A new model of projectile ballistic acceleration process based on closed vessel experimental data

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Abstract: *A new model for projectile ballistic acceleration process is proposed. The work behind the model explores the possibility to use in a nontraditional way the characteristic diagrams obtained in closed-vessel tests for interior ballistics study. The new approach consists in an algorithm based on multi-dimensional interpolation of tests diagrams obtained from closed-bomb tests with similar heat loses as in gun barrel. The method shows promise and useful results could be obtained after building a signal database representing pressure versus time measurements in closed vessels with different volumes.*

Key-Words: - **interior ballistics, algorithm, iterative mathematical model, burned propellant fraction**

1 Introduction

Interior ballistics processes are a very complex phenomenon which involves the ignition and combustion of propellant, generating the burning gases at very high temperature, the transfer of gases caloric energy into kinetic energy of combustion gases – projectile – recoiling mass system and movement of the above mentioned system. All these processes are interdependent and occur simultaneously. The projectile acceleration due to expanding combustion gases is a problem which can be modeled with various degree of refinement, depending on the hypotheses assumed and precision of mathematical model [1].

A necessary step in modeling interior ballistics processes is to determine the propellant properties as burning rate law or propellant force. These characteristic values are fitted by regression procedures applied on pressure vs. time test curves, acquired in closed vessels[2]. As known, for all practical purposes the ballistic properties of a gun propellant are described by the three concepts of Force, Vivacity and Form Function. These cover respectively the energy content, the intrinsic rate of burning and the geometry of the propellant grain as a controlling factor in the rate of energy release. These concepts as normally defined are not invariable and moreover it is not possible to determine them exactly in an absolute sense. More than that, they are dependant on propellant nature and temperature, igniter nature and ignition process, propellant grain surface and real burning law, which is not similar to the theoretical assumed burning law [8]. The analysis for calculating burning rates from closed vessel firings and for calculating the mass fraction burning rate in interior ballistic codes requires knowledge of the surface area and volume of a propellant grain as a function of depth burned. The assumption that the propellant burns perpendicular to all surfaces at the same rate (which is not the real case) allows analytic equations to be derived for the complete surface area and volume as a function of the depth burned, including the slivering phase (if occurs). These form functions are normally used for both interior ballistic calculations as well as burning rate determination. It is therefore necessary, for practical applications, to define them in relation to an agreed method of determination. Mathematical treatment includes correction of an important but unavoidable phenomenon: heat loss [3] in bomb (vessel) wall.

Similar phenomenon of heat loss is specific to gun barrel [4,5,6]. Further, we present in this paper an original interior ballistic model that exploits the similitude between heat loses in ballistic bombs wall and in gun barrel wall, based on a series of measurements in closed vessels at different relative propellant densities. Instead to process closed bomb test data in order to obtain propellant ballistic properties, afterwards used in lumped parameter (0-dimensional or thermodynamic) models or one and two dimensional models of interior ballistic process, we propose a fast, friendly algorithm based on multi-dimensional interpolation of closed bomb experimental data. The assumptions of this work is only to consider closed vessels with similar heat loses as in gun barrel and the uniform burning gases state behind projectile .

A short discussion on the proof of this model will be made in the concluding paragraph.

2. Interior ballistic model

There are several interior ballistic models, starting with classic models, up to so called *3rd generation models*, which cover a wide area of hypotheses, more or less realistic. In classic models, the solution is entirely analytical, supposing that all the physicochemical phenomena can be modeled by polynomial or differential equations, with known coefficients. For example, is to consider the Muraour law for burning rate of propellant grain as a function of pressure [9]:

$$v(p) = a \cdot P^n + b \tag{1}$$

These models are no longer satisfied, while the real behaviour of burning propellant is far away from this hypothesis. The modern models use numerical analysis and allow to skip some analytical expressions, instead of using experimental data like form function and burning rate as input data in a source code, but this doesn't let us to avoid a number of simplifying hypotheses. In the 2 nd generation models (compared with 1st generation called 0-dimensional), the pressure behind projectile and the pressure on the breech are no longer calculated based on the medium pressure measured with the piezoelectric transducer. So, the space between breech block and the projectile is divised into a number of finite elements (volumes) and the pressure is determined using CFD algorithms. In 3rd generation models the biphasic flow is considered, as the gases generation process is not instantaneous, but there is, in the first part of burning process, a mixture between gases and unburned or partial burned propellant grains.

At this point is easy to see why an expeditious but reliable algorithm for evaluating the projectile movement in gun barrel could improve the work within design process or within test and evaluating procedures for weapon systems, at least as a key step for more detailed analysis.

