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Numerical Analysis of Initiation of Main Explosive Charge in an Artillery Projectile

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The importance of investigation of main explosive charge initiation using booster charge stems directly from the objective to optimize the mass of booster charge needed to ensure steady state detonation of main explosive charge in order to achieve maximum projectile efficiency. Considered configuration consists of two explosives and three metal parts which represent elements of fuze and projectile. The main objective of this paper is to develop a numerical model of initiation of main explosive charge of an insensitive artillery ammunition. Through this research two variants of detonation point location were analyzed, ideal and stochastic one. The effects of the detonation transfer are analyzed using the Jones-Wilkins-Lee and Ignition and Growth equation of state models for explosives, applying the Coupled Eulerian-Lagrangian approach in the Abaqus/Explicit software. Analytical computation is introduced in this paper with a purpose to present P-u interaction between configuration elements and for comparison with results obtained by numerical method. The results of analytical and numerical approach are presented and discussed in detail. It is shown that suggested numerical model enables simulation and optimization of explosive train in fuzes of HE projectiles.

Key words: **explosive charge, explosive initiation, HE projectile, fuze, hexogen, TNT.**

Introduction

NOWADAYS, all the armies of the world strive to protect the security of soldiers. Therefore, high demands are placed on designers of projectiles in this regard. Today, modern artillery projectiles are considered to be insensitive, both because of their resistant design and due to low sensitivity of used explosive composition. To enable initiation and steady state detonation of the main explosive charge of such projectiles, additional "booster" charges are used. The role of these charges is to provide conditions that will cause steady state detonation of the projectile main explosive charge, leading to achievement of maximum efficiency of the high-explosive (HE) projectile.

Due to their significantly lower sensitivity to external influences, compared to primary explosives, for the needs of booster charges, secondary explosives are being used. Among these explosives is hexogen – RDX ($C_3H_6N_6O_6$) which is mixed with certain phlegmatizers such as wax [1].

Mechanism of explosive initiation is assumed to be in form of hot-spots. This is the process where transition shock wave passes through interparticle gaps, leading to gas compression inside those gaps, interparticle viscous heating, as well as friction, adiabatic shear and particle breakage. Thus, localized and high-intensity, thermal energy exceeds the energy required for the initiation of explosive crystals. As a shock wave passes through explosive, it constantly gains energy from local reactions and grows to steady state detonation.

In order to check validity of analytical approach for a given example, a numerical approach using finite element method (FEM) is used to test both behavior of explosives and metal elements used in the examples.

Analytical model

For the purpose of this research, a simple theory of steady ideal detonation or ZND model, after Zeldovich, Von Neumann, and Döring, who all developed it independently in the early 1940s is used [2]. This simple theory makes assumptions with the terms that the mathematics become tractable so the first-order engineering problems could be solved. These assumptions are:

1. The flow is one-dimensional.
2. The front of the detonation wave is a jump discontinuity.
3. The reaction product gases leaving the detonation front are in chemical and thermodynamic equilibrium and the chemical reaction is completed.
4. The chemical reaction zone length is zero.
5. The detonation rate or velocity is constant; this is a steady state process; the products leaving the detonation remain at the same state independent of time.
6. The gaseous reaction products, after leaving the detonation front, may be time dependent and are affected by the surrounding system or boundary conditions.

A graphical representation of the considered configuration is shown in Fig.1. This configuration represents positions of shown elements in deep cavity of a HE projectile. Casing is a thin-walled aluminium structure in which pressed

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cylindrically shaped phlegmatized hexogen is housed. Nut represents a bottom part of the fuze in which the casing is placed, just below the safe and arm mechanism.

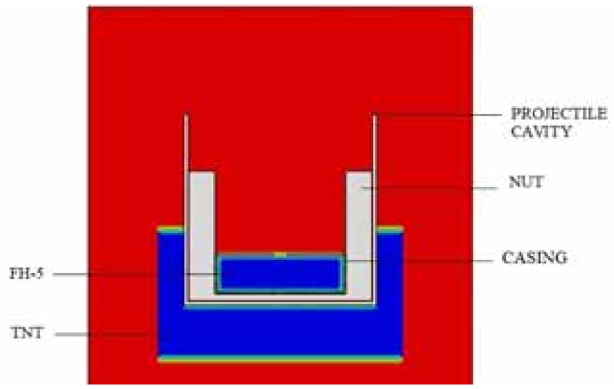

Figure 1. Considered configuration of fuze and HE projectile

Although the whole process from the initiation of booster charge up to the steady detonation of main explosive charge itself takes place in several microseconds to few dozens of microseconds, an analytical computation model allows to separate individual action of detonation wave on each element. For the elements and explosives, the relevant data are shown in Tables 1 and 2.

