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Numerical Study of Modular 5.56 mm Standard Assault Rifle Referring to Dynamic Characteristics

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ABSTRACT

The paper describes investigations carried out to verify a loading mechanism of a newly designed modular assault rifle MSBS-5.56. A complex character of interaction between its elements during a reloading process encouraged the authors implement a numerical approach based on the multibody system to specify the essential dynamic characteristics. The achieved results were compared to the data recorded during the experimental tests on the shooting range. Owing to the proposed modelling methodology, a good agreement between experimental and numerical studies has been achieved. A numerical model presented in the paper will be applied in further investigations to analyse strength parameters of the reloading mechanism and to conduct additional optimisation studies.

Keywords: Assault rifle, numerical investigations, multibody system, slide motion, reloading process

1. INTRODUCTION

Modularity is one of the most important characteristic feature of contemporary assault rifles developed by world leading armament producers. It allows configuration of alternative types of weaponry (standard assault rifle, short assault rifle, sniper rifle, machinegun) based on the same main subassemblies simultaneously maintaining battlefield requirements. The presented concept of weapon design allows for cost reduction and significantly avoids possible limitations during both manufacturing and maintenance processes. Moreover, the soldier training process could be more effective owing to similar operation modes of alternative types of weapon.

The literature review[1] shows that the most popular solution used in the design process of modular weaponry is either an automatic or semi-automatic gas operated solution with short stroke of a gas piston. Contrary to the system invented by Kalashnikov, in most of such rifles, the gas piston is not connected to the slide. This allows design of the integral subassemblies of the barrel that could be easily and quickly replaced.

The idea of assault rifle operation with short stroke of a gas piston is widely known. Some of the publications present significantly limited data[2,3], which may pose a problem. Such basic data as: materials properties, pressure impulse histories recorded in a barrel chamber as well as the system dynamic response (e.g. displacement and velocity of a piston, slide or bolt) subjected to the pressure impulse are neglected in most of cases.

Since 2008, the Institute of Armament Technology, Military University of Technology in Warsaw, in cooperation with 'Archer'– Radom Arms Factory LLC, has been conducting the research project purposed to develop Polish modular small arms system cal. 5.56 mm (MSBS-5.56)[4]. The main aim of this project was focused on development of the assault rifle in both a standard and a bull-pup version (Fig. 1). Several alternative conceptions of weapon design were finally elaborated within the project. To evaluate the correctness of the design assumptions, numerical and experimental tests were performed. The results obtained at the initial stage have been already published[5-8]. To increase the functionality and reliability as well as to improve ergonomic features of assault rifles, some additional improvements were introduced focused mainly on the structure of the main elements and subassemblies as shown in Fig. 1.

Unfortunately, this adaptation caused a necessity of reloading mechanisms modification. The main elements such as a slide, bolt, and rod of the gas piston were modified as well. Taking into consideration the range of the applied alterations, it was essential to verify the correctness of rifle behaviour during its operation. Due to complex character of dynamic interaction between the elements during the firing process, the numerical simulations were carried out. The results achieved during the computer simulations were compared with the data obtained in the experimental tests.

The methodology used to verify an influence of geometrical adaptations in reloading mechanisms on the rifle behaviour during firing is described.

2. NUMERICAL MODEL

A complex character of interaction of reloading assemble elements of the assault rifle during the firing process is difficult

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(a) (b)

Figure 1. MSBS assault rifles before and after geometrical modifications: (a) classic version and (b) bull-pup version.

to be defined and solved using a classical, mathematical approach described by algebraic and differential equations[9,10]. It results in the fact that numerical simulations are widely used in the design process of the contemporary weaponry[2,11-16]. To predict the dynamic response of the main elements of the reloading mechanism (e.g., slide, bolt, gas piston) under impact of powder charge deflagration gaseous products, two alternative numerical methods are used. The first is the multi body systems (MBS)[17-19], the other is the finite element method (FEM)[20,21]. Both of them allow dynamic characteristics of moving elements to be defined; however, the MBS is much more applicable and useful. The MBS is a method widely used in simulations carried out for, among others, automotive industry[22,25], robotics[26], biomechanics[27] .

