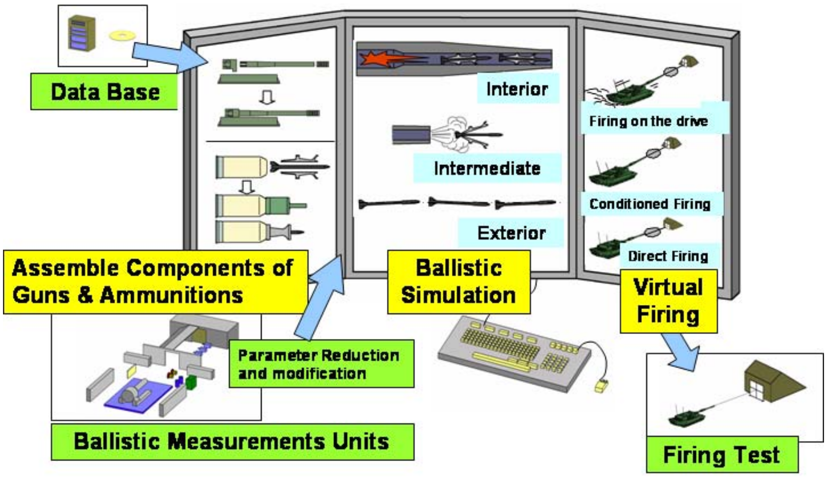

Figure 1 Concept of integrated ballistic simulator (IBS)

INTEGRATED BALLISTIC SIMULATOR (PHASE 1) OVERVIEW

The main objective of IBS project is to establish the basic common building block for the integrated ballistic simulation software from interior, intermediate, exterior, and terminal ballistics, and gun dynamics. In order to validate and improve the accuracy of simulation software, the IBS includes the ballistic data measurement unit, and the instrumented projectiles. The main object of IBS (Phase 1) is smooth bore tank gun and its ammunition.

The IBS software employs modular design, consisting of combustion, in-bore projectile motion, gun dynamics, intermediate ballistic, and exterior ballistic modules and their management modules. The combustion module has three different fidelity models; 2D two-phase flow combustion model, 1D two-phase flow combustion model, and lumped parameter combustion model. The in-bore projectile motion module is composed of structural dynamics, heat transfer, and band wear computation. The gun dynamics module is composed of structural dynamics, heat transfer, and deformation due to heat. The intermediate and exterior ballistic module is composed of empirical computation and standard 6 DOF (degree of freedom) rigid body dynamics.

The ballistic measurement unit and the instrumented projectile provide the important ballistic data supporting the validation of IBS software in unified time and space coordinate system. Gun tube motion and in-bore projectile attitude are measured simultaneously to validate the modeling and the accuracy of IBS software.

Integrated ballistic simulation software

Whole ballistic phenomena involve wide variety of scientific disciplines. Upon the design phase of IBS, system study was conducted to derive the major mathematical models for the IBS. The snapshot of the mathematical modelling result of interior ballistic region is shown on figure 2.

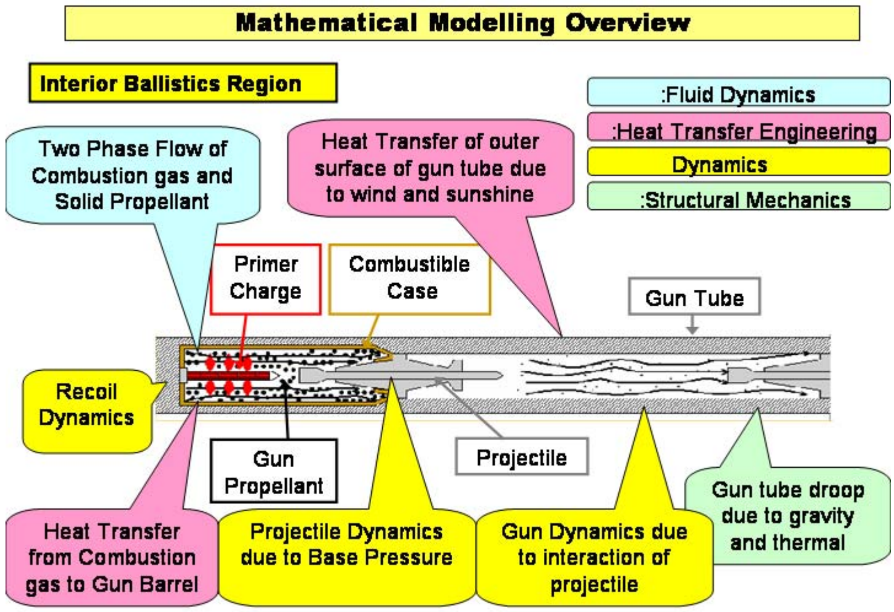

Figure 2 Mathematical modelling of interior ballistic region in IBS (phase1)