Considering that electrodetonating cap initiated and produced steady state detonation of FH-5, in the very first moment, shock wave of FH-5 acts on the aluminium casing. According to a simple 1D shock wave propagation model [2], [10], right-going shock wave pressure can be calculated as:

$$P = \rho_0 C_0 u + \rho_0 s u^2 \tag{1}$$

where, ρ_0 is density, C_0 and s are parameters in linear Hugoniot equation of state and u is particle velocity.

Due to lack of parameters C_0 and s for FH-5, left-going Hugoniot in detonation products is being approximated by eq. (2) [2] using parameters given in Table 2, where u_{CJ} is the particle velocity of detonation products at CJ pressure.

$$\begin{aligned} P = 2.412 p_{CJ} - (1.7315 p_{CJ} / u_{CJ}) u + \\ +((0.3195 p_{CJ}) / (u_{CJ}{}^2)) u^2 \end{aligned} \tag{2}$$

Stress in elements can be simply calculated:

$$\Delta P = \rho_0 C_L \Delta u \tag{3}$$

where C_L is longitudinal sound velocity.

Table 1. Properties of TNT, aluminium and steel used in analytical model [2]

Material	Density (g/cm^3)	C_0 (km/s)	s	C_L (km/s)
cast TNT	1.614	2.390	2.050	/
Aluminium	2.7	5.041	1.420	6.420
Steel	7.896	4.569	1.490	5.790

Table 2. Properties of FH-5 used in analytical model [3]

Explosive	Density (g/cm^3)	Chapman-Jouguet pressure p_{CJ} (GPa)	Detonation velocity (km/s)
FH-5	1.6	24.96	7.93

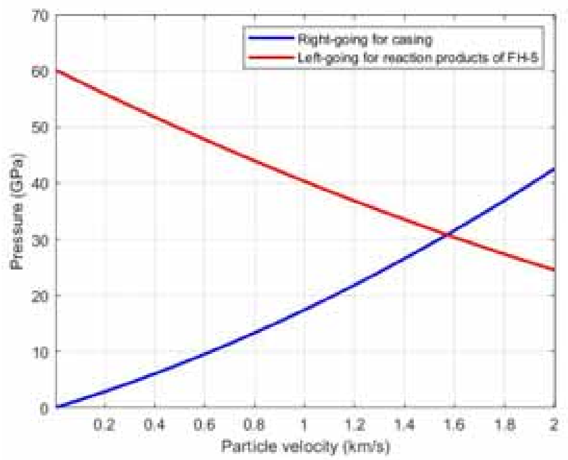

Figure 2. Interaction of casing and FH-5 reaction products in P-u plane

Left-going wave through elements, where particle velocity is twice of its initial value, $u_0 = 2u_1$, can be calculated:

$$P = \rho_0 C_0 (u_0 - u) + \rho_0 s (u_0 - u)^2 \tag{4}$$

Velocity of left-going shock wave in aluminium fragment and time for which this wave passes through aluminium are defined by eqs. (5) and (6), respectively.

$$U = \left(\frac{P_1 - P_0}{u_1 - u_0}\right) / \rho_0 \tag{5}$$

$$t_1 = \frac{d}{|U|} \tag{6}$$

Velocity of rarefaction wave and time for which this wave passes back through aluminium:

$$R = -\left(\frac{dP}{du}\right) / \rho_0 = C_0 + 2su \tag{7}$$

$$t_2 = \frac{d}{R} \tag{8}$$

$$\Delta t = t_1 + t_2 \tag{9}$$

Energy per unit area produced in main explosive charge due to fragment impact is calculated by:

$$E = \frac{(P^2 \Delta t)}{(\rho_{TNT} U_{TNT})} \tag{10}$$

where $U_{TNT} = C_0 + su$. Substituting data in eq. (10), fragment impact energy value is obtained:

$$E_{impact} = 160.8 \frac{\text{J}}{\text{cm}^2}$$

Critical impact energy needed to produce steady detonation of TNT [2]:

$$E = 77 \frac{\text{J}}{\text{cm}^2}$$

As it has been calculated $E_{impact} > E$, it means that detonation will occur due to fragment impact. However, critical energy by itself is not sufficient do describe the whole process in engineering terms. Explosive does not instantly attain full steady detonation due to shock. Shock wave must travel finite distance into the explosive before steady-state detonation is achieved. This “run-distance“ is not a constant, but varies with the peak input shock pressure. The higher the pressure, the shorter the run distance is needed. “Pop-plot“ data, named after Alfonse Popalato [2], provides equations of input shock pressure as a function of run distance for each explosive tested.

Pop-plot equation for TNT [2] for calculating travel distance X expressed in millimeters of input shock wave pressure in units of GPa before steady state detonation is established, has the form:

$$\log P = 1.0792 - 0.3919 \log X \tag{11}$$

Distance over which the shock maintains constant peak pressure:

$$x_{run} = \frac{U_{HE} R_{HE} t}{R_{HE} - U_{HE}} \tag{12}$$

Detonation wave velocity equation has the form:

$$U = C_0 + su \tag{13}$$

Minimum fragment thickness to assure detonation can be calculated:

$$x_f = \frac{x_{run}\left(R_{HE} - U_{HE}\right)}{U_{HE} R_{HE}\left(\dfrac{1}{U_f} - \dfrac{1}{R_f}\right)} = 13.655\,\text{mm} \tag{14}$$

where subscript HE reffers to high-explosive and f to fragment.

Run distance for this impact pressure is x_{run}. Good design practice is to ensure that the required run distance is equal to or less than the constant-pressure height. Cone is approximately 45º at the base and diameter is about twice the height, so the fragment diameter should be:

$$x_d = 2X_{run} = 9.75\ \text{mm} \tag{15}$$

Minimum fragment thickness is greater than the projectile cavity thickness, which is 1 mm, so this means that the initiation of main explosive charge by fragment impact is not physically possible. However, calculated pressure P_4 from Table 3, exceeds critical pressure for producing steady state detonation of TNT [4]. Values given in Table 3 are presented by schematic view in Fig.3.

All pressure and velocity values can be simply calculated by substituting material data given in Tables 1 and 2 in eqs. (1-4).

Table 3. Values of pressure and velocity calculated using analytical model

Pressure (GPa)	Velocity (km/s)
$P_1 = 30.82$	$u_1 = 1.57$
$P_2 = 40.5$	$u_2 = 1.42$
$P_3 = 22.29$	$u_3 = 0.873$
$P_4 = 5.49$	$u_4 = 0.831$

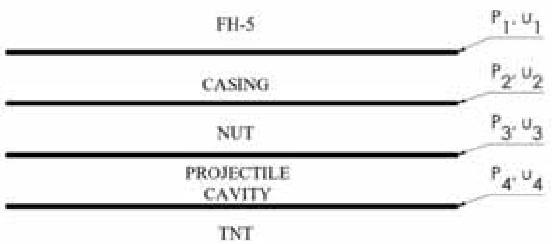

Figure 3. Schematic view of pressure and velocity data given in Table 3

Numerical model

In the analytical model, it is shown that thick slab of FH-5 will produce steady state detonation of TNT according to the criterion of critical pressure. Through the analytical computation it is not possible to obtain the value of mass needed for this action, so a numerical model can be used to provide a clearer insight into this phenomenon. Numerical simulation by the Coupled Eulerian-Lagrangian (CEL) approach was performed using FEA software Abaqus/Explicit [5]. The simulation time of 6 µs is found to be enough for capturing relevant parameters. The Eulerian 3D hexahedral element (EC3D8R) was used for domain with nonreflecting outflow where explosives were treated as the Eulerian parts as well. For metal parts, which are treated as the Lagrangian elements, 3D hexahedral element with reduced integration (C3D8R), with exception for nut where full integration element (C3D8), was used. Total number of elements is approximately 1.4 million. Having in mind that the whole process takes place at high speed with high energy release, a simple general contact between all parts was introduced in the simulation.

