264. Development of mortar simulator with shell-in-shell system – problem of internal ballistics

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Abstract.

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. Initial velocities of the warhead determined in the problem of external ballistics form the set of initial data for the problem of internal ballistics of mortar simulator with shell-in-shell system.

The ballistic barrel (reusable component of the mimicking shell) must be ejected from the mortar tube and its flight path must be only few meters. Moreover, the propelling charge can be located only in the warhead and the blast energy must be distributed between the warhead and the ballistic barrel. That turns the problem of internal ballistics into a complex non-linear dynamical problem. Its solution involves building of the numerical model, optimisation of system parameters and experimental investigations. Presented mortar simulator proved its effectiveness in combat training exercises and is fully adopted in Lithuanian Army training facilities.

Keywords: mortar, internal ballistics, dynamics, simulator

1. Introduction

Development of military training equipment is an important factor minimising costs and maximizing training effectiveness [1, 2, 3, 4]. The goal of the project is to develop mortar simulators with re-usable 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 re-usable 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 steps of the firing process of the mortar simulator are illustrated in Fig. 1. The warhead (consumable component) and the ballistic barrel (re-usable 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.

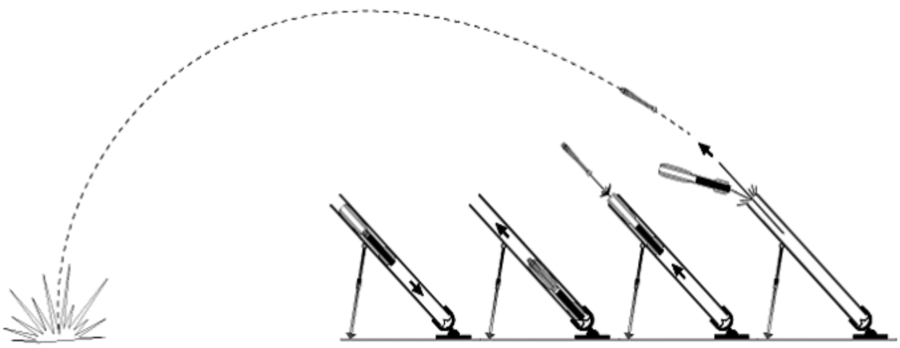

Fig. 1. Illustration of the firing process

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.

Initial velocities of the warhead determined in the problem of external ballistics form the set of initial data for the problem of internal ballistics. It can be noted that problems of external and internal ballistics cannot be considered separately – the complexity of analysis is illustrated in Fig. 2.