Dynamics of guns and ammunitions are modeled by their components. Gun tube is divided into tube, bore evacuator, breechblock, cradle, trunnion mount, recoil brake, and recuperator. The tube is further subdivided into several discrete rigid bodies connected by beams in order to model the gun tube bending and deformation effects. KE type ammunitions are modeled by penetrator, and a set of sabot. These elements are further subdivided into several rigid bodies connected by beams in order to model the projectile and sabot bending and deformation effects. Heat MP projectile is modeled by a shell and its subdivision. Variety of contact types such as screw contact between gun tube and breech block, rigid contact recoil brake and trunnion mount or gun cradle, is defined. The contact between gun tube and rotating band is also modeled including normal force and frictional forces of band wears, static and dynamic friction. The gravitational force is modeled for correct gun tube droop, and the base pressure and its counter-part, breech pressure are extracted following combustion calculations.

Combustion gas and solid propellants are modeled by the two-phase flow, fluid dynamic modeling. Depending on the fidelity of the model, we have developed lumped parameter, 1D, and 2D axisymmetric two-phase flow model. The detailed solution are described the following section.

Recoil brake and recuperator mechanics are modeled by the simple spring elements, but its recoil length and force relationship can be adopted for various recoil mechanics.

Heat transfer from the combustion gas to the gun barrel is modeled on the empirical heat transfer correlations. Heat conduction inside the gun tube is modeled based upon 1D heat conduction equations. Outer surface heat transfer has a significant effect on the gun tube droop, and is modeled with solving the heat conduction equations using the empirical heat transfer relationship.

Overall relationship of software sub-modules is described in figure 3. Most of the sub-modules are time-integrated with standard 4th order Runge-Kutta method, but combustion sub-module and heat conduction equation are integrated by separate methods, and have interface routines to synchronize the state variables.

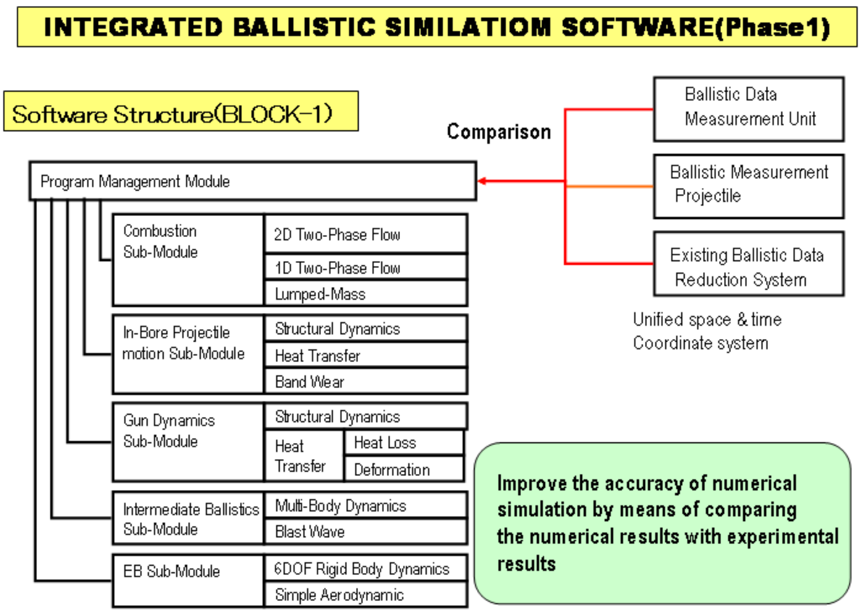

Figure 3 Modular design of IBS (phase 1)

Ballistic Data Measurement Unit

The ballistic data measurement unit is divided into three units: interior ballistic measurement unit, intermediate ballistic measurement unit, and exterior ballistic measurement unit (figure 4). For the software validation purpose, these units are deliberately designed to have the same unified time & space coordinate system.

