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Development of mortar simulator with shell-in-shell system – problem of external ballistics

A. Fedaravicius*, V. Jonevicius, M. Ragulskis*****
**Kaunas University of Technology, Kestučio 27, 44025 Kaunas, Lithuania, E-mail: alfedar@ktu.lt*
***Kaunas University of Technology, Kestučio 27, 44025 Kaunas, Lithuania, E-mail: Vaclovas.Jonevicius@mil.lt*
****Kaunas University of Technology, Kestučio 27, 44025 Kaunas, Lithuania, E-mail: minvydas.ragulskis@ktu.lt*

1. Introduction

Development of military training equipment is an important factor minimising costs and maximizing training effectiveness [1-4]. The goal of the project is to develop mortar simulators with reusable shells mimicking the combat shooting process. Mortar simulators must be applicable in field training of early career soldiers as well as in different combat training scenarios. Double-mass shell system is exploited. It comprises a ballistic barrel (reusable component) and a warhead (consumable component). The relatively heavy ballistic barrel must be ejected from the barrel of the mortar after the blast. Its flight distance must be only few meters, – so that the operators could quickly collect the reusable external shells. The flight distances of the warhead must be 10 times shorter compared with the combat shells (data from combat firing tables). Moreover, only one propelling charge in the warhead is allowed – the blast energy must be distributed between the ballistic barrel and the warhead in proper proportions. This project raises several problems. The first is the problem of interior ballistics of two interacting masses. Mass, geometric shape of ballistic barrel and warhead, quantity and sort of powder for the propelling charge is to be determined so that the initial velocity of the warhead would reach the levels determined in the problem of exterior ballistics.

The problem of exterior ballistics requires the determination of air damping coefficient of the warhead. Then the initial velocities of warheads for each propelling charge must be determined so that the flight distances would fulfil the predefined requirements. Finally, the results of analysis from the problems of interior and exterior ballistics must be coupled together. The object of this paper is to describe the problems of external ballistics that must be solved during the design process of the mortar simulator.

2. Description of the firing process

The steps of the firing process of the mortar simulator are illustrated in Fig. 1. The warhead (consumable component) and the ballistic barrel (reusable component) are assembled together and inserted into the mortar barrel. It can be noted that no modifications are allowed to the mortar barrel. Moreover, assembled warhead and ballistic barrel must mimic a combat shell in terms of mass, geometry and functionality.

The warhead's propelling charge is ignited after the assembled shell simulator hits the bottom of the mortar barrel. As the warhead's charge is the only charge used in the system, the blast energy must be distributed between the warhead and the ballistic barrel. The blast energy is distributed through the holes in the cartridge that is fixed inside the cylindrical hole of the ballistic barrel. The warhead is fired out of the cartridge (and out of the ballistic barrel and out of the mortar tube); its flight path length is 10 times shorter than of the combat shells. The ballistic barrel is ejected from the mortar tube; its flight path length is only about 10 meters so it is easy to pick it up and prepare for the next shot.

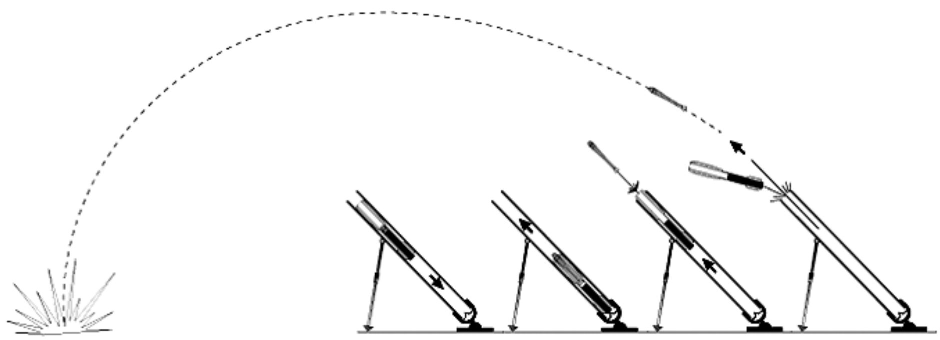

Fig. 1 Illustration of the firing process

3. Problem of external ballistics

The main problem of external ballistics was to determine the initial velocities of the warhead in order to guarantee the scaled length of its flight path. Two other problems must be solved theretofore - to reconstruct air damping coefficient acting to a combat shell and air damping force acting to the warhead. The apparent simplicity of this problem is misguiding – the only initial data available are the combat shell (60 mm diameter) firing table (Table 1), mass and geometric shape of the warhead, and the requirement that the warhead's length of the flight path is 10 times shorter compared with the combat shells.