The main assumption of this method is that all elements of the reloading mechanism are described by rigid elements subjected to different types of forces (external or internal forces, concentrated or distributed load, with or without friction and connected with joints). Depending on the applied type of joints (e.g., linear, cylindrical, spherical, rotational joints), the appropriate definition of degrees of freedom are formulated. The process of developing a numerical model begins with defining the geometry of all elements. The characteristic dimensions of elements need to be specified at this stage. Moreover, in dynamic analysis, the masses of all elements and forces acting on mechanism need to be defined[17,18].

Literature studies lead to the conclusion that the presented numerical method (MBS) of computer simulations should be appropriate to solve the described problem[3,11-13]. The first stage of preparation of the computer simulation consists of the process of developing the numerical model and specifying the initial boundary conditions. The geometrical features of all elements, kinematic properties of moving elements such as positions and velocities as well as characteristics of forces acting on the elements need to be determined during this process. The above mentioned data are subsequently used in the process of formulation of algebraic and differential equations of motion. Owing to application of alternative procedures of numerical integration, this system of equations is possible to be solved.

The numerical approach applied to determine kinematic and dynamic characteristics of the moving elements of the reloading mechanism during the firing process requires an appropriate model. The MBS method, proposed by the authors, allows the usage of the data obtained directly from CAD system. Characteristic dimensions of the elements were defined based on the imported geometry. Figure 2 presents the right-side view of CAD model of MSBS-5.56 rifle. The elements which are not involved in the process of weapon reloading were deactivated. The elements such as springs, nuts and screws were removed from the model. The final version of the model was verified with the use of an automatic collision checking procedure.

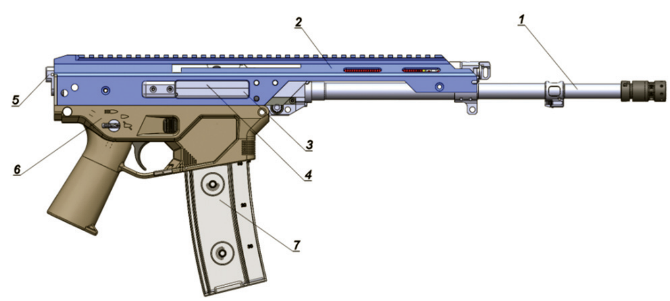


Figure 2. The right-side view of main subassemblies used in preparation of the numerical model of 5.56 MSBS assault rifle.

To perform numerical investigations, a geometrical model of the assault rifle should contain the following subassemblies: 1-barrel, 2-upper receiver, 3- bolt, 4- slide, 5- recoil mechanism, 6- lower receiver, 7- magazine with 5.56 mm × 45 mm rounds. Each of the mentioned subassemblies contains individual elements responsible for the reloading process. These elements are presented in detail in Fig. 3. The developed model of the reloading mechanism was finally implemented into MSC. ADAMS software to specify the initial and boundary conditions and perform series of computer simulations[28].

At the first stage, the boundary conditions were defined.

