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THE NUMERICAL SIMULATION OF THE PYROTECHNIC ACTUATOR FOR THE ACTIVE BUMPER

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Abstract

The paper contains the description and classification of pyrotechnic actuators focusing on the automotive industry applications. This paper also explains the compatibility issues during frontal impact of a passenger car with a large truck. The construction of the pyrotechnic actuators for the "active bumper" is presented here. The processes occurring within the pyrotechnic actuators after ignition of a pyrotechnic propellants have been explained. The investigations are focused on the dependence of a shape of the actuator's combustion chamber and the piston stroke time. It appears that the appropriate design of the combustion chamber can decrease the time required for a piston stroke using this same type of a propellant. This also allows to reduce the amount of propellant when the more rapid stroke is not required. This is because of the characteristics of the detonation waves which are responsible for the piston movement. The visualization of the detonation waves occurring due to ignition of the propellant is crucial for understanding the dependence between the construction of the actuators interior and the piston stroke time. Therefore, the approach of simulating numerically the detonation waves aroused. This simulation was conducted with aid of ANSYS Workbench 13 environment using the AUTODYN module. The numerical tests consists on modelling the actuator without changing the overall dimensions as well as the parameters of the propellant. The only elements modified were piston and the bottom of the cylinder shape.

Keywords: *vehicles compatibility, pyrotechnic actuators, shock wave, AUTODYN*

1. Introduction

Pyrotechnic actuators are widely used in automotive industry due to the fact that such a construction provides very short time of reaction. Furthermore, pyrotechnic actuators are able to produce large amount of energy no requiring much space to store. Mostly such a devices are used in pyrotechnic seat belts pretensioners, in pop-up hood system for pedestrian protection, systems which open doors of a crashed vehicles in order to provide easier access to the injured occupants etc.. The pyrotechnic actuators differs from each other mainly with size ranging from micro actuators for aerospace industry to the actuators whose cylinder have 20 cm diameter. Such a construction are used for instance to emergency gates close/open [1] or like it is pointed out in publication referred under [2] for an emergency landing scenario for the space shuttle. This particular actuator has length of 33cm with piston fully deployed.

The pyrotechnic actuator was selected as main component of the "active bumper" concept. This concept constitutes an improvement of well-known system FUPS (Front Underrun Protection System) which is legally required in all large trucks. It is to be understood that most of impact energy is normally accumulated by means of the frame side members. Of course, in case of such different class as passenger cars and large truck the frame side member are on the different height. FUPS is a rigid bumper located in the lower position ensuring that a passenger car will collide with it rather than going under the larger vehicle

The concept of the "active bumper" is an approach to improve FUPS system. In this case the bumper is fixed with pyrotechnic actuators whose piston rod is made of deformable material (e.g. aluminium foam) when the on-bard computer of the truck classifies the oncoming vehicle as threaten the actuator will be fired and in consequence artificially elongate the deformation zone of the truck. Such a solution is capable of reducing severity of frontal impacts of vehicles representing those two classes.

2. The operation principles of the pyrotechnic actuators

The piston of the pyrotechnic actuator is trusted forward upon the ignition of the pyrotechnic charge. This pyrotechnic charge produces a large amount of gases as combustion products in the time of milliseconds. The ignition of the charge, therefore generates a wave which acts on the piston forcing it to advance forward. The shock wave in terms of pyrotechnics is defined as a pressure wave of high intensity characterised by a very rapid initial increase in pressure followed by a slow falling off [3]. This wave is reflected by the piston, and then reflected back again by the bottom of the cylinder. This process (i.e. number of the reflection) depends on the wave velocity, and therefore energy. The repeatable reflection causes weakening of the reflected shock wave while the compression waves still propagates forward. Ultimately both of the waves will coalesce and form a new shock wave in front of the wall [4]. It has been found that the actuator operation and acoustics timescales are very similar (in the order of approximately 0 μs). This suggests that wave interaction may influence the performance of the device [2]. The shape of a shock wave has an influence on the speed with which it travels. Generally, the detonation of a charge is dependent on the detonation wave velocity, the radius of a charge, and the shape of a wave front [5]. Thus it is possible to influence the performance of the device with appropriate forming the shape of the shock wave. Most of actuators design, however, constitutes a piston with flat surface as well as flat death bottom centre. Very often the pyrotechnic gas generator is located on side of the cylinder, in consequence the flow is directed from the cylinder with smaller diameter into the main, larger chamber. Such a solutions significantly mitigates the energy of a pyrotechnic gas generator, hence some potential is lost. This may cause of longer time required for the piston full deployment or necessity of employing gas generator with greater power.