Starting point of the model proposed is the perspective on the propellant and burning gases state. In both, closed vessel and gun barrel, the dual phase (propellant-burning gases) physical state can by defined at any moment of time by some global parameters as pressure, temperature, burned propellant mass fraction, relative propellant density. The biphasic state may be expressed by the equations bellow:

$$\begin{aligned} E_b &= E_b(P,\psi,T,\Delta) \\ E_g &= E_g(P,\psi,T,\Delta) \end{aligned} \tag{2}$$

where: E_b - dual phase state in closed vessel;

E_g - dual phase state in gun barrel;

P - gases pressure;

ψ - burned propellant mass fraction;

T - gases temperature;

Δ - relative propellant density (propellant mass versus closed vessel or barrel internal volume ratio.

Further, for sake of simplicity and assuming the hypothesis of closed vessel tests data with similar heat loses as in gun barrel, we could neglect the temperature evolution and its effects. In this case, the equation (2) becomes:

$$\begin{aligned} E_b &= E_b(P,\psi,\Delta) \\ E_g &= E_g(P,\psi,\Delta) \end{aligned} \tag{3}$$

This doesn't mean we totally neglect the thermic loses in gun barrel, only assume that the ballistic parameters measured in closed vessel at constant volume are similar to the ballistic parameters of propellant in loading chamber (which is not fitted for ballistic measurements), even after the projectile starts to move, and the physicochemical transformations are in a variable volume. From the Δ definition, is obvious that for closed bombs, this has a constant value and for gun barrels the value decrease as projectile move.

Accordingly, for a propellant type, each closed vessel test evolution [all obtained in the same closed vessel test device] at a specified Δ_i is characterized by a curve in (P,ψ) space. In this way, entire space can be covered if enough available test data are acquired, Fig. 1. This space is limited in ψ axis by 0 and 1 value.

Also, the process in gun barrel for the same propellant type can be described by a curve in (P,ψ) space; the difference is that Δ has not a constant value, Fig.1.

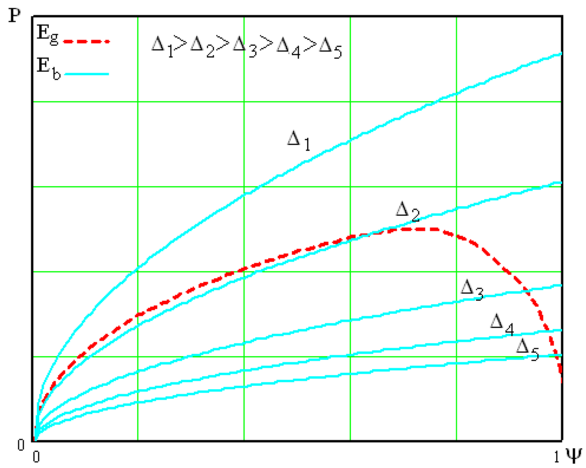

Fig. 1 (P,ψ) space and characteristics curves for closed vessel test and gun barrel

At this point, the problem is how could be find E_g evolution in (P,ψ) space starting from a series of knew E_b evolutions in the same space.

For that purpose is necessary for the problem to be linked to time. All closed vessels data are acquired and processed as time evolutions: $P(t)$, Fig. 2, or $\psi(t)$.

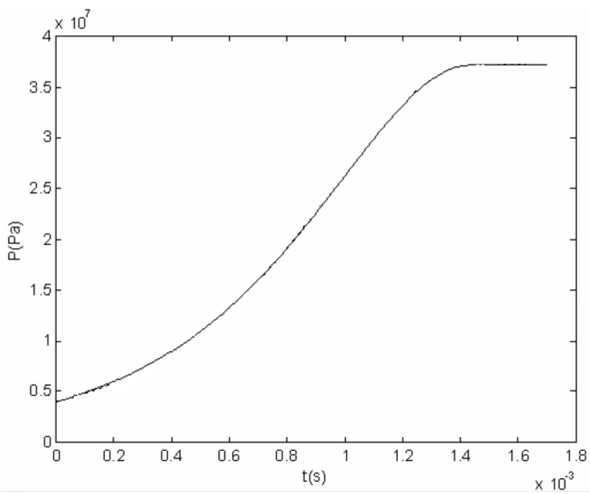

Fig.2 Typical idealized pressure time evolution in a closed vessel test [7]

Also, the fundamental equation of internal ballistics is written with respect to time and represents the movement equation of projectile:

$$\ddot{x} = \frac{PS}{\varphi m}, \tag{4}$$

where:
$\ddot{x}$ - projectile acceleration;
S - transversal bore area;
m - projectile mass;
φ - adjusting coefficient for energy loses.

Typical evolutions of gun barrel chamber pressure and projectile velocity are shown in Fig. 3.