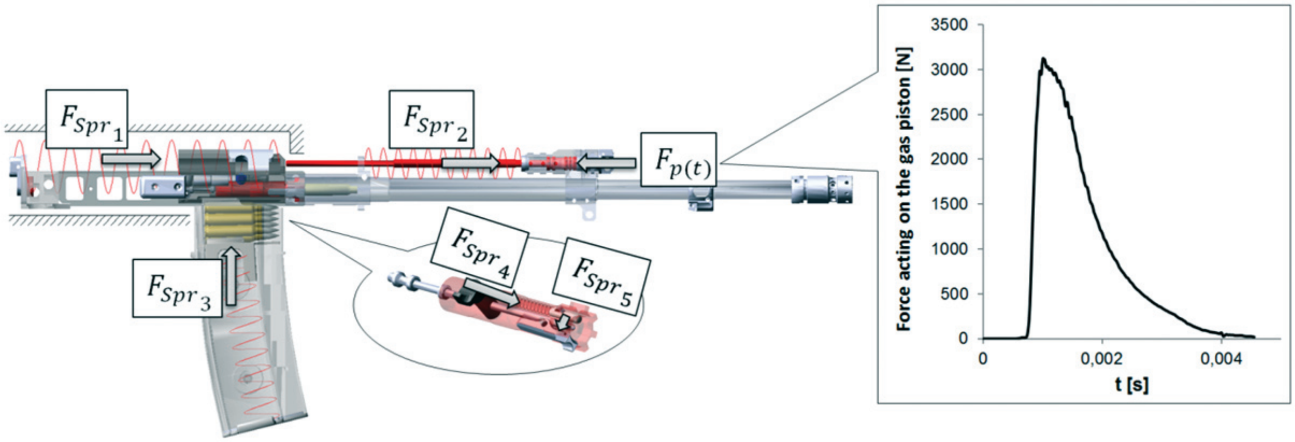


Figure 3. The model used in numerical investigation and the main forces acting on moving elements during the firing process.

This process consisted in defining appropriate geometrical and dimensional relations between the elements. As that simulation was performed for dynamic conditions, mass and inertial characteristics for all elements were determined based on the volume of elements and their densities (obtained from material specification datasheet).

The next stage of numerical model development was focused on defining the scheme of forces acting on the moving elements. Spring forces, marked in Fig. 3, were represented by applying discrete spring-dumper elements. The following springs were introduced to the numerical model: (Spr_1) – recoil mechanism spring, (Spr_2) – spring positioning the gas piston rod, (Spr_3) – magazine follower spring, (Spr_4) – ejector spring, (Spr_5) – extractor spring. A time history of the force resulting from gas pressure $F_p(t)$ history, marked in Fig. 3, was applied as the main load responsible for motion of the reloading mechanism. This force results from interaction of gaseous products of deflagrations with the rear surface of the gas piston. The character of this load was depicted by the curve presented in Fig. 3. This characteristic was obtained as a result of the experimental research during firing tests carried out on the special laboratory stand described in detail[29].

The next stage of preparation of the computer simulation was defining the mutual interaction between the moving elements. The applied software allows usage of one of three methods specifying the contact definition. The first of them is formulated based on the principle of momentum conservation. The mathematical description of this procedure is as follows[28]:

$$m_a u_a + m_b u_b = m_a v_a + m_b v_b \tag{1}$$

$$c_r = \frac{v_b - v_a}{u_a - u_b} \tag{2}$$

where c_r – means the restitution coefficient, velocities v_a and v_b are expressed by the following equations:

$$v_a = \frac{m_a u_a + m_b u_b + m_b c_r\left(u_b - u_a\right)}{m_a + m_b}, \tag{3}$$

$$v_b = \frac{m_a u_a + m_b u_b + m_b c_r\left(u_a - u_b\right)}{m_a + m_b}. \tag{4}$$

The second method, an alternative option of a contact definition, is determined by the *IMPACT* function. This method is more complex. It is a modified expression of the model proposed by Hertz[28]. Four variables such as: stiffness, force exponent, damping and penetration depth are supposed to be specified during definition of the *IMPACT* function. This formula contains the following set of parameters corresponding to the properties of material and models geometry[28]:

$$IMPACT\left(x, \dot{x}, x_1, k, e, c_{\max}, d\right) \tag{5}$$

where

x –distance dependent variable used to compute the *IMPACT* function,

$\dot{x}$ - time derivative of x to *IMPACT*,

x_1 - free length of x. If x is less than x_1, then Adams calculates a positive value for force, otherwise, the force value is zero,

k - contact stiffness scaling interaction forces,

e - positive real variable defining the exponent of the force-deformation dependency. For a stiffening spring characteristic, $e > 1.0$, for a softening spring characteristic, $0 < e < 1.0$,

$c_{\max}$ –maximum damping coefficient,

d –penetration value for which full damping is applied.