The interior ballistic measurement unit consists of three measurement units: the testing gun unit, the gun tube dynamics measurement unit, and the in-bore projectile measurement unit. The testing gun measurement unit contains gun chamber pressure sensors, recoil length and velocity sensor, and recoil brake and recuperator force sensors. The gun tube dynamics measurement unit and the in-bore projectile measurement unit are explained in detail in [2].

The intermediate ballistic measurement unit consists of orthogonal flash X-ray unit to measure the sabot separation process and the interaction between muzzle blast and projectile. The digitized x-ray film is used for recording. The projectile and sabot attitude are extracted from the pair of x-ray film.

The exterior ballistic measurement unit is the modernization of the existing Shimokita Spark Range equipment [1]. Most intriguing modification is the employment of digital camera for recording spark shadowgraph. Since digital image data is simultaneously obtained, the analysis to extract projectile attitude is simplified. Calibration process to establish the relationship of the camera coordinates and the reference coordinate system is highly automated and time-efficient.

Instrumented projectiles

The instrumented projectiles consist of two types; Blunt-nose projectile with build-in memory, and Heat MP projectile with wired sensors, and their main function is to obtain the validation data of IBS software.

Blunt-nose projectile is intended for the measurement of base pressure and acceleration during in-bore region for KE projectile. Pressure and acceleration sensors, signal conditioning unit, memory unit, and battery unit are enclosed inside the projectile shell to withstand the high-g environment. First electric circuit of instrumented projectile is activated, and the projectile is loaded and fired as usual. Then the projectile is recovered, and the memory unit is extracted from the projectile body to read out the memory contents. The charge system is the same as the KE projectile, but the maximum acceleration during firing can be changed by adjusting the charge weight. The successful measurement of instrumented projectile depends on the recovery conditions.

It is possible to measure the acceleration of conventional KE projectile by elaborate construction of recovery structure.

Heat MP projectile is designed for the measurement of base pressure, acceleration, and strain of shell deformation at the initial projectile move. The projectile contains only the sensor unit, and the signal conditioning unit and the recording unit are located at the side of testing gun. The projectile is connected to the signal conditioning unit by the electric wire. The wire would be eventually disconnected at the initial stage of projectile motion, but until that time, all of the sensor signals are recorded.