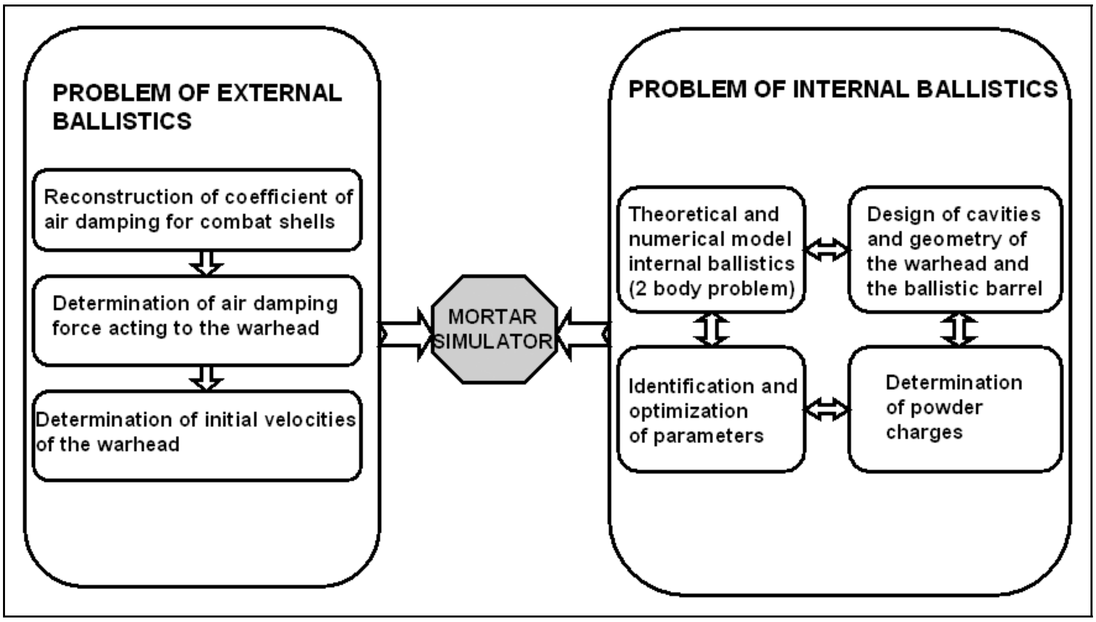

Fig. 2. Relationship between the problems if internal and external ballistics

2. Formulation of the model of the system

Full analysis of the problem of internal ballistics would require solution of chemical, non-linear fluid and gas dynamics, multi-body dynamics problems. Instead a number of simplifications are assumed in order to develop a phenomenological model of the system presented in Fig. 3, where X_1 is the coordinate of the ballistic barrel, X_2 – coordinate of the warhead, L is the length of the mortar tube, L_1 – the length of the ballistic barrel, L_2 – depth of the warhead in the cartridge (when assembled together), l_1 and l_2 – distances of the ballistic barrel and the warhead from the bottom of mortar tube in the status of assembly, R – internal radius of the mortar tube, r – internal radius of the cartridge, e is the thickness of the cartridge wall, p – the thickness of the cartridge bottom, A and B are the volumes under the warhead and the ballistic barrel.

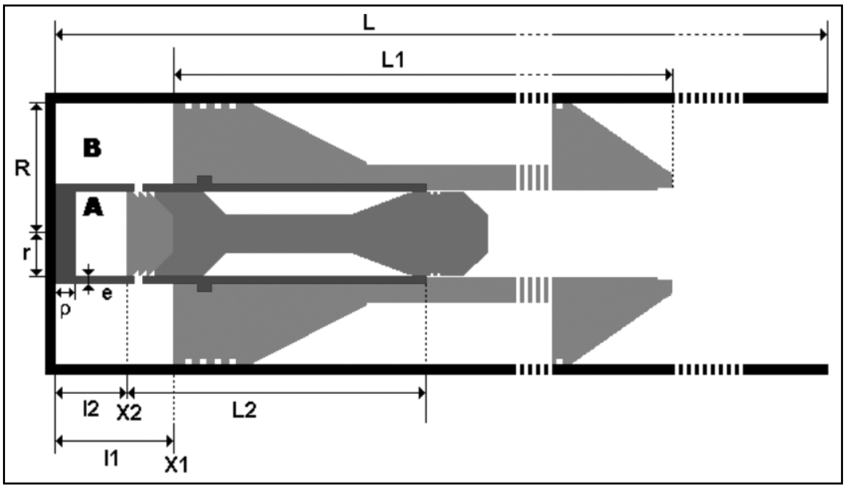

Fig. 3. Schematic diagram of the mortar simulator

The holes in the cartridge walls are closed when the warhead is inside the cartridge; the propelling charge is located in volume *A*. When the propelling charge is ignited and the warhead starts moving, the holes are opened and part of the blast energy is transferred to volume *B*. Cartridge is assembled with the ballistic barrel and is ejected from the mortar tube together with the ballistic barrel – after the warhead is already in its free flight. 60 mm diameter shell simulator components are presented in Fig. 4. The warhead is mounted into the cartridge and inserted into the internal cylindrical hole in the ballistic barrel.