The first three arguments of the *IMPACT*, function concern the model geometry and are specified for every integration time step during the computer simulation. The following parameters: $k, e, c_{\max}, d$ are used to specify the normal contact force. The value of the force is computed based on the following formula[28]:

$$F_N = \begin{cases} 0 \Rightarrow x \geq x_1 \\ Max(0, k\left(0, k\left(x_1 - x\right)^e - STEP\left(x, x_1 - d, c_{\max}, x_1, 0\right) \cdot \dot{x}\right) \Rightarrow x \leq x_1 \end{cases} \tag{6}$$

where $x \geq x_1$, no penetration occurs and the force is zero (penetration $p = 0$)

$x < x_1$, penetration occurs (penetration $p = x_1 - x$)

It results from the equation that when $p < d$, an instantaneous damping coefficient is a cubic step function of penetration (p).

The *IMPACT* procedure is activated when the distance between the mating elementsis below the nominal free length $\left(x_1\right)$. As long as the distance between the mating elements is greater than x_1 , the force is zero. This function consists of two components, a spring or stiffness component, and a damping or viscous component. The stiffness component is proportional to k , and is a function of penetration. The damping component of the force is a function of penetration speed.

On the basis of the theoretical studies, it was found that for materials such as steel the value of a stiffness coefficient is $k = 1 \cdot 10^5 \frac{N}{m}$, and the value of an exponent, $e = 2.2$. For materials with lower strength parameters, e.g., aluminum, copper is $e = 1.5$. For soft materials like rubber, foams, the value of an exponent is $e = 1.1$. For the analysed case, the damping components were as follows[28]: $d = 0.01mm$, $c_{\max} \leq 0.01k$.

The discussed contact procedures allow a dissipation phenomenon caused by friction to be taken into account. The mathematical definition of friction is formulated based on the Coulomb's theory[28].

To reduce the number of contact pairs and, additionally, to shorten the time of computer simulations, appropriate kinematics constrains (e.g., linear, revolute, cylindrical, constrained) were defined.

The final stage of numerical model development was focused on the choice of a numerical integration subroutine. This algorithm allows solution of the algebraic-differential equations system defining the motion of the elements during the reloading process. For the presented case, the GSTIFF algorithm was chosen. The algorithm is characterized by an efficient variable-order and a variable-step size computational method of integration[28].

3. RESULTS AND DISCUSSION

The evaluation process of the reloading mechanism geometrical modification correctness was performed based on the results obtained during the computer simulations. The kinematics characteristics of the slide were compared with experimental data to verify the quality of the numerical results. Real characteristics of slide motion were acquired during the firing tests on the shooting-range with the use of a high speed camera (Phantom v.12)[30]. Figure 4 presents the view of the laboratory stand used for these tests.

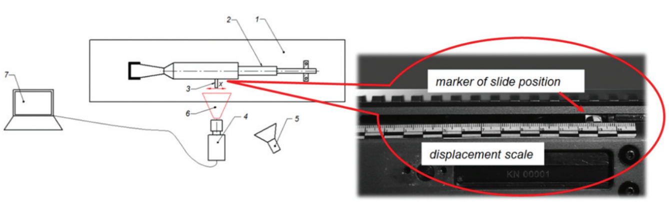


Figure 4. View of the laboratory stand used for acquisition of kinematic characteristics of slide motion during experimental tests: 1 – base plate, 2 – assault rifle, 3 – marker on the slide, 4 – high speed camera, 5 – additional source of light, 7 – computer with data acquisition software.