The shock wave mitigation properties of designs representing two diameters has been proven by number of researchers. It appears that less energy is lost during the smooth transition from the smaller to larger diameter [7]. The longer distance of transition the more energy remains not dissipated. This is because of the trajectory of so called triple point formation. Those points arises due to collision of shock wave reflected from the walls and each other [6]. The sketch of such a triple points is shown in Fig. 1. The collection of the triple points generates cells with shape resembling fish shell pattern which is a measure of the reactivity of the mixture representing a length scale that characterises the chemical reaction occurring in the shock wave. Another words the more reactive mixture, the smaller the cell [7, 8], and therefore the more of the triple points, whereas long chemical reaction or induction times correlates with large detonation cells [10]. The comparison of a shock wave propagating from a cylinder with smaller diameter into the larger one with various shapes of transition area was performed by Vasil'ev et al. [9]. It has been found that the critical value of a cone angle of the transition area is 60 degrees . When this value is exceeded the influence of diameters between the two ducks is no longer important. Another words at greater cone angle a part of the mixture at the cone edge does not contribute to detonation region. This is because the amplitude of the diffracting wave is too low [10]. Furthermore, Vasil'ev conducted investigation in terms of possibilities to shock waves quenching by means of diffraction. What was found was that the energy of a shock wave can be altered by orders of magnitude by appropriate design of the shock wave surrounding [9].

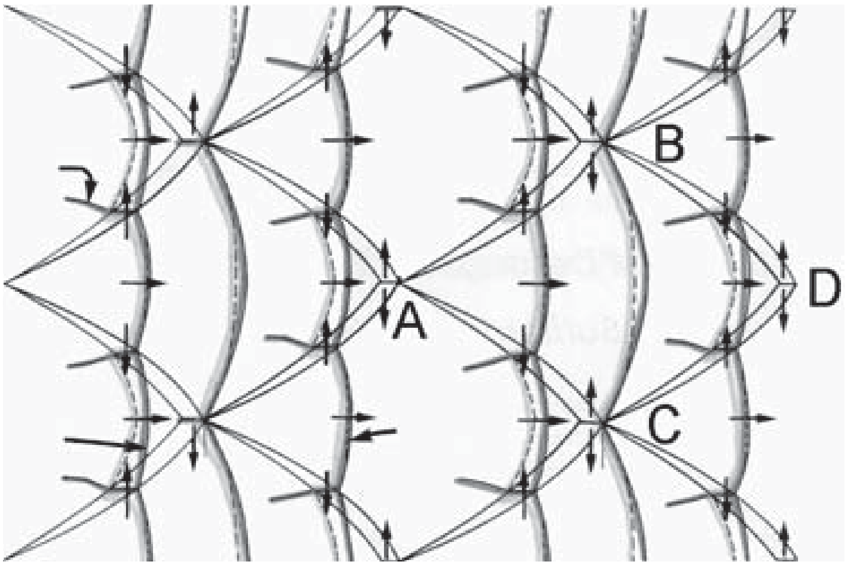

Fig. 1. The structure of and idelize two dimetnional ustable deetonation at difrent time (after [6}

2.1. The shock wave reflection

Bull et al. [11] investigated the properties of the reflected shock interaction, and stated that wave reflection process is subject to two mechanisms, which are leading to failure of the ideal theory of the reflected waves behaviour. The first mechanism is an result of reflected wave's interaction with the boundary layer formed along the tube wall, behind the incident shock. The second is related to the instabilities which may develop in the contact region. Thus the contact region no longer remains a flat plane, but may prematurely encroach upon the region of the shock heated gas of the closed end of the tube. A incident shock wave bifurcates after the reflection . in another words the reflected incident wave develops a Mach interaction near the wall of the tube. Then, the Mach stem and transverse shock grows as the reflected shock recedes from the end plate. It has been shown that the bifurcation of the shock arise due to interaction with the boundary layer wall because the stagnation pressure of the gas is lower than freestream gas under certain conditions. Therefore the penetration of the reflected shock is impossible. Hence, this is the origin of the triple ppoint.