Ignition and growth (I&G) equation of state (EOS) [6] which defines the rate of reaction for initiated explosive, used for TNT modeling, can be written in the form:

$$\begin{aligned}\frac{dF}{dt} &= I(1-F)^b\left(\frac{\rho}{\rho_0} - 1 - a\right)^x + G_1(1-F)^c F^d P^y + \\ &+ G_2(1-F)^e F^g P^z\end{aligned} \tag{16}$$

where I is an initial pressure, a is a product covolume, G_1 is the first burn rate coefficient, G_2 the second burn rate coefficient, $F_{ig(max)}$ the initial reacted fraction, F_{G1max} the maximum reacted fraction for the growth term and F_{G2min} is minimum reacted fraction for the completion term. This equation contains JWL parameters for both solid explosive and its gaseous products. First addend of I&G EOS represents a shock wave which initiates small amount of explosive. Second term applies to decomposition of solid explosive to gaseous products and release of resulting energy. Third one models formed of solid carbon particles, which is a slow and diffusion-controlled process. I&G and JWL EOS parameters used in this paper are given in Tables 4 and 5. For each of these three terms given in eq. (16), limits are put on the fraction used. These are respectively:

$$\begin{aligned} &0 < F < F_{ig\max} \\ &0 < F < F_{G1\max} \\ &F_{G2\min} < F < 1 \end{aligned} \tag{17}$$

Two cases of FH-5 detonation point are analyzed. First one is ideal detonation point, where ED cap produced steady state detonation of FH-5 on its surface, and the second one is stochastic detonation point representing that ED cap produced steady state detonation of FH-5 faster than in the first case.

For FH-5, Jones-Wilkins-Lee (JWL) equation of state [7] is used:

$$\begin{aligned} p &= A\left(1 - \frac{\omega\rho}{R_1\rho_0}\right)\exp\left(-R_1\frac{\rho_0}{\rho}\right) + \\ &+ B\left(1 - \frac{\omega\rho}{R_2\rho_0}\right)\exp\left(-R_2\frac{\rho_0}{\rho}\right) + \omega\rho E_m \end{aligned} \tag{18}$$

where parameters A, B, R_1, R_2, ω are material properties, specific for each explosive used. This equation defines the change in pressure of gaseous detonation products as a function of their expansion, which occurs due to the release of chemical energy from the explosive.

Ductile and shear mechanical properties were used for modeling of steel and aluminium parts [8].

Table 4. JWL parameters for FH-5, solid TNT and TNT detonation products [1,9]

Explosive	FH-5	TNT solid state	TNT gaseous state
ρ_0 (g/cm3)	1.6	1.624	/
A (GPa)	573.43	17101	673.1
B (GPa)	0.96006	-3.745	21.988
R_1	4.2750	9.8	5.4
R_2	0.3175	0.98	1.8
ω	0.2178	0.5675	0.3
E_m (GPa)	8.7	0	7.0
C_v (GPa/K)	/	2.70386e-3	1.0e-3

Specific energy E_m and specific heat capacity C_v from Table 4 need to be divided by the corresponding explosive densities before implementing them in Abaqus/Explicit.

Table 5. I&G model rate parameters for TNT detonation [9]

I (1/s)	$5.0e^7$	G_2 (1/s)	0
a	0.065	e	1
b	0.667	g	0.111
x	4.0	z	1.0
G_1 (1/s)	$3.6e^8$	F_{igmax}	0.03
y	1.2	F_{G1max}	1.0
c	1.0	F_{G2min}	0
	d	0.667	

Influence of the booster charge ideal detonation point

In order to examine the influence of detonation point on initiation of the main explosive charge, two different detonation points were introduced in the numerical model. Detonation point (X, Y, Z) = (0, 0.00467, 0) m above origin of coordinate system shown in Fig.6, represents a case of ideal detonation point.

Mass of pressed cylindrical booster charge used in simulation is 11 g, and thickness of the steel nut bottom is 2 mm.