The assault rifle was mounted on the base plate. The linear scale was marked on the upper receiver to define the reference data necessary for determination of kinematic characteristics of the slide. The field of the camera view was set up to allow continuous observation of marker motion during reloading. Based on the recordings, it was possible to define both the displacement and velocity histories. The TEMA software[30] was applied to process the recordings as well as to collect the required data. Figure 5 presents the comparison of numerical and experimental data of slide motion. The numerical data such as displacement *Ds_MBA(t)*, and velocity *Vs_MBA(t)* were marked by continuous curves. The experimental data (resultant from 10 tests) was marked by doted curves.

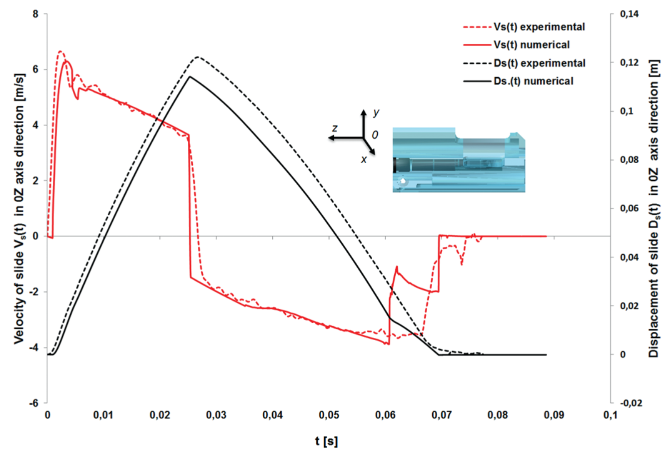


Figure 5. Kinematic characteristics of slide motion – displacement and velocity in OZ axis direction.

Taking into consideration the shape of the velocity curves, it could be found that they are in a good agreement. The adopted assumption of a rigid character of the bumper geometry is the main cause of differences between shape of displacement curves. Motion of the slide to the rear position was shortened in numerical investigation, what results in the fact that the slide reaches faster the initial position.

The kinetic energy of the moving slide was applied to execute some stages of the reloading process. During its motion to the rear position, the operations such as: unlocking the barrel chamber, ejection of the firing case, tension of the trigger spring were carried out. Afterwards, when the slide reached the final position, the motion was realized in opposite direction. During this stage, loading the round and locking the barrel chamber operations were carried out.

The plots as shown in Fig. 6 contains the curves of both velocity and displacement of the bolt. The maximum value was reached at the end of the unlocking process. Movement of the guide block to the rear position and its impact onto the rear side of the slide socket (connector between slide and bolt) resulted in a rapid decrease of the bolt velocity. After the unlocking process, the position of the bolt is defined by both the guide lock and the guide slide. During this stage of motion, the bolt velocity was the same as the slide velocity. This stage of motion lasted until the process of locking the barrel started. The change of the bolt velocity in the final stage of its motion resulted from dynamic interaction between the lock rim of the bolt with the spline sleeve and the barrel.

The change of the bolt position was determined in the mass center in OZ direction. Due to the slide motion, interaction between a curvilinear socket and a bolt guide resulted in bolt

