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Development of a Fast Lumped Parameter Interior Ballistic Model for the Investigation of Novel Grain Geometry Performance

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ABSTRACT

The use of an Interior Ballistic model for gun system design allows the designer to evaluate the performance of propelling charges in an efficient manner. The implementation of a lumped parameter interior ballistic model that incorporates a number of grain geometry form functions for different propellant types is described in this report. The model has been developed for the testing of novel grain geometries that may be produced by non-conventional means, e.g. additive manufacturing. The code was required to have a fast run time, and be suitable for parametric optimisation to allow the performance of different grain geometries to be evaluated. The lumped parameter model provides a simplified simulation of the internal physical processes within the gun barrel. The time history of variables including the chamber pressure, chamber temperature, and projectile internal trajectories are calculated based upon a number of input parameters defining the gun system. The code also makes use of existing libraries for grain geometry form functions, enabling any additional grain geometry types to be shared with other existing tools. An example test case is also provided for validation purposes against another similar Interior Ballistic code.

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Executive Summary

The use of an Interior Ballistic model for gun system design allows the designer to evaluate the performance of propelling charges in an efficient manner. The implementation of a lumped parameter interior ballistic model that incorporates a number of grain geometry form functions for different propellant types is described in this report. The model has been developed for the testing of novel grain geometries that may be produced by non-conventional means, e.g. additive manufacturing. These novel grain geometries have the potential to deliver significant increases in the performance of a gun system.

The code was required to have a fast run time, and be suitable for parametric optimisation to allow the performance of different grain geometries to be evaluated.

The lumped parameter model provides a simplified simulation of the internal physical processes within the gun barrel. The time history of variables including the chamber pressure, chamber temperature, and projectile internal trajectories are calculated based upon a number of input parameters defining the gun system. The code also makes use of existing libraries for grain geometry form functions, enabling any additional grain geometry types to be shared with other existing tools. An example test case is also provided for validation purposes against another similar Interior Ballistic code.

This code provides the ground work for analysing the performance of novel propellant grain geometries, and enables fast optimisation to be conducted to tune the dimensions of the propellant grain to suit a given gun system.

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Nomenclature

a	Projectile acceleration [m/s^2]
A	Area [m^2]
A_s	Propellant Surface Area [m^2]
b	Co-volume [m^3/kg]
c_v	Specific heat at constant volume [J/(kg K)]
d	Projectile displacement [m]
D	Diameter [m]
E	Energy [J]
I	Moment of inertia [kg.m^2]
m	Mass [kg]
n	Propellant burn rate pressure index [n]
q	Combustion Energy [J/kg]
r	Radial regression [m]
$\dot{r}$	Rate of Radial regression [m/s]
T	Temperature [K]
T_O	Ambient air temperature [K]
R	Gas constant
V	Volume [m^3]
v	Projectile velocity [m/s]
x	Distance along barrel [m]
α	Propellant burn rate coefficient [m/s/MPa^n]
β	Propellant burn rate modifier?? [cm/s]
γ	Ratio of specific heats
ν	Specific volume [m^3/kg]
ρ	Density [kg/m^3]
τ	Barrel rifling twist rate
ω	Rotational velocity [rad/s]

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1. Introduction

The implementation of a fast lumped parameter model for analysing interior ballistic problems in gun systems is described in this report. The model is required to evaluate the performance of novel grain geometry gun propellants that could be manufactured via non-conventional means, e.g. additive manufacturing. The model is required to be fast running, and suitable for parametric optimisation to allow different geometries to be analysed and their performance optimised.

The model is based on a set of equations derived from a conservation of energy and mass analysis of the system. These equations take a number of input parameters describing the gun, projectile, and propellant and are solved in a time stepwise fashion. The resulting output provides internal projectile trajectories along with propellant gas temperature and pressure histories.

The code has been written in C and utilises existing libraries developed by Defence Science and Technology (DST) Group to calculate propellant grain burning regression in a number of geometric forms. The existing libraries form part of a more complex 2D axisymmetric interior ballistic code [1]. The advantage being that any modifications made to the form function library (e.g. adding additional form functions for new geometries) can then be used by both codes.