The numerical investigation of shock wave properties reflected from the cylindrical reflector has been performed by Henshaw et al. [12]. What was investigated was the shock wave with various Mach number reflected from the circular reflector. The shock wave was divided in to the weak and strong wave. It appeared that only the strong shock wave (i.e. shock wave propagating with relatively high Mach number) are influenced by shape of the reflector. In case of weak shock wave this relationship is rather not important. The reflected shock wave generates so called shock-shocks at location being dependant on the shock wave Mach number and the curvature of the reflector. The shock-shocks arises as a consequence of shock wave reflection from the concave wall towards the centre of the chamber and arise from discontinuities in the shock front [13]. In another words the shock-shocks is a 3D equivalent of the 2D triple points. It has been found that the Mach number can be significantly increased at the point of shock-shocks occurrence. The increase can be significant enough for the weak wave to be considered as a strong one. Similar behaviour has been observed by Johansson et al. [13]. They had investigated the possibility to form a specific shape of the shock wave enclosed in the confine polygonal space. This investigation has proven that the shock wave can be formed in the way to resemble shape of the reflector. In this investigation polygonal shape of a shock wave was obtained with corresponding location of the shock – shocks. Hence the energy of the shock wave is changed with accordance to the shape of the reflector. Moreover, Gui et al. [14] investigated the shock wave reflection from the planar and cylindrical wall of a shock tube. It appears that the shock wave reflected from a planar surface has lower velocity comparing with the shock wave reflected from the concave wall. This suggests that the wave reflected from concave surface is capable of maintaining during longer period of time, hence to perform the work (i.e. piston movement).

Taking above into consideration it can be assumed that the piston movement of an actuator is dependent on the shape of the piston surface and the bottom of a cylinder. Therefore, the approach of a numerical modelling of such a relationship arose. The model presented here is a theoretical comparison of two different piston constructions. The output value of this investigation is the piston velocity and the shock wave distribution which force the piston to accelerate.

3. The numerical investigation

The numerical investigation comprises the comparison of two embodiments of a pyrotechnic actuator performed with aid of ANSYS AUTODYNE solver. The first (basic) embodiment of the actuator contains a flat surface of piston and inclined bottom of the cylinder (see Fig 2a). The second embodiment contains a concave piston surface and inclined bottom of the cylinder(see Fig 2b). The angle of bottom inclination is the same in both of the embodiments. It should be pointed out that only 2D simulation was conducted since the construction of both embodiments is assumed to be axisymmetric. As it can be seen in Fig 2a, b the numerical model is equipped with gauges located in this same position. Gauges from 1 to 12 are fixed so they cannot move with respect to the piston. Those gauges are set to measure pressure. Gauge 13 is movable and fixed on the piston so it can measure the pistons response to applied pressure. The piston was moved upon ignition of HMX (Her Majesty's Explosive) explosive ($C_4H_8N_8O_8$). This propellant was selected due to the fact that it is very common in pyrotechnically driven devices [2, 15, 16]