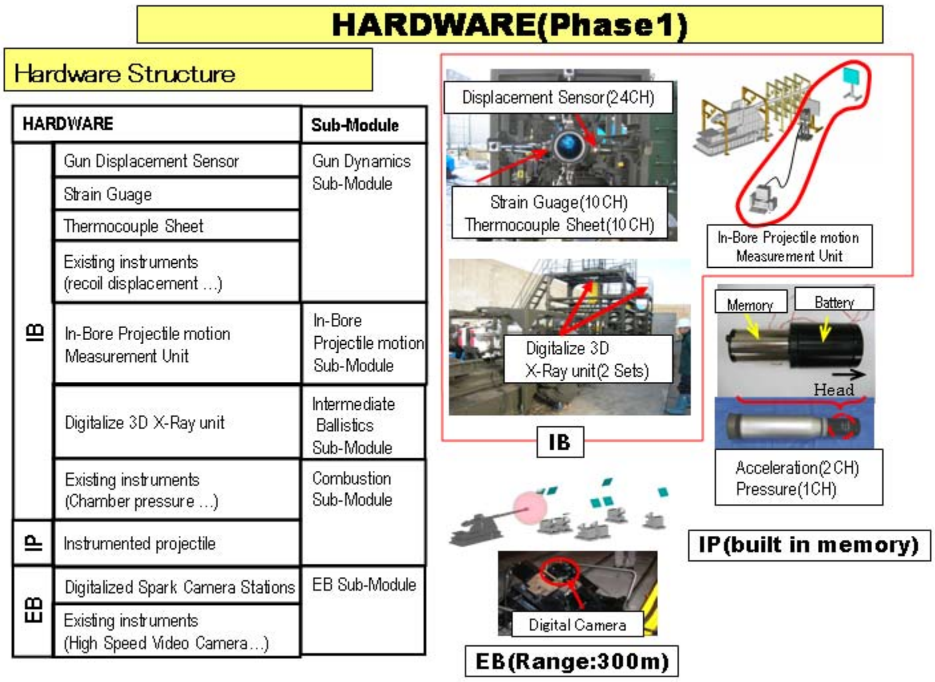

Figure 4 Overview of IBS hardware and their related software sub-module

SOME RESULTS ON INTERIOR BALLISTICS SIMULATION

Combustion of solid propellants is of most influential factor to the overall gun performance. In IBS (phase 1), interior ballistics is the important part. Lumped parameter, 1D and 2D combustion sub-modules are developed in IBS. 1D and 2D combustion sub-modules are formulated based on the two-phase mixture theory. Heterogeneous burning in the gun chamber is modeled by two-phase mixture of combustion gas and solid composed of average of granular propellant, combustible case, and primer charge. Following the conventional internal ballistics formulation [3], gas phase is treated as compressible flow, and the solid phase is treated as incompressible flow. The governing equations of gas phase are the conservation of mass, momentum, and energy of compressible flow. The governing equations of solid phase are the mass and momentum of incompressible flow for each propellant type.

To calculate co-volume and specific heat of gas phase, the knowledge of composition of combustion gas is necessary. We employ the molecular weight, and specific heat ratio as independent variables, and solve their convection equations for the current implementation. (Note that these equations are not conservative.) Energy equation of solid phase is substituted by the simple polynomial surface temperature profile. To close the system, co-volume equation of states is used. The other constitutive relationships of solid phase are fluid drag and intergrannular stress model.

1D combustion sub-module utilizes Lagrangian grid moving along the chamber volume expansion. On the other hand, 2D combustion sub-module utilizes Eulerian grid system, and the boundaries of chamber and projectile base are represented as cell mask.

Convective flux term is discretized by MacCormack scheme for 1D sub-module, and FCT (Flux Corrected Transport) scheme for 2D sub-module, respectively. Time integration is conducted explicitly. Time step is adjusted to satisfy the CFL condition.

Validation of internal ballistic simulation was conducted. 1D combustion sub-module computation on the blunt-nose projectile in a reduced charge setting is compared with the experimental data. The comparison of breech pressure after some adjustment of burning rate, heat transfer coefficients, and initial bore resistance, is shown in figure 5.

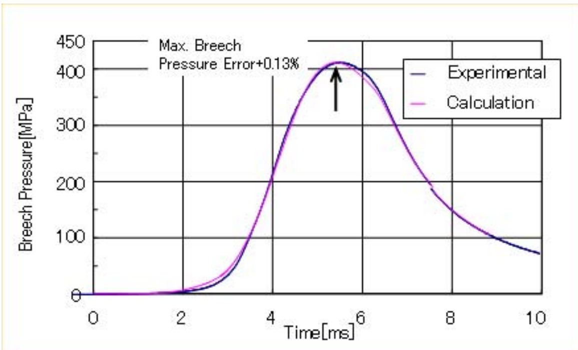

Figure 5 Comparison of 1D computation with experimental data.

Next example shown in figure 6 is the computation of AGARD gun with 1D and 2D combustion sub-modules. The maximum breech pressure of 1D and 2D computations, ranges from 330 to 400MPa which is comparable to the reported results [4,5]. For more precise evaluations, effects of ignition, grid spacing, boundary treatments, FCT parameters should be investigated.

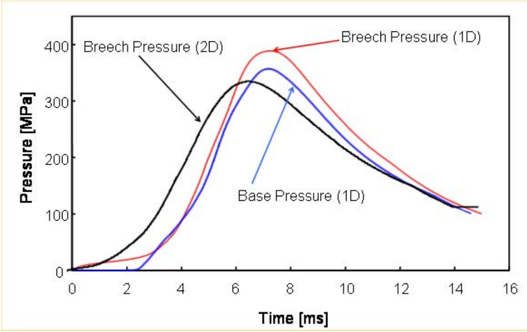

Figure 6 Comparison of 1D and 2D combustion sub-module computations on AGARD gun.

CONCLUDING REMARKS

Integrated Ballistic Simulator (phase 1) project is on-going activities for the establishing the ultimate simulation technology on ballistics. Integration of multi-disciplinary simulation technology has been done. Preliminary validation results on combustion sub-module of interior ballistics are presented, and validation activities are now on the way. In the future, rifled gun or mortar capability, and more elaborate modelling of intermediate and exterior ballistics regions are planned for future extension.

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