Modeling and Simulation of the Firing Cycle for an Automatic Small Arm

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Abstract: The presented work intends to illustrate how Beretta approaches the study of automatic small arms' firing cycles, from the launch of firing pin to locking mechanism being subjected to the gas pulse, to the recoiling of the moving parts operating the extraction and ejection of the spent cartridge case, and finally the feeding of a fresh cartridge into the firearm's chamber. Using finite element analysis for the study of such engineering problems benefits the product development cycle for its ability to provide key insights in the areas of reliability and durability. Through calculation of the dynamics of the moving parts, it is possible to qualify the functionality of the product, thus proving its reliability; and by using the load histories for each component during the firing cycle an accurate estimation of fatigue life can be established, proving the durability of the design. Starting from the parasolid-based model assembly, this paper describes the use of Abaqus to create a complete mechanical model of an automatic small arm for a realistic simulation of the entire firing cycle.

Keywords: Bullet, Cartridge Case, Contact, Gas Pressure, Ejection, Extraction, Feeding, Locking, Recoil-Operated, Rotating Barrel, Spring Preloading, Unlocking.

1. Introduction

The intention is to illustrate the finite element simulation of a semiautomatic pistol during the firing of a single shot. The investigation is of great interest in the firearms field because of the opportunity it offers to assess aspects related to durability, reliability and safety of the product. In general, the firing cycle for a semiautomatic pistol develops through a very rapid sequence of events starting from the action exerted by the shooter on the trigger (cocking) which is followed by the launch of the firing pin. At the end of its travel the firing pin hits the primer which is mounted into the base of the cartridge in the barrel and the propellant is ignited generating gases at very high pressure and temperature. Using a part of gas energy according to well-defined operating principles (e.g.: blowback or recoil-operated) ensures that the functions can be executed automatically: locking, which must prevent the escape of gases from the breech and must guarantee an adequate support to the cartridge case until gas pressure and temperature inside the barrel are significant; unlocking, when the gas pressure has dropped to a safety level with the launch of the recoiling parts; extraction and ejection of the fired cartridge case and, finally, the return to the battery with the feeding of a fresh cartridge into the barrel chamber. The simulation of how these events happen over the entire cycle of firing allows us to determine the load histories to which each component is subjected, which is essential to continue with more detailed FE analyses performed at single-component level in order to predict the fatigue life. The ambition is to offer designers durability assessments no longer expressed in terms of stress and strain regimes but as life expectation with reference to a well-defined service condition (i.e. cartridge). The FE analysis which covers the entire firing cycle even allows us to assess a firearm design from a reliability point of view: through velocity histories with which the recoiling parts move; through animations which show in detail how the key functions are performed, such as the ejection of the fired cartridge, the feeding of a new cartridge taken from the magazine, and the return to the original locking configuration. For example, to guarantee the functioning, it is important that ejection be as powerful and repetitive as possible: in this respect the simulation permits the identification of potential variability when striking between the fired cartridge case and the ejector takes place and if and how the ejection window in the slide intercepts the cartridge case in its movement. It is possible to keep the feeding under control by observing the contacts that drive a fresh cartridge from the magazine tube into the barrel chamber. The benefits of performing an FE analysis of a firearm over a complete firing cycle are remarkable. To do this you need to face a number of rather difficult numerical aspects. The FE modeling of the system formed by the firearm, the cartridge and the shooter. A pistol consists of a relatively high number of components (about seventy) which interact with each other through continuous contacts, impacts and detachments. The propellant burning into the powder chamber must also be modeled. The present work analyses the firing of a single shot, not a rapid sequence of shots, so it would be reasonable to ignore the effect of thermal shock on the firearm response. Gas pressure is the only external load considered here. Another crucial numerical point is the preloading condition to which a number of components is subjected and which you must consider in order to get a realistic simulation. To find the numerical solution of the firing, the Abaqus/Explicit code has been used because of the duration of the event which is in the order of some tens of milliseconds. All of this will be discussed with reference to the Beretta Mod. PX4 pistol, 40 S&W, in its full size version when firing a 155 grs FMJ standard (commercial) cartridge.