Table 1

60 mm combat shell firing table

Initial velocity v_i, m/s	121		162		195		220	
Firing angle, α	45°	80°	45°	80°	45°	80°	45°	80°
Length of flight path S, m	1246	427	1993	683	2619	896	3130	1047

Data in the combat shell firing table is provided for 4 different charges. The first problem of external ballistics is the determination of air damping coefficient acting to the combat shell. It is calculated as the result of numerical optimisation problem where the following residual is minimised

$$\left.\begin{aligned} R(h) &= \left(\sqrt{\frac{(x_1(h)-1246)^2+(x_2(h)-427)^2+(x_3(h)-3130)^2+(x_4(h)-1074)^2}{4}}\right) \\ h^* &= \min_h(R(h)) \end{aligned}\right\} \quad (1)$$

where h is the air damping coefficient; x_1, x_2 are lengths of flight paths of combat shell fired at 121 m/s initial velocity and angles 45 and 80° appropriately; x_3, x_4 are lengths of flight paths of combat shell fired at 220 m/s initial velocity and angles 45 and 80° appropriately. Lengths x_1, x_2, x_3 and x_4 are calculated solving the following system of nonlinear differential equations

$$\begin{cases} m\ddot{x} + F_v \dfrac{\dot{x}}{\sqrt{\dot{x}^2+\dot{y}^2}} = 0 \\ m\ddot{y} + F_v \dfrac{\dot{y}}{\sqrt{\dot{x}^2+\dot{y}^2}} + mg = 0 \end{cases} \quad (2)$$

where m is the mass of the combat shell; x and y are coordinates of the shell; g is acceleration of gravity; F_v is the air damping force proportional to the square of velocity and inversely proportional to the cross section area of the shell [5, 6]

$$F_v = 4h\frac{\dot{x}^2+\dot{y}^2}{\pi d^2} \quad (3)$$

where d is the diameter of the shell. It is assumed that m = 1.5 kg; d = 60 mm (mass and external diameter of the combat shell). The minimised parameter h^* represents specific geometric shape and properties of friction of the shell.

It can be noted that computational determination of parameter h (Eq. (1)) is a complex nonlinear mathematical programming problem. The set of differential equations (Eq. (2)) must be integrated at different initial velocities and firing angles. The flight trajectories are computed using time marching techniques until the co-ordinate y is nonnegative. The integration is terminated when y takes a negative value (shell hits the ground) and the current x coordinate is assumed as the length of the flight path. Such calculations are performed at different values of h; the relationship of the residual (Eq. (1)) and parameter h is presented in Fig. 2. The reconstructed (optimal) value of h^* is 0.000255. It can be noted that the value of residual at this value of h^* is $R(h^*)$ = 9.3745 m. This is a very good result – the fluctuations around the specified flight distances are less than 0.6 percent.

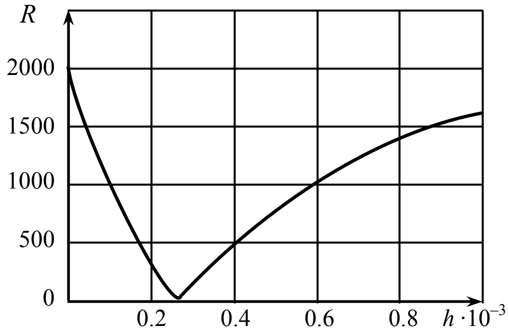

Fig. 2 Minimization of parameter h for combat shells

60 mm diameter shell simulator components are presented in Fig. 3. The warhead is mounted into the cartridge and inserted into the internal cylindrical hole in the ballistic barrel. It can be noted that the geometrical shape of the warhead is similar to the shape of the combat shell (disregarding the size), though the air damping force acting on the warhead is very much different from the force acting on the combat shell. Nevertheless, the air damping force acting on the warhead is also proportional to the square of its velocity and inversely proportional to its diameter. Keeping in mind the scaled geometrical similitude it is assumed that the coefficient h (Eq. (3)) is the same for the combat shell and the warhead. This is a rather straightforward assumption, but experimental identification of this coefficient would be complicated and would require costly measurements in a wind tunnel. Such assumption is understood as an initial approximation, which can be revised during experimental investigations on the mortar simulator.