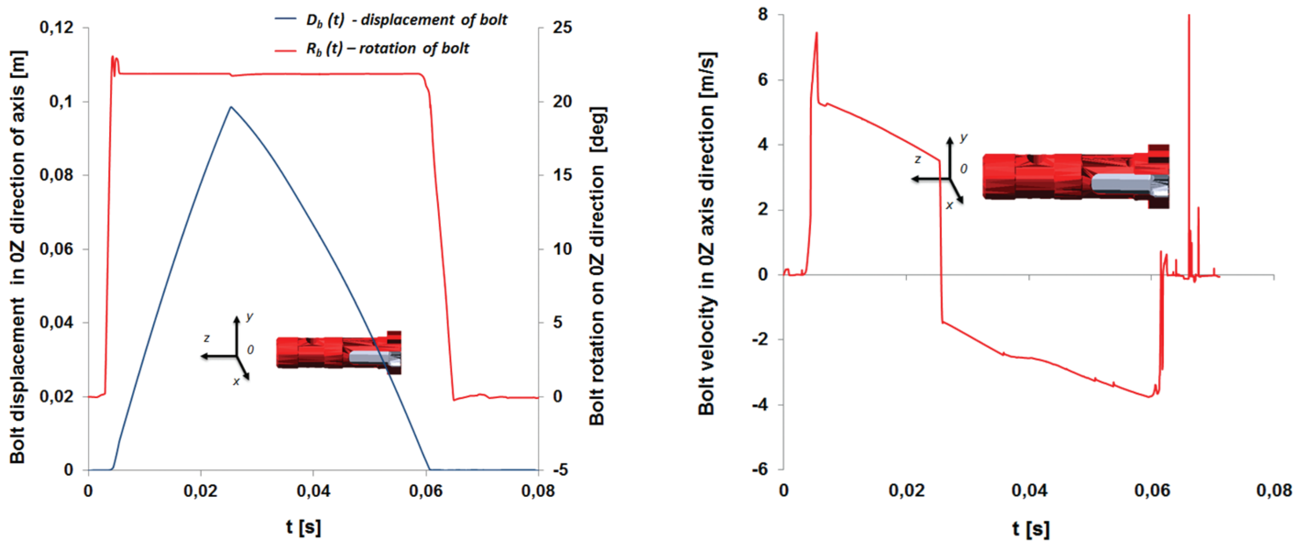
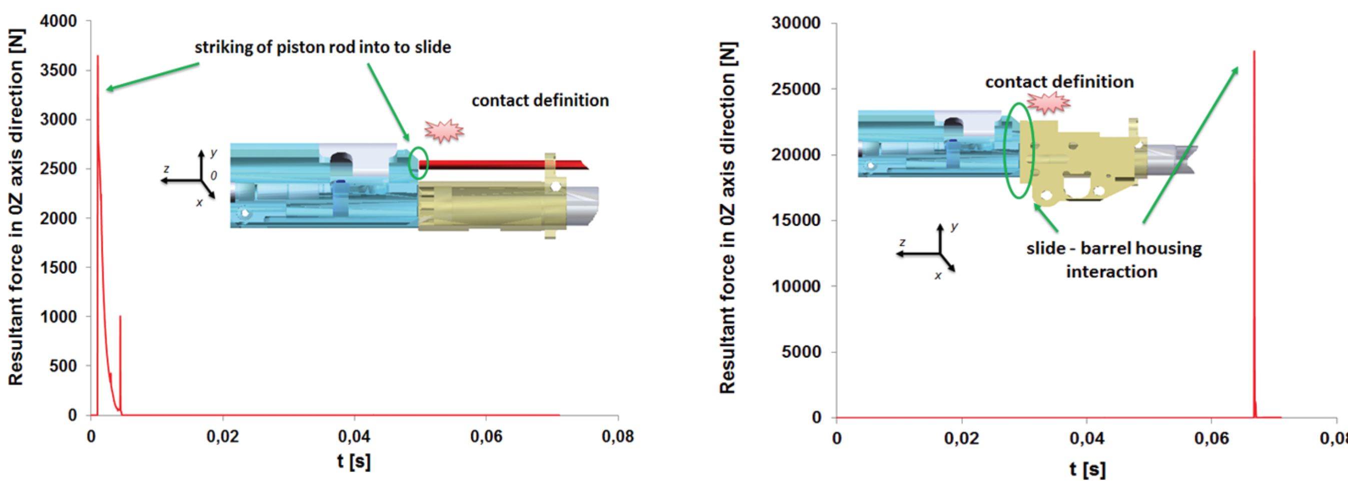


Figure 6. Kinematic characteristics of bolt subassemblies: displacement, rotation and velocity.