This report details the set of equations used for the simulation, along with how they are implemented within the code. The assumptions used for the analysis are also stated. The basic principles of this model is essentially the same as that described in [2].

Also included is a validation example comparing the output from this code with that of another well validated, lumped parameter model code (IBHVG2) [3].

2. Interior Ballistic Model

2.1 Assumptions

The lumped parameter model that is implemented here makes a number of assumptions. Later versions of the model may address these assumptions, potentially improving the model's accuracy. The assumptions include:

- Heat loss to the gun and related components is ignored.
- The recoil energy and associated movement is ignored.
- All propellant within the chamber is ignited simultaneously on commencement of the simulation.
- The primer is completely consumed before the simulation commences.
- The initial gas within the chamber consists only of primer combustion products (i.e. no ambient air within chamber).

It has been assessed that these assumptions are suitable for this lumped parameter model, and provide results of reasonable accuracy that are useful for overall performance analysis of a gun system. Complex phenomena such as propellant ignition models and simulation of pressure waves are not treated, and are more suited towards computational fluid dynamic (CFD) type codes such as that described in [1].

2.2 Propellant Gas Temperature and Pressure

The lumped parameter model uses an energy balance between the propellant and gas energy. A time-stepping approach is used, where initial values of energy, pressure, and temperature are calculated, then updated at each time-step. At each step, the propellant energy gas is equal to the energy released by burning of the propellant minus the projectile kinetic (including rotational) energy and other energy losses present in the system, i.e.

$$E_{gas} = E_{propellant} - E_{projectile} - E_{losses} \tag{1}$$

The gas energy (which initially consists only of the fully consumed primer) can be expressed as:

$$E_{gas} = T_{gas}\left(c_{v_{primer}}.m_{primer} + c_{v_{propellant\ gas}}.m_{propellant\ gas}\right) \tag{2}$$

Assuming the specific heats are constant over the temperature ranges considered. Combining these two equations, this can be rewritten to find the internal gas temperature:

$$T_{gas} = \frac{E_{propellant} - E_{projectile} - E_{losses}}{c_{v_{primer}}.m_{primer} + c_{v_{propellant\ gas}}.m_{propellant\ gas}} \tag{3}$$

The Nobel-Abel equation of state is often used as an appropriate model for the propellant gas in lumped parameter models [4]:

$$P_{gas}\left(v_{gas} - b\right) = R_{gas}.T_{gas} \tag{4}$$

Using this, the pressure can then be found by using the previously determined gas temperature after rearrangement:

$$P_{gas} = \frac{R_{gas}.T_{gas}}{\left(v_{gas} - b\right)} \tag{5}$$

The energy released by the propellant is given by:

$$E_{propellant} = q.\int \dot{m}_{gas\ production}\, dt \tag{6}$$

Where the mass rate of gas produced is equivalent to the mass rate of propellant consumed and can be found by:

$$\dot{m}_{gas} = \dot{m}_{solid\ consumed} = \rho_{propellant}.\dot{V} \tag{7}$$

The rate of change in volume is calculated from the grain geometry form function for the type of propellant used in the simulation.

$$\dot{V} = \frac{\delta V}{\delta t} \tag{8}$$

Where, the volume before and after each time step is calculated based on the regression distance, determined from the regression (or burning) rate that uses the steady state burning law [5]:

$$\dot{r} = \alpha.{P_{gas}}^{n} + \beta \tag{9}$$

2.3 Projectile trajectories and Losses

Once the projectile is in motion (i.e. chamber pressure is greater than the shot start pressure) the acceleration, velocity and displacement of the projectile can be determined by:

$$a_{projectile} = \frac{\left(P_{base} - P_{resistance} - P_{precursor}\right).A_{base}}{m_{projectile}} \tag{10}$$