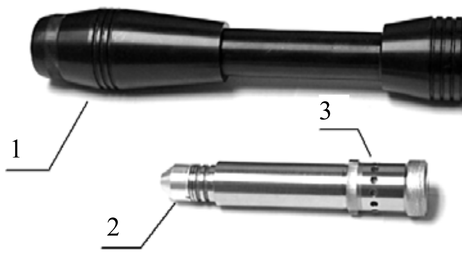

Fig. 3 60 mm shell simulator: *1* - ballistic barrel; *2* - warhead; *3* - cartridge

It can be noted again that the main task of the problem of external ballistics is to determine initial velocities of the warhead at which its length of flight path is 1/10-th of the described one in Table 1. Four separate optimisation problems must be solved minimising the following residual

$$\left.\begin{aligned} R_1(v) &= \left(\sqrt{\frac{\left(s_1(v)-124.6\right)^2+\left(s_2(v)-42.7\right)^2}{2}} \right) \\ v_1 &= \min_v \left(R_1(v) \right) \end{aligned}\right\} \quad (4)$$

where v is initial velocity of the warhead to be determined; s_1 and s_2 are lengths of flight paths of the warhead at firing angles 45 and 80°; numbers 124.6 and 42.7 are scaled lengths (1:10) from the Table 1 at the first charge. The lengths s_1 and s_2 are determined solving the same system of equations in Eq. (2) at $m = 0.2$ kg and $d = 25$ mm (warhead's mass and external diameter). The process of the minimization of the residual for the first charge is illustrated in Fig. 4, the results of optimisation of four problems – in Table 2.

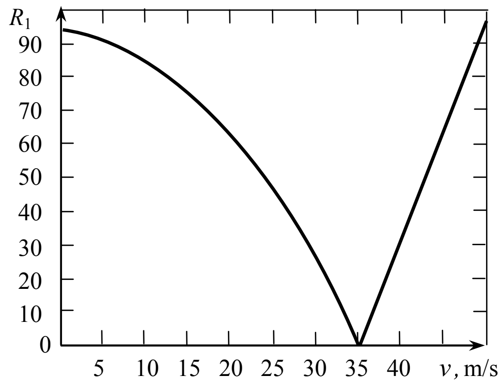

Fig. 4 Determination of initial velocity v_1

Table 2

Reconstructed initial velocities of the warhead

v_i, m/s	v_1=35 m/s		v_2=45 m/s		v_3=52 m/s		v_4=57 m/s	
α	45°	80°	45°	80°	45°	80°	45°	80°
s, m	124.41	42.47	197.94	67.26	260.20	87.89	314.15	105.54

4. Experimental verification of the reconstructed

A set of experimental measurements of the relationship between the initial velocities of the warhead and its flight distance were performed in order to verify and validate numerical estimations. A muzzle laser sensor is mounted on the end of the mortar tube and connected to a real time digital signal analyser (Fig. 5). Is blocked by the warhead and the ballistic barrel. The continuous laser beam

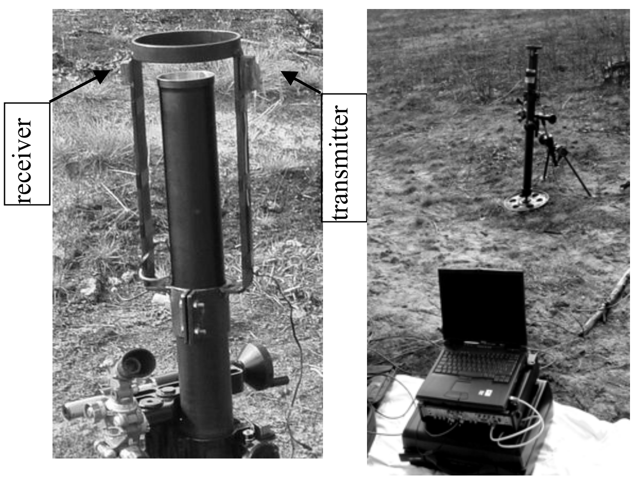

Fig. 5 Experimental set-up for the measurement of initial velocities

when they are ejected from the mortar tube and the corresponding variation of the voltage signal is registered in the real time signal analyser (Fig. 6).

The initial velocities of the warhead and the ballistic barrel can be reconstructed from the variation of the voltage signal of the laser sensor. The first hollow in Fig. 6 corresponds to the warhead flight; the second – to the ballistic barrel. Appropriate velocities can be calculated as a straightforward ratio of the object lengths (predefines quantities) and the time durations while the objects were blocking the laser sensor beam (easily reconstructed from Fig. 6). Such experiments were repeated for a set of different propelling charges what enabled the construction of experimental of between the initial velocity of the warhead and its flight distance (Fig. 7).