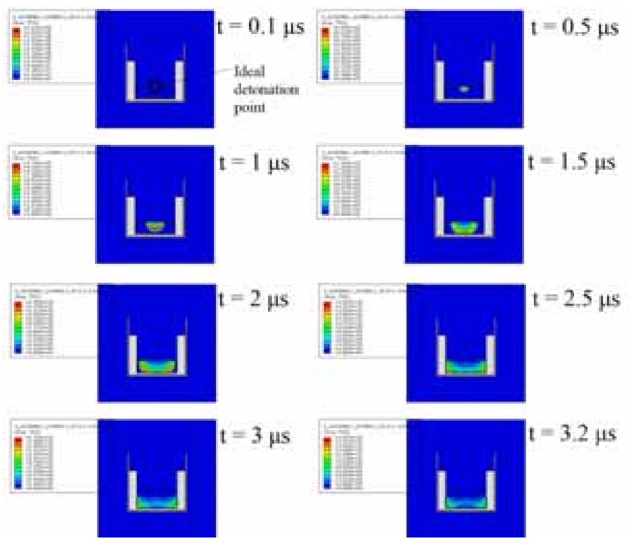

Figure 4. FH-5 detonation wave propagation in terms of pressure field (Pa) for ideal detonation point

Propagation of detonation wave shown in Fig.4 is in shape of a half sphere and the maximum pressure of 17.16 GPa is achieved before initiation of main explosive charge occurred. Referring to Fig.4, due to detonation wave propagation, Y-direction is chosen for obtaining maximum values of velocity.

Distribution of the pressure due to detonation wave of FH-5 before initiation of TNT for casing, nut and projectile cavity are shown in Figures 5-7. Maximum values of the pressure (marked in red in figures) and velocity (marked in blue), are given in Table 7.

Table 7. Maximum values of pressure and velocity data in casing, nut and projectile cavity given in Figures 6-8

Part	Pressure (GPa)	Velocity (km/s)
Casing	17.12	0.78
Nut	17.82	0.66
Projectile cavity	8.16	1.13

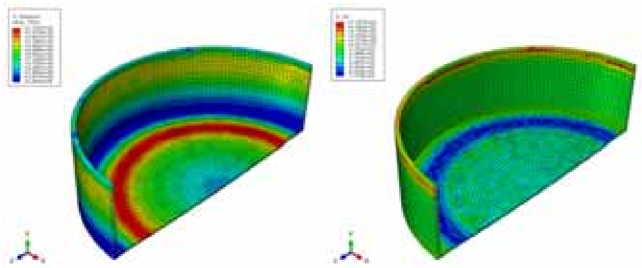

Figure 5. Casing pressure (Pa) and velocity (m/s) in Y-direction, t = 2.42 µs

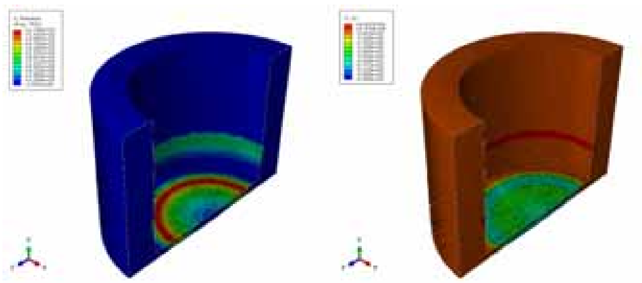

Figure 6. Nut pressure (Pa) and velocity (m/s) in Y-direction, t = 2.42 µs

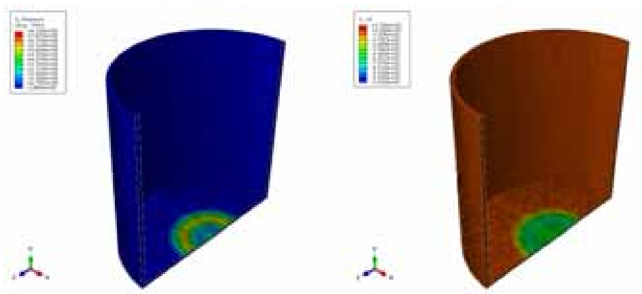

Figure 7. Projectile cavity pressure (Pa) and velocity (m/s) in Y-direction, t = 2.42 µs

Comparison of pressure and velocity values calculated by the analytical and numerical approach for ideal detonation point are given in Table 8, and it is concluded that there is a significant error deriving mainly from eq. (2), where approximation of left-going wave for FH-5 detonation products was introduced, and also from other simplifications in the analytical model. For error estimation, values obtained by the numerical approach are used as accepted values.