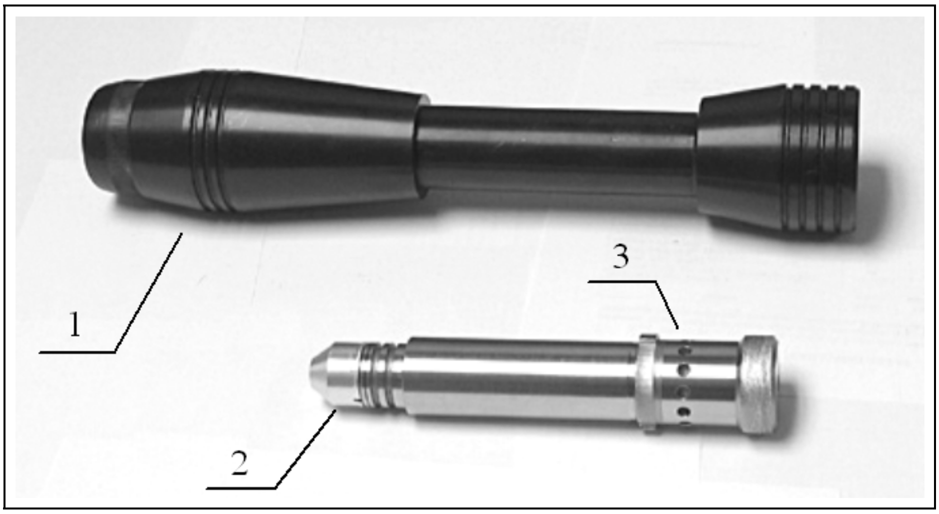

Fig. 4. 60 mm shell simulator: ballistic barrel – 1; warhead – 2; cartridge – 3

The development of phenomenological model of the system suitable for effective numerical simulation and representation of the processes taking place in the stage of internal ballistics requires several assumptions. The problem itself is segmented into several sub-problems: pressure formulation of the problem of internal ballistics; force formulation of the problem of internal ballistics; construction of differential equations describing the process of internal ballistics.

First is the pressure formulation of the problem. Again, several sub-problems describing different stages of the firing process are formulated using analytic relationships.

The first sub-problem describes the ignition and exponential pressure increase in volume A when both coordinates X_1 and X_2 are frozen and holes between volumes A and B are closed:

$$P_A = P_{A\max}\left(1-\exp\left(-k_0 t\right)\right) \tag{1}$$

where P_{Amax} – maximum pressure which could build up in closed constant volume A; k_0 – coefficient describing the exponential velocity of pressure increase.

All of the sub-problems described in this section are embedded into a time marching algorithm that integrates a system of differential equations describing the model of the shell-in-shell system. At every time step all sub-problems are solved sequentially what is schematically illustrated in Fig. 5. Thus, at every time step, increase of pressure P_A resulting from ignition is:

$$\begin{aligned} &P_{A\max}\left(1-\exp\left(-k_0 t_2\right)\right) - P_{A\max}\left(1-\exp\left(-k_0 t_1\right)\right) = \\ &= P_{A\max}\left(\exp\left(-k_0 t_1\right) - \exp\left(-k_0 t_2\right)\right) \end{aligned} \tag{2}$$

It is clear that this pressure increase tends to zero when time tends to infinity.

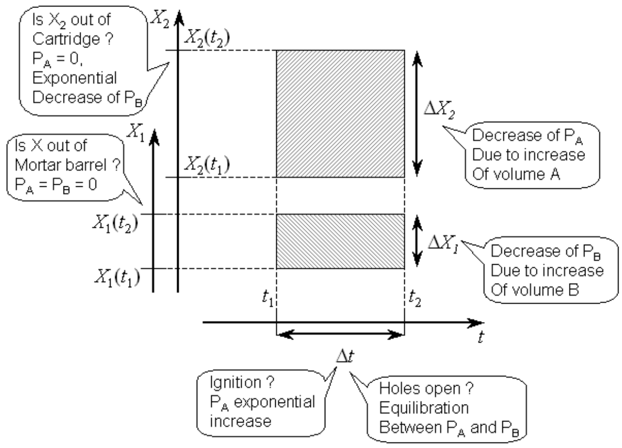

Fig. 5. Pressure formulation of the problem of internal ballistics

Next sub-problem describes pressure decay in volume A (volume B) when volume A (volume B) increases while the warhead (the ballistic barrel) moves in the mortar tube and the holes between volumes A and B are closed (Fig. 3). Explicitly,

$$\begin{aligned} P_A\left(t_2\right) &= P_A\left(t_1\right)\frac{X_2\left(t_1\right)-\rho}{X_2\left(t_2\right)-\rho} \\ P_B\left(t_2\right) &= P_B\left(t_1\right)\frac{X_1\left(t_1\right)}{X_2\left(t_2\right)} \end{aligned} \tag{3}$$