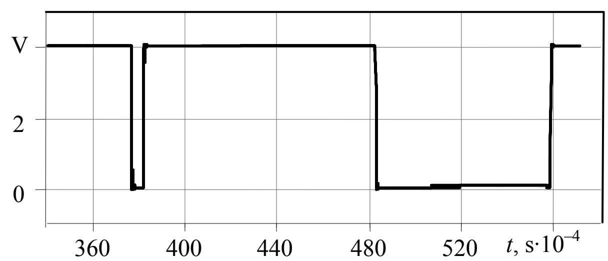

Fig. 6 Voltage over time during firing process of the mortar simulator

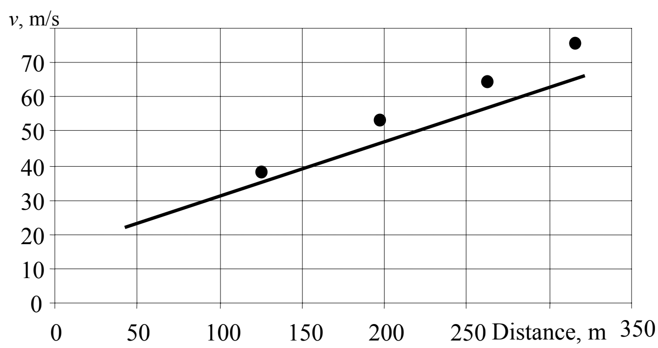

Fig. 7 Comparison of experimentally (dots) and numerically (solid line) reconstructed relationships between the initial velocity and the flight distance of the warhead

It can be noted that experimentally and numerically reconstructed relationship of the initial velocity and the flight distance of the warhead show very good correspondence. Thus, numerically reconstructed initial velocities in Table 2 can be used in the problem of internal ballistics where the main problem is the design of the cartridge and the selection of appropriate propelling charges.

5. Conclusions

Mortar simulator with reusable shells is a complex nonlinear dynamical system. Many factors influence the functionality of the simulator comprising a shell-in-shell system. Solution of the external ballistics problem (determination of the required initial velocities of the warhead) is only the first step of the whole design problem and serves as an input data for the problem of external ballistics.

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A. Fedaravičius, V. Jonevičius, M. Ragulskis

MINOSVAIDŽIŲ TRENIRUOKLIO KŪRIMAS PAGAL MINA MINOJE SISTEMĄ – IŠORINĖS BALISTIKOS UŽDAVINYS

R e z i u m ė

Minosvaidžių treniruokliuose taikoma mina minoje sistema atskleidė keletą nestandartinių techninių ir skaičiavimo problemų, pradedant reikalavimu paskirstyti metamąją sprogimo energiją tarp galvutės ir balistinio vamzdžio ir baigiant reikalavimu, kad galvutės skrydžio kelio ilgis būtų apskaičiuotas pagal kovinių sviedinių šaudymo lenteles. Treniruoklio sukūrimo uždavinys susideda iš dviejų dalių: pirmojo išorinės balistikos uždavinio, kai nustatomi pradiniai galvutės greičiai, ir antrojo vidinio balistikos uždavinio, kai projektuojamas užtaisas ir balistinis vamzdis.

A. Fedaravičius, V. Jonevičius, M. Ragulskis

DEVELOPMENT OF MORTAR SIMULATOR WITH SHELL-IN-SHELL SYSTEM – PROBLEM OF EXTERNAL BALLISTICS

S u m m a r y

The shell-in-shell system used in the mortar simulator raises a number of non-standard technical and computational problems starting from the requirement to distribute the propelling blast energy between the warhead and the ballistic barrel, finishing with the requirement that the length of warhead's flight path must be scaled to combat shell firing tables. The design problem of the simulator is split into two parts – the problem of external ballistics where the initial velocities of the warhead must be determined and the problem of internal ballistics – where the design of the cartridge and the ballistic barrel must be performed.

А. Федаравичюс, В. Ионявичюс, М. Рагульскис

СОЗДАНИЕ МИНОМЕТНОГО ТРЕНАЖЕРА ПО СИСТЕМЕ МИНА В МИНЕ – ЗАДАЧА ВНЕШНЕЙ БАЛЛИСТИКИ

Р е з ю м е

Примененная в минометных тренажерах система "мина в мине" раскрыла несколько нестандартных технических и расчетных проблем, начиная с требований распределения энергии взрыва между имитационной головкой и баллистическим стволом и кончая требованием расчета дальности полета головки по таблицам стрельбы боевыми снарядами. Задача создания тренажера состоит из двух частей: первой, когда из задачи внешней баллистики определяются начальные скорости головки, и второй задачи внутренней баллистики, когда проектируется заряд и баллистический ствол.

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