2. The case of 40 S&W PX4 Pistol

Beretta PX4 series pistol are (short) recoil-operated firearms using a rotating barrel locking (breech) system, single/double action and exposed hammer. Figure 1 illustrates the full size pistol in caliber 40 S&W which is the version we are examining.

Figure 1. Beretta Mod. PX4, Full Size, 40 S&W.

Figure 2 points out the main parts of the pistol: the barrel, the central block, the slide, the recoil spring and spring guide assembly, the frame and the magazine. When the pistol is fired the recoil impulse pushes the slide and barrel backwards. The barrel and slide remain locked and recoil together for a short distance until the powder gas pressure has dropped to a safe limit. The PX4 pistol uses a locked breech in which the barrel rotates on recoil to unlock itself from the slide. The rotating motion of the barrel is controlled by the top-projecting stud of the central block, which follows the cam track in the barrel lug. When the barrel has turned about 30 degrees, the barrel locking lugs clear the locking recesses on the slide. The barrel then stops against the central block while the slide continues its backward travel extracting and ejecting the fired cartridge case through the ejection port, rotating the hammer and activating the recoil spring. Pushed by the recoil spring, the slide then moves forward feeding the next cartridge from the magazine into the chamber, causing barrel rotation through cam action against the central block tooth, and barrel-to-slide locking.

Figure 2. PX4 pistol partially disassembled.

3. Pistol FE Modeling

The pistol assembly consists of 67 parts and the weight is 810 g approximately (40 S&W, pistol unloaded, empty magazine). The only parts that the FE model has not taken into account are the back-strap on the grip and the sights. Figures 3-5 show the Abaqus/CAE model of the pistol-cartridge assembly for analyzing the complete firing cycle: on closer inspection you note a cartridge in the magazine in order to simulate the feeding operation actuated by the operating system of the pistol when the slide comes back into the battery.

Figure 3. CAE model of the pistol with hammer cocked.

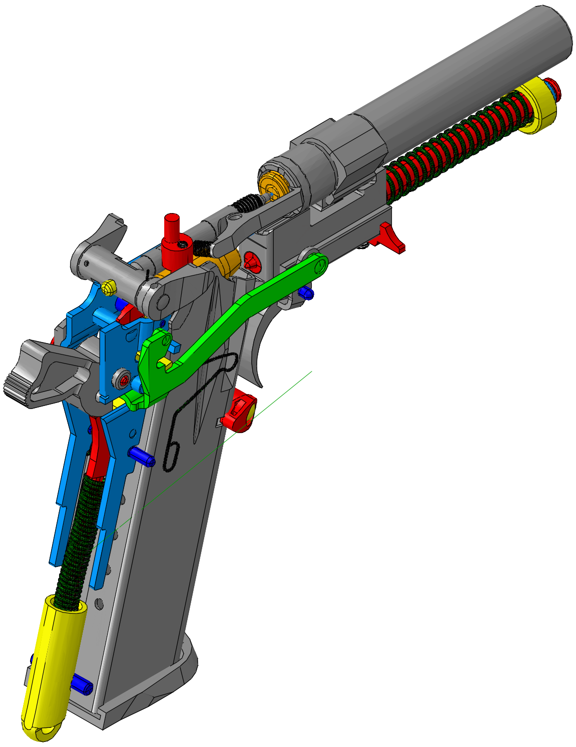

Figure 4. Interior of the pistol CAE model.