(a) (b)

Figure 7. Plots of resultant contact forces interactions: (a) between gas piston and slide and (b) between slide and barrel housing.

rotation on OZ axis. This phase of motion was the first step of barrel chamber unlocking operation. Afterwards, linear displacement of the bolt was realised in OZ direction as an additional mass of the slide. When the slide reached the initial position, the barrel locking process was initiated by interaction of the guide lock with the curvilinear surface of the socket in the slide case (the bolt was rotated in OZ axis). Owing to the applied numerical approach, it was possible to define dynamic characteristics of slide interaction (Fig.7).

The resultant contact force between slide and piston rod, presented in the figure, is adopted to carry out some stages necessary for reloading the assault rifle. Additionally, in the same figure, the effect of slide and barrel interaction is presented. This force indicates the highest value of contact force. Due to the necessity of executing some stages of the reloading process, the slide needs to indicate appropriate kinetic energy during the second stage of its motion. The proper stiffness of the recoil mechanism spring and the value of initial tension, ensures the energy to be provided properly.

The dynamic interaction between the slide and the bolt guide could be analysed based on the plot as shown in Fig. 8. The force curve shape indicates a very dynamic and impulsive character of the process.

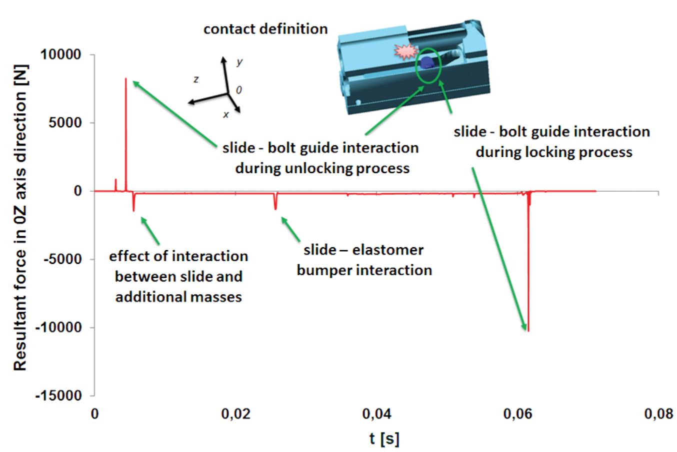


Figure 8. Plot of resultant contact force between slide and bolt guide.

4. CONCLUSIONS

Based on the results achieved during numerical investigations using the multi body system, the correctness of the reloading mechanism of MSBS-5.56 assault rifle were verified. The proposed geometrical modifications of the reloading mechanism caused by ergonomic adaptation of the assault rifle were correctly verified. Taking into account the presented kinematic characteristics of the main elements of the reloading mechanism, the following conclusions could be drawn:

- The proposed numerical model of the reloading mechanism represents accurately the real model. Kinematic characteristics of the slide motion obtained during computer simulations are in a good agreement with the experimental data obtained during firing tests on a shooting-range.
- Owing to the numerical approach, the process of verification of design assumptions could be realized fast and allow minimisation of time consuming and cost effective experimental studies.
- The applied numerical model takes into consideration a wide range of additional options that are simplified in the classical analytical approach (e.g., contact definitions with the *IMPACT* function implementation, energy dissipation phenomenon caused by friction, ejection of the firing case, loading the round into the barrel chamber, the impulsive effects generated by interaction between moving masses in the slide hole).
- The definition of interaction of rigid bodies is one of the main limitations of the proposed numerical approach.
- The presented kinematic characteristics may be used in additional numerical investigations To determine the strength parameters of the reloading mechanism.
- Implementation of additional features of MSC.ADAMS software makes an optimisation process possible. These features can be useful in further investigations of the reloading mechanism.

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