Table 8. Comparison of analytical and ideal detonation point numerical computation data

Part	Velocity (km/s)		Error	Pressure (GPa)		Error
	Analytical computation	Numerical computation		Analytical computation	Numerical computation	
Casing	1.57	0.78	57.16%	30.82	17.12	80.02%
Nut	1.219	0.66	84.7%	22.29	17.82	25.08%
Projectile cavity	0.831	1.13	35.98%	5.49	8.16	32.72%

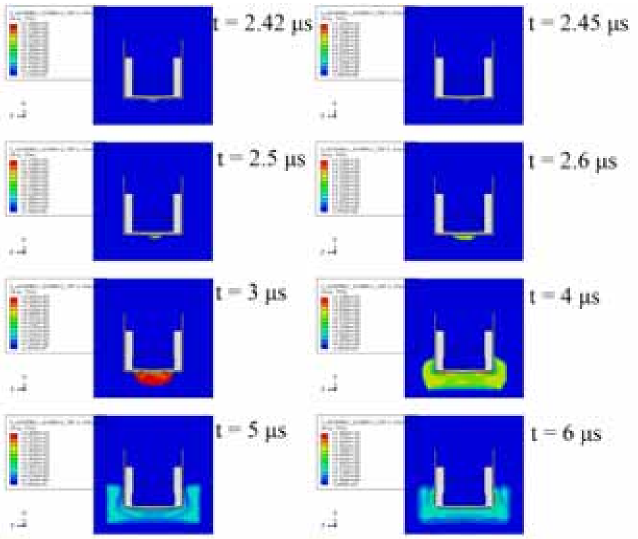

Figure 8. TNT initiation point and detonation wave propagation in terms of pressure (Pa)

Time of 2.42 µs corresponds to the pressure of (6 – 7.3) GPa acting on main explosive charge surface. Initiation of main explosive charge occurs in the central zone of the bottom part of projectile cavity at the time of 2.45 µs, which is represented in Fig.8. At the time of 5 µs detonation products of main explosive charge achieved maximum pressure of approximately 28 GPa, and at the time of 6 µs this pressure value drops to approximately 18.8 GPa, which leads to a conclusion that full volume already detonated at 5 µs.

Influence of the booster charge stochastic detonation point

Stochastic detonation point represents a case when ED cap blast characteristic is over-dimensioned, but it is not positioned at the center of the booster charge. In this case, ED cap produced steady state detonation of booster charge earlier than in the ideal case when ED cap is properly dimensioned. Coordinates used for detonation point are (X, Y, Z) = (-0.007, 0.002, -0.005) m.

Maximum pressure achieved by the booster charge detonation wave, at the time of 2.32 µs when initiation of main charge occurs, is 16.43 GPa. Compared to the previous case, there are no significant changes in the values of the pressure and time of initiation of the main explosive charge observed. The comparison of these values is given in Table 9.

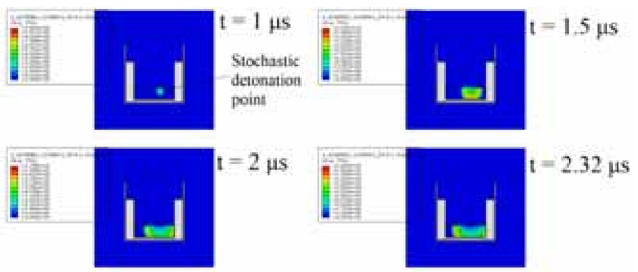

Figure 9. FH-5 Detonation wave motion in terms of pressure field (Pa) for stochastic detonation point

Table 9. Comparison of ideal and stochastic detonation point maximum pressure and initiation time values

Analysis	Pressure (GPa)	Relative deviation	Time (µs)	Relative deviation
Ideal point	17.16	4.25%	2.42	4.13%
Stochastic point	16.43		2.32	