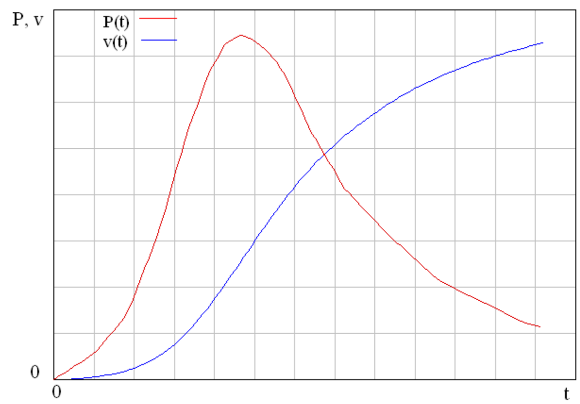

Fig. 3 Typical gun barrel pressure and projectile velocity time evolution

Equation (4) can be written as

$$\frac{dv}{d\psi} = \frac{dt}{d\psi}\frac{PS}{\varphi m} \tag{5}$$

The Δ evolution in barrel gun is expressed by

$$\frac{d\theta}{d\psi} = \frac{dt}{d\psi}\frac{Sv}{\omega} \tag{6}$$

where: $\theta = \frac{1}{\Delta}$;
ω - propellant mass.

From the equations (5) and (6), knowing that both time and pressure can by arised from closed vessel data by interpolation as function of (ψ,θ) arguments Fig. 4, we are composing the system of differential equations as bellow:

$$\begin{cases} \frac{dv}{d\psi} = F_2(\psi,\theta)\frac{PS}{\varphi m} \\ \frac{d\theta}{d\psi} = F_2(\psi,\theta)\frac{Sv}{\omega} \\ \frac{dP}{d\psi} = F_1(\psi,\theta) \\ \frac{dt}{d\psi} = F_2(\psi,\theta) \end{cases} \tag{7}$$

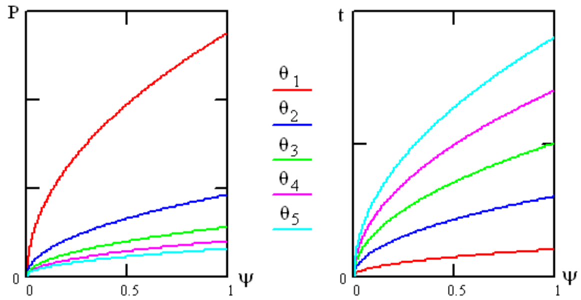

Fig. 4 Pressure and time as (ψ,θ) functions

3 Numerical method for solving the system of equations

To solve the system (7), a numerical method was developed which implies iterative and interpolation features.

There is assumed that are available $P(\psi)$ and $t(\psi)$ diagrams for a θ_i series [$i=1..N$] from closed vessel tests.

Also, we assume that the E_{g_k} state is knew at ψ_k, by the fallowing parameters P_k, θ_k, t_k and v_k - projectile velocity.

To find the correspondent $E_{g_{k+1}}$ state for ψ_{k+1}, is necessary to find P_{k+1}, θ_{k+1}, t_{k+1} and v_{k+1}. The ψ_{k+1} is given by

$$\psi_{k+1} = \psi_k + d\psi\ , \tag{8}$$

where $d\psi$ represent fix increasing step value [e. g. 0.001].

To initialize the iterative algorithm of $E_{g_{k+1}}$ determination, it is assumed that in the $[\psi_k;\psi_{k+1}]$ interval the E_g processes follow a path similar to E_b for θ_k. In this way we define initial value for θ_{k+1},

$$\theta_{k+1_1} = \theta_k\ . \tag{9}$$

By interpolation form available diagrams, P_{k+1_1} and t_{k+1_1}, the values for $(\psi_{k+1},\theta_{k+1_1})$ pear are found.

If short enough intervals are considered, any continuous function can be approximated by a linear evolution and his differentiate by a constant value. Assuming that $d\psi$ obey that condition, first two equations of the system (7) can be rewritten as

$$\begin{cases} v_{k+1_1} = v_k + \dfrac{t_{k+1_1} - t_k}{d\psi}\dfrac{P_{k+1_1} + P_k}{2}\dfrac{S}{\varphi m} \\ \theta_{k+1_2} = \theta_k + \dfrac{t_{k+1_1} - t_k}{d\psi}\dfrac{v_{k+1_1} + v_k}{2}\dfrac{S}{\omega} \end{cases} \tag{10}$$

A second value for θ_{k+1} is obtained as θ_{k+1_2}.