Next sub-problem describes equilibration of pressures in volumes A and B depending on the size of holes when X_1 and X_2 are frozen. It can be noted again, that the process of equilibration is considered in the time interval Δt only (Fig. 3). Nevertheless, it is necessary to evaluate the target pressure P_T to which the both pressures in volumes A and

B would equilibrate if time would tend to infinity (and coordinates stay frozen), in order to describe the exponential law of pressure equilibration in time interval Δt. Explicitly,

$$P_T = \frac{r^2\left(X_2(t_1)-\rho\right)P_A(t_1)+\left(R^2-(r+e)^2\right)X_1(t_1)P_B(t_1)}{r^2\left(X_2(t_1)-\rho\right)+\left(R^2-(r+e)^2\right)X_1(t_1)} \quad (4)$$

$$P_A(t_2)=P_T+\left(P_A(t_1)-P_T\right)\exp\left(-k_h(t_2-t_1)\right)$$
$$P_B(t_2)=P_T+\left(P_B(t_1)-P_T\right)\exp\left(-k_h(t_2-t_1)\right)$$

where k_h – coefficient characterising the size of the holes between the volumes A and B.

The coordinates X_1 and X_2 are controlled in every time step to check if the warhead did not fly out from the ballistic barrel and if the ballistic barrel did not eject from the mortar tube. If

$$X_2 > X_1 - l_1 + l_2 + L_2 \quad (5)$$

then P_A is assumed to be zero; P_B exponentially decreases to zero as the powder gas flows out from the volume B through the holes in the cartridge:

$$P_B(t_2)=P_B(t_1)\exp\left(-k_h(t_2-t_1)\right). \quad (6)$$

If

$$X_1 > L \quad (7)$$

then both pressures P_A and P_B are equated to zero.

3. Differential equations and results of simulation

Next step if the force formulation of the problem. It is assumed that the driving forces acting to the warhead and the ballistic barrel are proportional to the pressures described in the previous step. Friction forces between the warhead and the cartridge are assumed as well as the inertia forces. Finally, a formulation based on variable system structure is developed – its simplified form is presented in Eq. (8), where M is the mass of the ballistic barrel (including the cartridge) and the warhead; m – mass of the warhead; r – coefficient of dry friction between the cartridge and the warhead; F_1 and F_2 – forces recalculated at every time step of integration and acting to the ballistic barrel and the warhead appropriately.

$$\begin{cases} M\ddot{x}_1 + r\cdot\operatorname{sign}(\dot{x}_1-\dot{x}_2)=F_1(x_1,x_2,P_A,P_B,t) \\ m\ddot{x}_2 + r\cdot\operatorname{sign}(\dot{x}_2-\dot{x}_1)=F_2(x_1,x_2,P_A,P_B,t) \end{cases} \quad (8)$$

The problem is solved in Matlab environment, using iterative algorithm formulation, solving a system of coupled structured differential equations. The pressure-based model of the problem of internal ballistics comprises a set of parameters (P_{Amax}, k_0 and k_h) that represent the amount of powder charge, properties of powder and size of holes in the cartridge. It is quite natural that the design of such complex dynamical system like a mortar simulator with shell-in-shell system would require long, expensive and tedious experimental investigations. Therefore computational analysis and design of the system components is an absolute necessity. The parameters P_{Amax}, k_0 and k_h must be selected in a such way, that the velocities of the warhead and the ballistic barrel would coincide with the defined ones in the problem of external ballistics. The results of simulations are presented in Fig. 6 and Fig. 7.