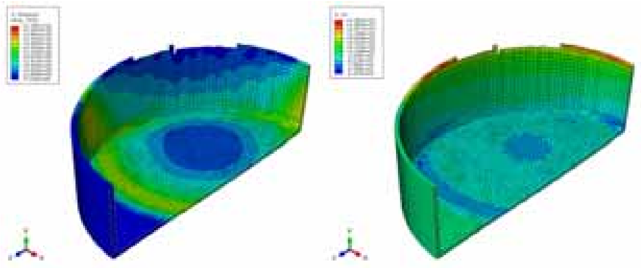

Figure 10. Casing pressure (Pa) and velocity (m/s) in Y-direction, t = **2.3** µs In the case of stochastic detonation point, maximum pressure and velocity values due to the booster charge detonation wave are obtained 0.02 µs before the initiation of TNT occurs.

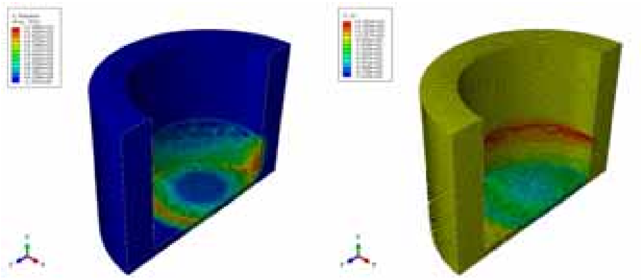

Figure 11. Nut pressure (Pa) and velocity (m/s) in Y-direction, t = 2.3 µs

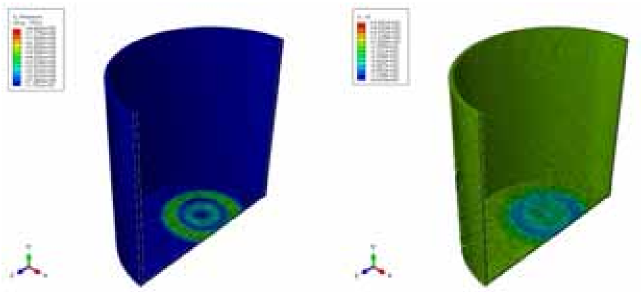

Figure 12. Projectile cavity pressure (Pa) and velocity (m/s) in Y-direction, t = 2.3 µs

Maximum pressure due to the booster charge detonation wave and before the initiation of main charge is obtained on side walls of casing and nut, shown in Figures 10 and 11, and it is a consequence of mismatch of the stochastic detonation point with the axis of symmetry of the parts. Maximum pressure and velocity in Y-direction values are given in Table 10.

Table 10. Maximum values of pressure and velocity data given in Figs. 10, 11 and 12

Part	Pressure (GPa)	Velocity (km/s)
Casing	23.41	1.26
Nut	20.05	0.76
Projectile cavity	8.48	0.84

In the case of stochastic detonation point, there is a better match with calculated values of pressure and velocity with analytical computation than in the case of ideal detonation point. This comparison is given in Table 11.

Table 11. Comparison of analytical and stochastic detonation point numerical computation data

Part	Velocity (km/s)		Error	Pressure (GPa)		Error
	Analytical computation	Numerical computation		Analytical computation	Numerical computation	
Casing	1.57	1.26	24.6%	30.82	23.41	31.65%
Nut	1.219	0.76	60.39%	22.29	20.05	11.17%
Projectile cavity	0.831	0.84	1.07%	5.49	8.48	35.21%

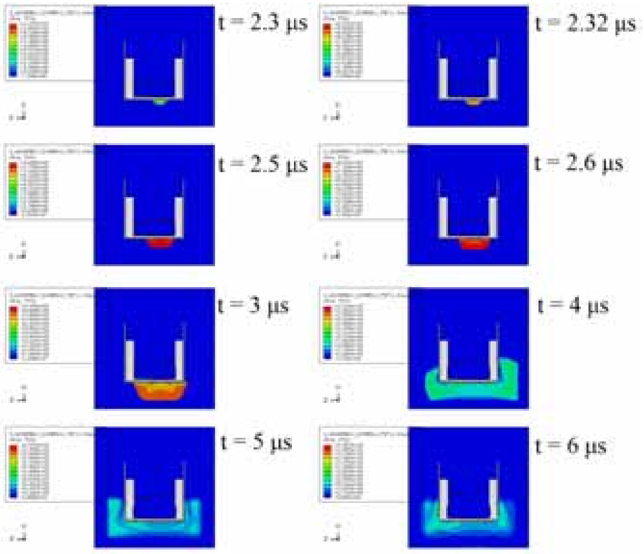

Figure 13. TNT initiation point and detonation wave propagation in contours of pressure (Pa)