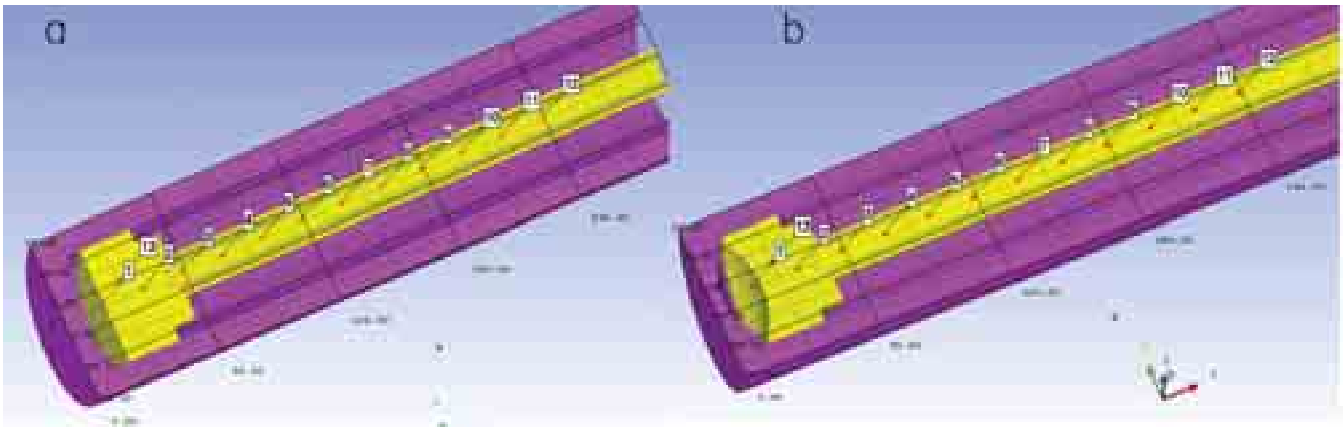

Fig. 2. The AUTODYN model of the pyrotechnic actuator

The investigation was performed in terms of piston shape influence to the piston velocity, hence the model was simplified. The simplification considered are listed below:

- the cylinder has unchanged construction in both embodiments,
- the system of piston and piston rod has this same mass in both embodiments,
- the movement of the piston is assumed to be frictionless, so only inertia forces are considered here,

- in both cases this same amount of HMX was employed,
- in order to ensure this same volume between piston and the bottom of the cylinder the piston in second embodiment (Fig 2b) is located nearer to the bottom,
- the cylinder and the piston are assumed to be rigid since the material response is not investigated.

4. Results and discussion

The investigation has shown the different pressure distribution even on the beginning of the tests. As it can be seen in Fig 3a the highest pressure is generated near the wall of the cylinder whereas in case of the concave piston (see Fig 3b) the pressure (at this same time) is focused near the axis. Then the pressure propagates equally towards the wall of the cylinder forcing the piston to accelerate. In case of the flat piston surface the pressure wave is being reflected from the cylinder wall perpendicular towards the axis. The difference of the initial behaviour presented in Fig 3 approximately equalize in time, however the pressure distribution in case of the concave piston will be always ahead of the pressure waves occurring in the first embodiment (Fig 3a). This causes faster piston start, and enables reaching greater velocity.

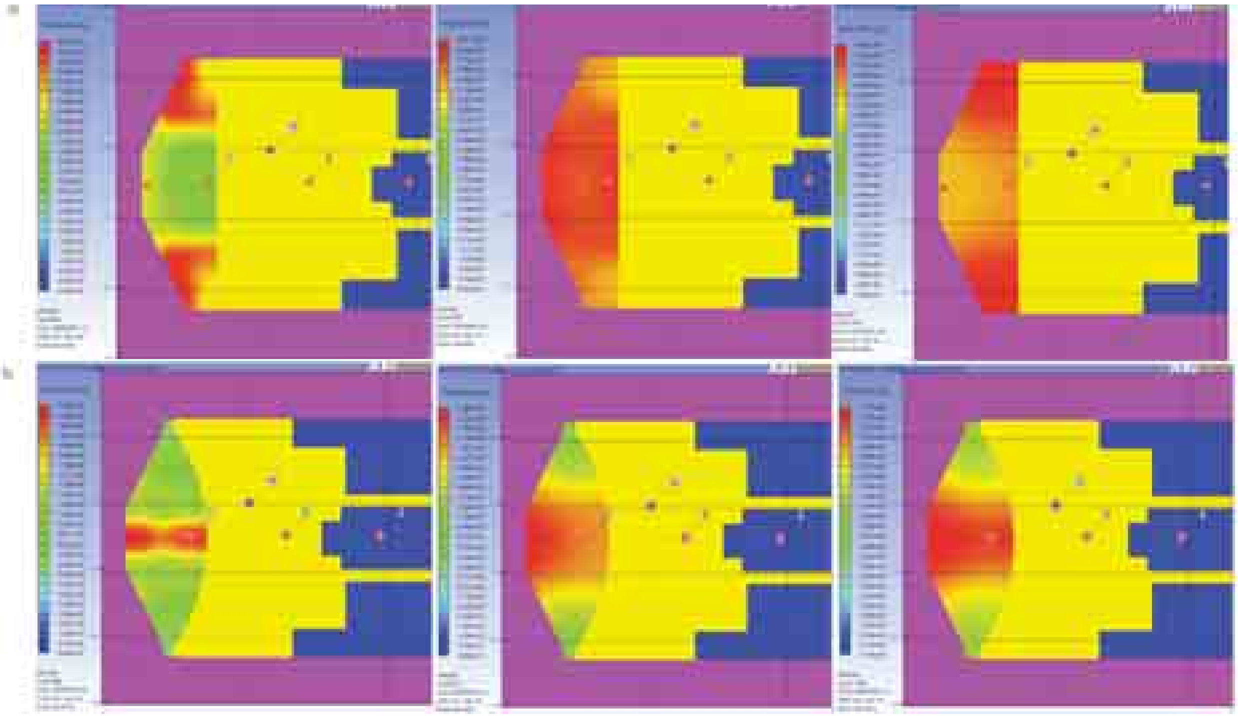

Fig. 3. The comparison of the pressure waves in both actuator embodiments, (a- flat piston surface, b- concave piston surface)