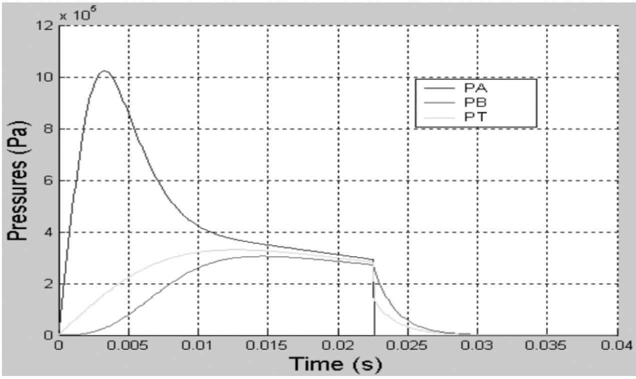

Fig. 6. Pressures in volumes A and B

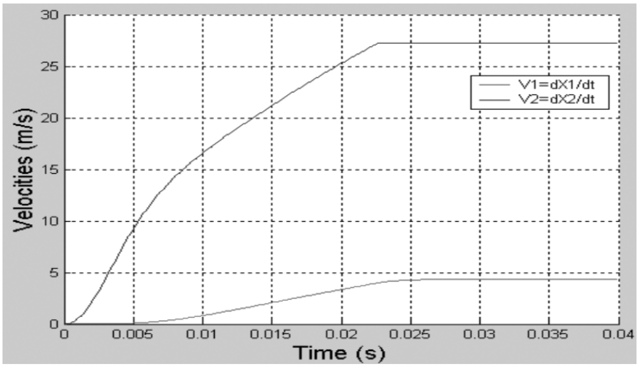

Fig. 7. Velocities of the warhead and the ballistic barrel

Variation of pressure and velocity represents the dynamical processes taking place from the moment of ignition up to the moment when the warhead and the ballistic barrel are ejected from the mortar tube.

3. Identification of parameters

Though the system parameters can be numerically identified, it is necessary to reconstruct their physical values. For example, parameter k_h defines the size of holes in the cartridge. The higher is the value of this parameter, the faster is exponential equilibration of pressures in volumes A and B (Eq. (4)). But what is the physical size of these holes if the numerical value of k_h is already determined? A number of experimental investigations are necessary in order to find answers to these questions. Fig. 8 shows an experimental set-up for measurement of powder pressures in the mortar tube. The experimental system is based on a bridge of strain gages and that the pressure can be measured only in an arbitrary scale. Nevertheless, pressure decay characteristics (typical exponential decay curves for a series of tests are presented in Fig. 9) provide valuable information and enable reconstruction of numerical values of system parameters and thus couple numerical and experimental investigations. It can be noted that the experimental measurements are performed under different conditions, including the set-up when the ballistic barrel and the warhead are rigidly fixed with the outer mortar tube and do not move during the blast. Nevertheless, the most important design parameters are the initial velocities of the warhead determined in the problem of external ballistics [5]. The reconstructed initial velocities of the warhead at four different powder charges are presented in Table 1 and serve as a target data for numerical simulations (Fig. 7).