In general, the iterative process can be expressed as bellow:

$$\begin{cases} t_{k+1_n} = InterpT(\psi_{k+1},\theta_{k+1_n}) \\ P_{k+1_n} = InterpP(\psi_{k+1},\theta_{k+1_n}) \\ v_{k+1_n} = v_k + \dfrac{t_{k+1_n} - t_k}{d\psi}\dfrac{P_{k+1_n} + P_k}{2}\dfrac{S}{\varphi m} \\ \theta_{k+1_{n+1}} = \theta_k + \dfrac{t_{k+1_n} - t_k}{d\psi}\dfrac{v_{k+1_n} + v_k}{2}\dfrac{S}{\omega} \end{cases} . \tag{11}$$

The stop condition for the iterative process is

$$\left|\theta_{k+1_{n+1}} - \theta_{k+1_n}\right| \le \varepsilon\ , \tag{12}$$

where ε represent the accepted error level.

The parameters which define $E_{g_{k+1}}$ for ψ_{k+1} will be then P_{k+1n}, θ_{k+1n}, t_{k+1n} and projectile velocity will be v_{k+1n}.

4. Application

At this time, we have not enough closed vessel and gun barrel data for all the situations we need. For that reason we have defined $P(\psi)$ and $t(\psi)$ diagrams for a θ_i series [$i=1..N$], diagrams which obey the features of real data test: high density Δ_i means higher pressure and shorter time to burn, Fig 4.

$$\begin{cases} t(\psi,\theta) = 0.55\theta\sqrt{\psi} \\ P(\psi,\theta) = \dfrac{1}{\theta}\sqrt{\psi} \end{cases} \tag{13}$$

Being interested in verifying the idea and the proposed algorithm, we don't draw attention over the measure units, values magnitude or characteristic shape.

We have defined also projectile weight, m, coefficient, φ, propellant weight, ω, initial volume, V, and bore cross section area, S. In Fig. 5 and Fig. 6 are presented typical results of application.

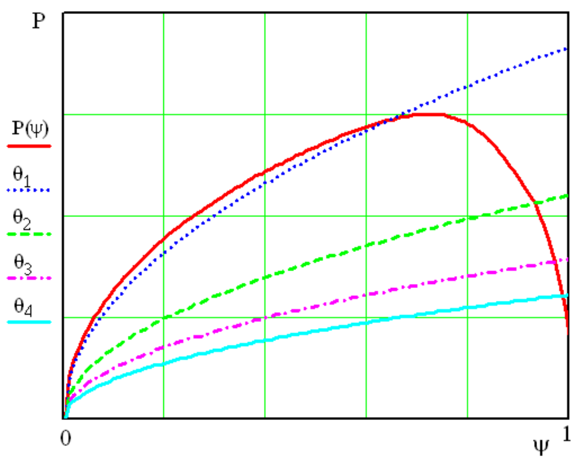

Fig. 5. Diagrams for closed vessel tests and gun barrel in (P,ψ) space

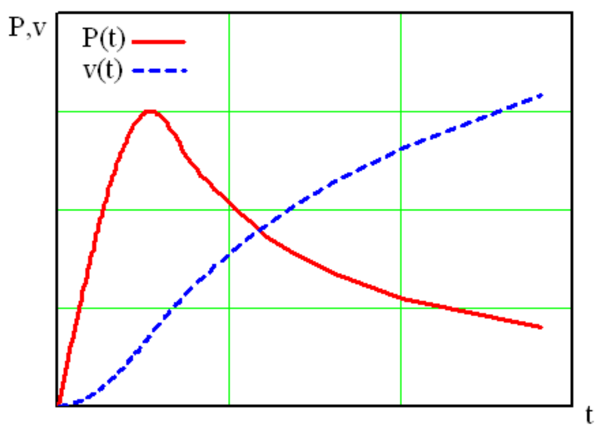

Fig. 6 Gun barrel pressure and projectile velocity evolutions calculated with proposed mathematical model

In Fig. 5 can be seen the way how the $P(\psi)$ curve for gun barrel process intersects the $P(\psi)$ curves for constant values of Δ, respectively θ, as ψ is changing from 0 to 1. This signifies that the volume behind projectile grows.

For the same application, In Fig. 6 are shown the input data time evolutions for pressure and projectile velocity. The evolutions are similar with characteristic evolutions presented in Fig. 3. The differences in shape for the initial stage are given by the fact that the diagrams used in application are not entirely similar with real ones.

5 Concluding remarks

This algorithm works only when closed vessel test data which cover the all phases of interior ballistic process are available and accurate.

As the application results show, the method is promising. Due to lack of insufficient real closed vessel experimental data, the model and work hypothesis were not verified entirely to date.

The reason for real data missed is that we are still trying to setup closed vessel tests or derived ones for high and low relative propellant densities values, tests which are necessary to cover the start and the end of interior ballistic process.

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