Comparing the velocity diagrams depicted in Fig. 4 it is easy to notice that a piston with flat surface (Fig. 4a) gained lower velocity comparing with concave piston surface (Fig. 4b). The maximum velocity of the flat piston was 21.7 m/s reached in 3.52 ms, whereas the concave piston reached velocity of 23.3 m/s in time of 3.1 ms.

The pressures captured in gauge 1 are shown in Fig. 5. The difference of pressure there is surprisingly high since the same amount of propellant was used. This can be caused by focusing all pressure waves at the axis. As it was already mentioned, the energy of a shock wave can be altered by orders of magnitude with appropriate shock wave surrounding [9]. After some time the pressure in both cases is approximately equalized.

The pressures captured by gauges 2-12 are presented in Fig. 6. It can be seen that the except for the gauge 2 the pressures are approximately at the same order although the pressures are reached during shorter amount of time. This is because of faster piston movement in case of the concave surface.

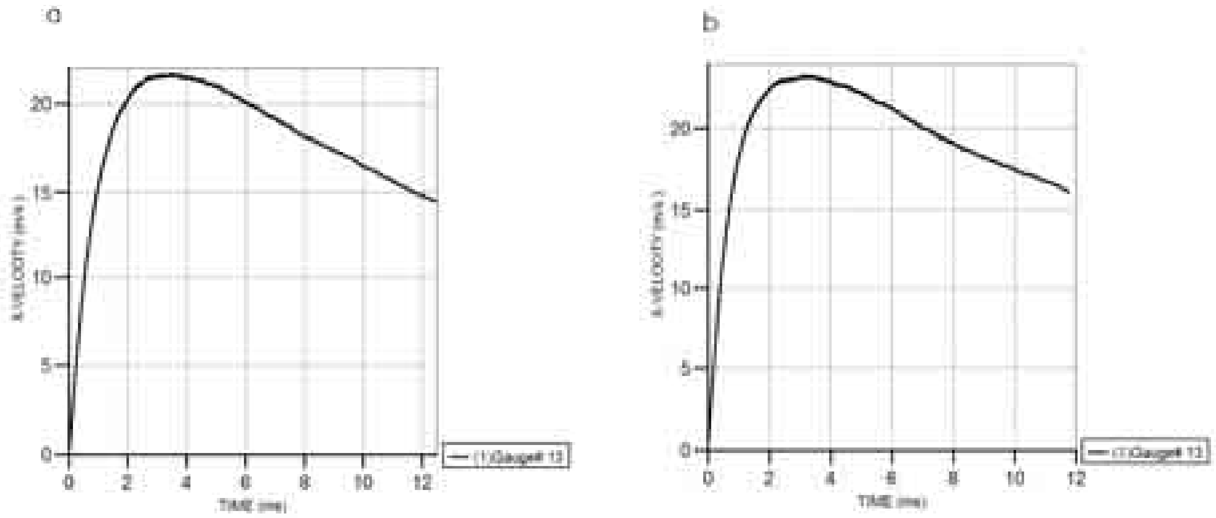

Fig. 4. The piston velocity (a- flat piston surface, b- concave piston surface)