Where the pre-cursor air pressure is given by the following relation [6]:

$$P_{air} = P_{ambient}.v_{proj}\,\frac{(\gamma_{air}+1).v_{proj} + \sqrt{16*\gamma_{air}.R_{air}.T_{ambient} + \left(v_{proj}.(\gamma_{air}+1)^2\right)}}{4.R_{air}.T_{ambient}} \tag{11}$$

And

$$v_{projectile} = \int a_{projectile} dt \tag{12}$$

$$d_{projectile} = \iint a_{projectile} d^2 t \tag{13}$$

To find the base pressure on the projectile, a Lagrangian pressure distribution [6] is assumed where the base pressure is found by:

$$P_{base} = \frac{3P_{mean} + \frac{m_{propellant}}{m_{projectile}}(P_{resistance} + P_{air})}{3 + \frac{m_{propellant}}{m_{projectile}}} \tag{14}$$

And similarly for the breech pressure:

$$P_{breech} = P_{base} + \frac{m_{propellant}}{2.m_{projectile}}(P_{base-}P_{resistance} - P_{air}) \tag{15}$$

The projectile energy can be represented by:

$$E_{projectile} = E_{kinetic} + E_{rotational} \tag{16}$$

This can now be determined using the mass and velocity of the projectile:

$$E_{kinetic} = \frac{1}{2} m_{projectile}.v_{projectile}^2 \tag{17}$$

Likewise, the rotational energy of the projectile is found by:

$$E_{rotation} = \frac{1}{2} I_{projectile} \omega_{projectile}^2 \tag{18}$$

Where the moment of inertia is approximated by a cylinder the same diameter as the bore:

$$I_{projectile} = \frac{1}{8} m_{projectile} D_{bore}^2 \tag{19}$$

And the rotational velocity dependent on the projectile velocity and twist rate of the rifling:

$$\omega_{projectile} = \frac{2\pi . v_{projectile}}{\tau . D_{bore}} \tag{20}$$

Finally, the remaining losses consisting of drag, frictional and propellant translational losses,

$$E_{Losses} = E_{prop\ trans} + E_{frict} + E_{drag} \tag{21}$$

can be found respectively by the following:

$$E_{prop\ trans} = \frac{1}{6} m_{propellant} v_{propellant}^2 \tag{22}$$

$$E_{frict} = A_{bore} \int P_{res}(x)\, dx \tag{23}$$

$$E_{drag} = A_{bore} \int v_{projectile} . P_{air}\, dt \tag{24}$$

Noting that the frictional drag component (22) requires an estimate of the barrel resistance which is typically given as a pressure as a function of projectile travel along the barrel.

3. Overview of Simulation Procedure

3.1 Implementation

The set of equations in Section 0 have been implemented in a C code to simulate the physical processes that are occurring during the firing.

The simulation calculates the initial gas pressure and temperature within the chamber based on the aforementioned assumption regarding complete combustion of the primer prior to the start of the simulation.

The routine then proceeds in an explicit time stepping fashion, at each stage calculating first the propellant burn regression and hence propellant mass burnt using the current chamber pressure. The resulting change in temperature and pressure is then calculated and values updated. A Lagrangian pressure distribution [6] is assumed and determined within the available volume.

The burning continues, along with an increase in pressure and temperature until the defined shot-start pressure has been exceeded. Once this occurs the energy losses and work done in accelerating the projectile and propellant gases are then also determined. This energy transfer reduces the available propellant gas energy within the volume, thus affecting the pressure and temperature.

As the projectile has started moving, the projectile trajectories can now be calculated at each time step.

After a certain time the propellant will be completely consumed, eliminating the need to calculate further addition of energy through combustion. However the remaining pressure within the barrel will continue to act on the projectile.

The routine continues in this fashion until the projectile leaves the barrel, whereupon the simulation ends. An error message is given in the event that the projectile becomes stuck in the barrel.

The output of the code writes values of pressure, temperature, and projectile trajectories at specified intervals to a text file. A brief summary report giving maximum and final values of pressures, muzzle velocity etc. is also produced at the conclusion of the simulation.