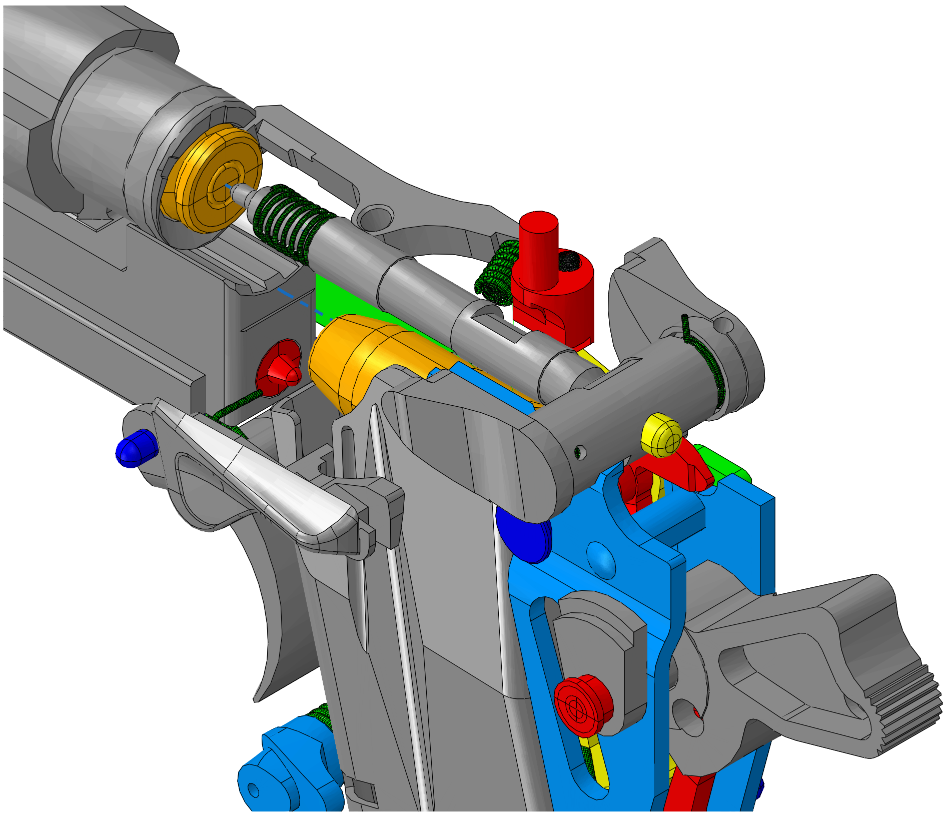

Figure 5. Detail of the pistol CAE model.

The pistol configuration with hammer in the firing position (cocked hammer) is assumed as the initial configuration. It is the configuration achieved when the hammer rotates by pulling the trigger during the cocking up to the point at which the hammer is free from the sear which is controlled by means of the trigger mechanism. The high speed dynamic event of the firing cycle begins with the sudden release of the energy stored by the hammer spring during the cocking. The hammer returns rapidly to its initial position, strikes the firing pin which at the end of its travel impacts the primer and activates the combustion of the powder charge in the cartridge. The picture points out the detail level reached in the FE modeling of each component. Careful examination of each component in any constructive detail has been made with the aim of minimizing the change in the geometry. Any change is designed to simplify the faces of the components whose edges go below a tenth of a millimeter. The principle of simplifying within respect of the dimension tolerances remains constant. It is a way of operatingwhich is consistent with the fact that durability and reliability of a firearm make it necessary to have very small play between reciprocating and/or rotating parts. That is a concern which accompanies the design of a firearm throughout over the entire cycle of development from the first mechanism sketches to the physical prototypes which leads to critical dimensions with very narrow tolerances of up to a few hundredths of millimeter. It is evident that a realistic simulation of the pistol dynamics when you fire depends on the rigorous respect of such dimensions. The pistol components are made of several materials, processes (machining, sheet metal forming, investment casting, MIM, sintering) and heat treatments. Mainly metals and polymers, fiber reinforced, defined by the classic elastoplastic model, von Mises yield criterion and kinematic (metals) or isotropic (fiber reinforced polymers) hardening. The mechanical properties for the steels are derived from uniaxial tensile tests conducted on samples subjected to the specific heat treatments. In alternative, the Metal Handbook is the reference text used to define the material data in a well defined condition. For polymers the mechanical property values are obtained from an extensive series of experimental tests where samples with different matrixes, fiber glass reinforcements and moisture grades have been subjected to both monotonic, tensile and compressive and cyclic uniaxial tests. Table 1 collects the FE discretization strategy used for the main parts: element, seeding, number of nodes/elements etc.