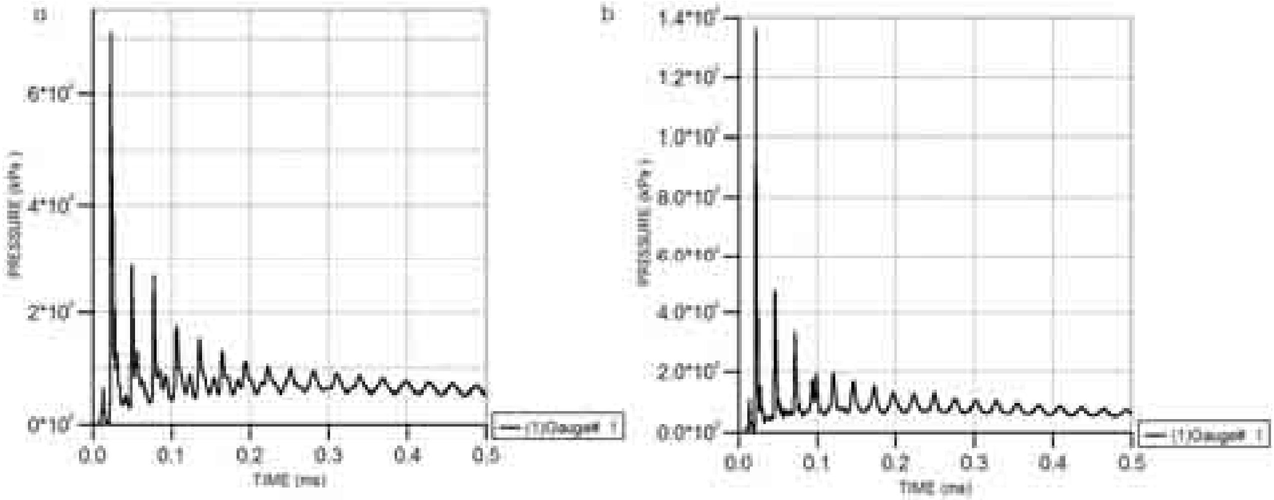

Fig. 5. Pressure at gauge 1 (a-flat piston surface, b- concave piston surface)

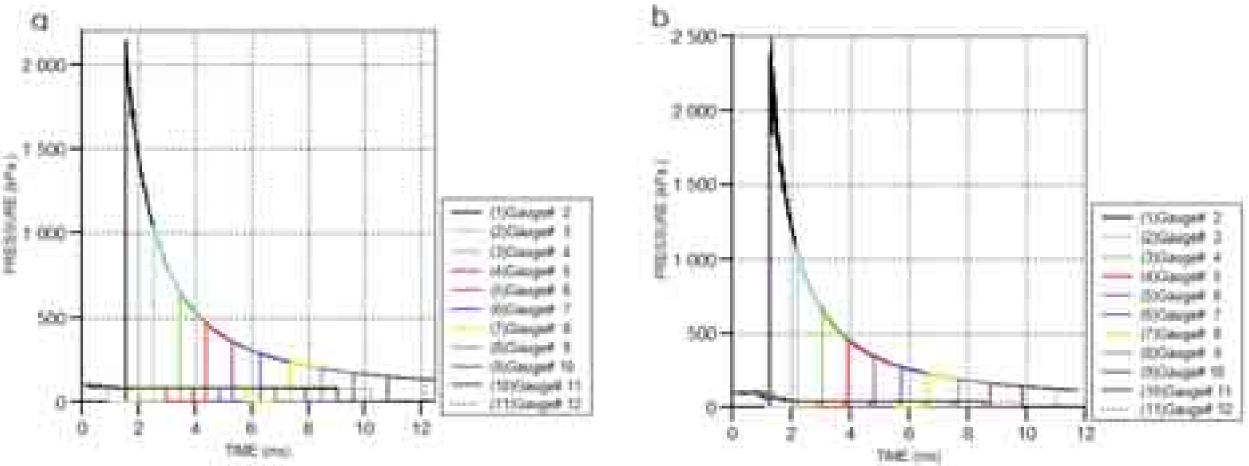

Fig. 6. The pressures within the cylinder (a- flat piston surface, b- concave piston surface)

5. Conclusion

The goal of the deliberation performed here was to investigate the relationship between the geometry of a pyrotechnic actuator and its characteristic (in this case the velocity of the piston). The model presented here contains many assumption and simplifications which makes it rather a theoretical deliberation than investigation of the real object. The times of the deployment presented here are impossible to obtain. This can be caused for example that the model was assumed to be frictionless so the burning propellant must overcome only inertia forces. Nevertheless, it was found that comparing two types of geometry in this same initial condition with use of this same amount of identical propellant the piston velocity can be changed. this brings the necessity of further investigation in this matter. For example full scale 3D modelling without neglecting the friction between the materials. Furthermore, most piston is made of different material then piston road. Therefore, different inertia forces and centres of gravity. Although the results obtained here constitutes the basics for further in-depth investigations.

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