Table 1. Reconstructed initial velocities of the warhead

v_i, m/s	35		45		52		57	
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

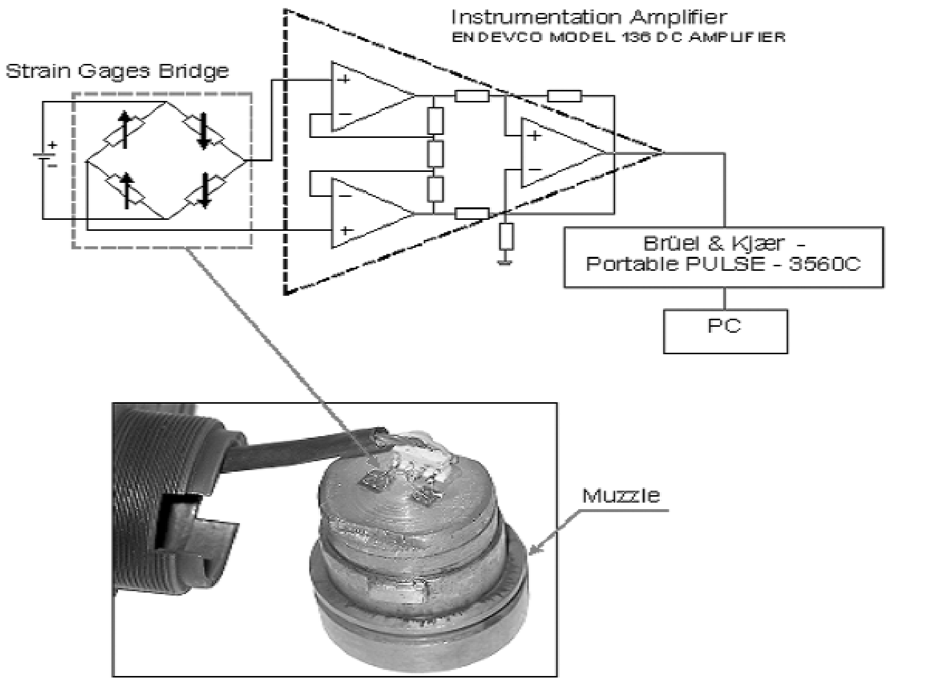

Fig. 8. Experimental set-up for determination of pressure inside the mortar tube

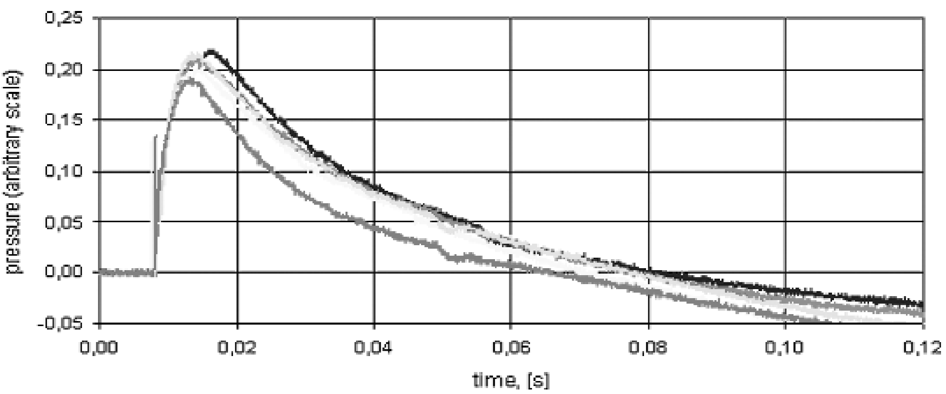

Fig. 9. Experimentally measured pressure decay for several test blasts (no holes in the cartridge)

Number of numerical and experimental investigations helped to determine a set of system parameters that guaranteed the required functionality and robustness of the mortar simulator. The actual values of parameters are presented in the following list.

Internal radius of the mortar tube, R	60 mm
Internal radius of the cartridge, r	12,5 mm
Length of the mortar tube, L	993 mm
Length of the ballistic barrel, $L1$	320 mm
Length of the cartridge, $L2 + l2$	139 mm
Length of the warhead	145 mm
Thickness of the cartridge wall, e	2,5 mm
Thickness of the cartridge butt, ρ	12 mm
Length of cartridge part protruding out of ballistic barrel when assembled, $l1$	37 mm
Mass of the ballistic barrel, M_B	3045 g
Mass of the cartridge, M_C	333 g
Mass of the reusable components, $M = M_B + M_C$	3378 g
Mass of the warhead, m	210 g
Number of holes in the cartridge	12
Diameter of a hole in the cartridge	6,3 mm

Concluding remarks

Mortar simulator with re-usable shells is a complex non-linear dynamical system. Many factors influence the functionality of such system. It is quite natural that computational simulations, optimisation and analysisis are an integral part of the project and helps to save many manhours of experimental investigations. It is clear that the presented numerical model is a simplification of an actual simulator. Nevertheless, such phenomenological model enables the description of main and most important dynamical effects taking place in the simulator during the firing process. Moreover, the results of optimisation of the three parameters – propelling powder charge, size of holes in the cartridge and the length of the cartridge were directly implemented into the experimental equipment.

Fig. 10. Mortar simulator in training exercise

The presented mortar simulators with re-usable shells mimicking the combat shooting process proved their effectiveness in combat training exercises and are fully adopted in Lithuanian Army training facilities.

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