4. Validation Example

4.1 AGARD Gun

For purpose of validation it is important to select an example that has been previously well analysed. Ideally the code would be compared with experimental data, however as this code uses the same mathematical approach as IBHVG2, which has been previously well validated [7], an appropriate exercise would be to compare the outputs of the two codes for a given test case.

For this example the test case selected is a theoretical "AGARD gun" that has been specifically established as a standard test case to aid in the development of interior ballistic codes [7]. The AGARD gun is a smooth bore, 132 mm diameter gun, with a uniform bore resistance of 13.79 MPa. The chamber is filled with cylindrical 7-hole grains, with a total propellant mass of 9.5255 kg. The relevant specifications of the gun system and propellant are listed in Table 1.

Table 1. AGARD gun test case specifications [7]

Gun caliber	132	mm
Travel of projectile	4318	mm
Projectile mass	45.359	kg
Propellant mass	9.5255	kg
Propellant geometry	Cylindrical 7-hole	
Propellant grain diameter	11.43	mm
Propellant burn rate pressure index	0.9	n
Propellant chemical energy	3.7369	MJ/kg
Propellant impetus	1.009	MJ/kg
Igniter specific heat ratio	1.25	
Igniter flame temperature	1706	K

Using these inputs, a simulation was run in both codes and the outputs compared. A summary of results is presented in Table 2.

Table 2. Summary of predictions from both codes

	IBHVG2	DST IB Code
Max Breech Pressure (MPa)	371.8	371.5
Max. Projectile Base Pressure (MPa)	337.8	337.6
Muzzle Velocity (m/s)	677.3	677.8
Time of shot exit (ms)	19.44	19.46
Time of max. breech pressure (ms)	11.61	11.63

Further, the mean pressure and temperature curves for both simulations have been plotted in Figure 1 and Figure 2 respectively. These plots show the DST IB code compares very well with the IBHVG2 code.

Several other example cases were tested - although not shown here - with both code's outputs being equally consistent in all cases.