Initiation of main explosive charge, shown in Fig.13, occurs at the time of 2.32 µs. This initiation point is slightly eccentric with respect to the projectile cavity axis, in the direction of stochastic detonation point. At the time of 2.3 µs, pressure acting on main explosive charge surface is in interval of (6.4 – 7.4) GPa. In regard to the pressure obtained in the case of ideal detonation point, this value of pressure and the travel distance of detonation wave going into the main explosive charge are significantly greater. It is observed that due to the asymmetric detonation point, the main explosive charge detonation wave propagates asymmetrically. As a result of asymmetric propagation at the time of 5 µs for stochastic detonation point, the main explosive charge did not evolve to achieve its maximum pressure as in the case of ideal detonation point.

Concluding remarks

The main objective of this paper is to point out a possibility for using numerical approach for optimizing the booster charge mass used in design of new artillery fuzes.

Comparing the results obtained by the analytical and numerical computations, it is concluded that the best match of the results is in the case of the stochastic detonation point obtained by the numerical method. Based on the analytical method, it was concluded that the initiation of TNT will not take place due to the fragment impact. As ductile and shear parameters for metal parts were introduced, numerical simulation confirmed that no fragmentation of projectile cavity occurred. According to maximum pressure value for TNT initiation, both analytical and numerical computations confirmed that initiation of TNT due to detonation of FH-5 is inevitable. In addition, the numerical enables determination of the booster mass necessary to develop a complete detonation of the main explosive charge made of TNT. Stochastic detonation point produces earlier initiation of TNT, but because of the booster charge asymmetric detonation wave, the main explosive charge does not produce maximum pressure which can lead to significant decrease in the projectile efficiency.

The obtained results refer to a specific example, but the methodology can be applied to other examples with different mass and geometry of the booster and main explosive charge, as well as with different explosives.

This important conclusion should be tested by an experimental approach.

The further improvement of numerical model can be obtained by implementing FH-5 I&G model, which would enable the simulation of complete explosive train.

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Numerička analiza inicijacije glavnog eksplozivnog punjenja artiljerijskog projektila

Značaj istraživanja inicijacije glavnog eksplozivnog punjenja usled dejstva dodatnog eksplozivnog punjenja proizilazi direktno iz zadatka optimizacije mase dodatnog eksplozivnog punjenja koja je potrebna da bi se ostvarila stabilna detonacija glavnog eksplozivnog punjenja, a sve to u cilju ostvarenja maksimalne efikasnosti projektila. Razmatrana konfiguracija sastoji se iz dva eksploziva i tri metalna dela koji predstavljaju delove upaljača i projektila. Osnovni cilj ovog rada je razvoj numeričkog modela inicijacije glavnog eksplozivnog punjenja artiljerijskog projektila smanjene osetljivosti. Kroz ovo istraživanje, analizirana su dva slučaja položaja tačke detonacije, idealna i stohastička. Efekti prenosa detonacije, analizirani su korišćenjem Jones-Wilkins-Lee i Ignition and Growth jednačina stanja eksploziva, primenjenih kroz Coupled Eulerian-Lagrangian pristup u softveru Abaqus/Explicit. Sa namerom da se prikaže P-u interakcija među elementima konfiguracije i radi poređenja sa rezultatima dobijenih numeričkom metodom, u rad je uveden i analitički proračun. Rezultati analitičkog i numeričkog pristupa su prikazani i detaljno razmotreni. Pokazano je da predloženi numerički model omogućava simulaciju i optimizaciju eksplozivnog lanca u upaljačima HE projektila.

Ključne reči: **eksplozivno punjenje, inicijacija eksploziva, HE projektil, upaljač, heksogen, TNT.**