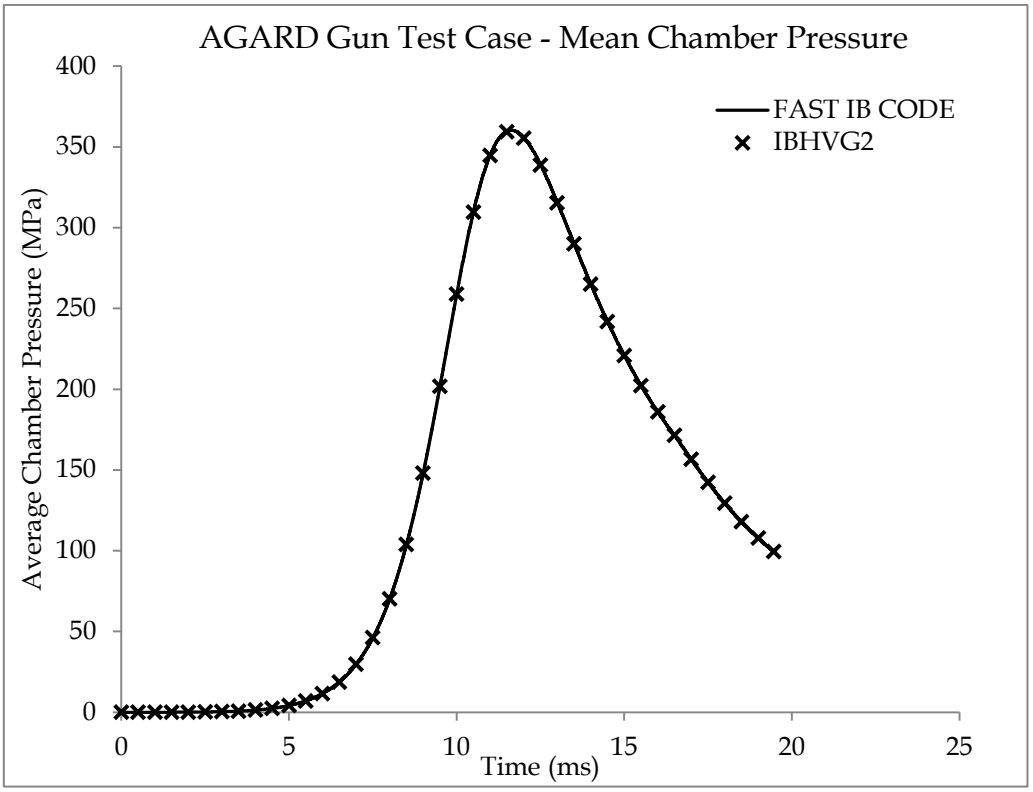

Figure 1. Comparison of pressure histories

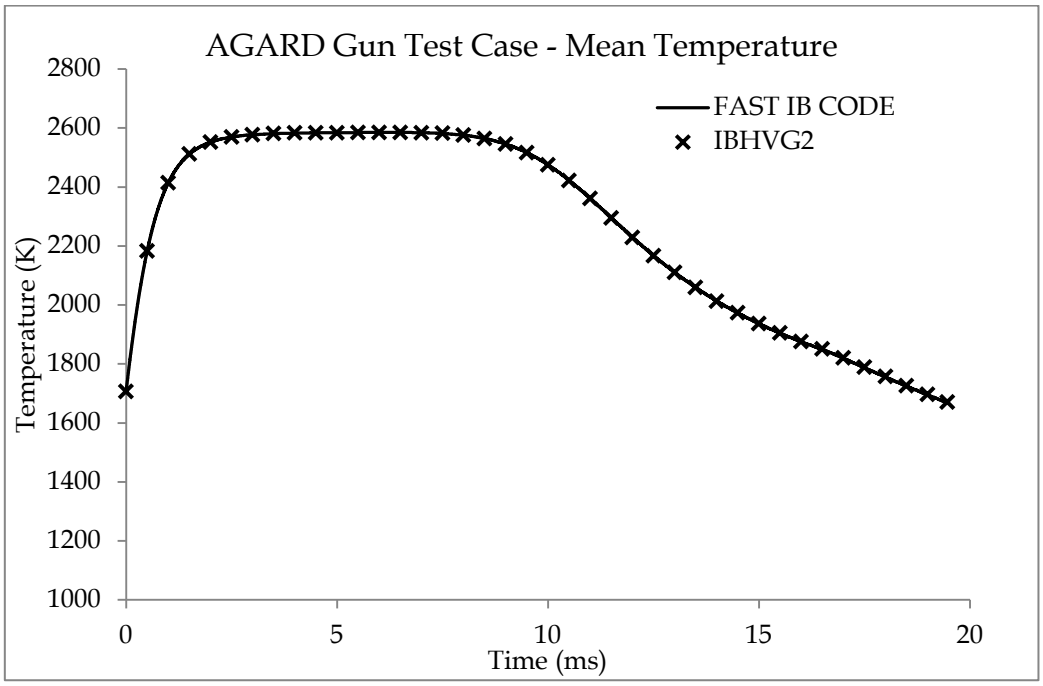

Figure 2. Comparison of temperature histories

One of the requirements of this code is that it be fast running in order to conduct optimisations that could potentially cover a large parameter range (e.g. 1000 or more simulations). To ensure this requirement was met the AGARD test case was run 1000 times and the running time compared against 1000 runs of the same case using IBHVG2. This large number of runs was chosen instead of a single run, to allow any time spent in pre-processing to be averaged out. In both cases, the data output was supressed, to ensure the run time consisted only of the interior ballistic calculations. The execution times from both codes can be seen in Table 1. Both codes were run on an Intel Xeon CPU E5-2687W @ 3.40 GHz running Linux Ubuntu 15.04.

Table 3. Execution Times for 1000 simulations of each code.

Code	Run Time for 1000 simulations (seconds)
Fast IB Code	0.74
IBHVG2	11.05

The results from these tests, show that the Fast IB code meet this requirement of being fast running, and ensures that it is well suited to running large numbers of simulations for optimisation purposes.

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