Table 1. Mesh parameters.

Component	Weight	Element Type	Seeding	Number of Nodes	Number of Element	Smallest Stable Time Increment
Barrel	91 g	C3D10M	1.70 mm	35130	20884	4.52E-09 s
Slide	315 g	C3D10M	2.0 mm	112939	68197	2.87E-09 s
Central Block	41 g	C3D10M	2.0 mm	14279	8214	4.47E-09 s
Frame	123 g	C3D10M	2.20 mm	171346	103873	1.90E-09 s
Firing Pin	8 g	C3D10M	1.20 mm	8746	5331	5.14E-09 s
Hammer	21 g	C3D10M	1.50 mm	14724	8619	2.62E-09 s
Magazine	71 g	C3D10M	3.0 mm	24157	11925	4.51E-09 s
Recoil Spring	7 g	C3D8R	0.50 mm	71873	56064	3.13E-09 s
…						

Rounding off the edge by means of very small radius in the order of a few tenths of a millimeter is a very common circumstance in modeling firearms. It is mandatory to avoid the discretization with C3D10M elements depicted in Figure 6, where one element edge only, which joins the two endpoints of the fillet, appears. Abaqus/Explicit solver assigns an high gradient of plastic strain to this FE distribution since the first increments of the analysis in absence of any acting load.

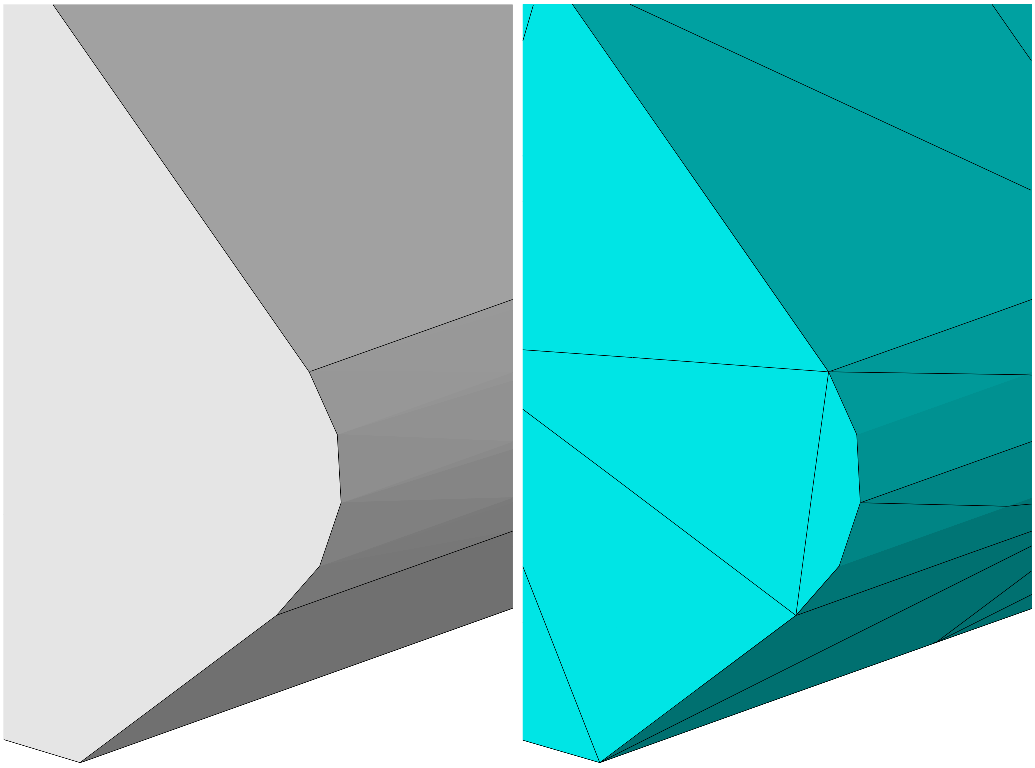

Figure 6. Mesh leading to "false" plastic strains.

Very accurate must be the FE discretization of complex mating surfaces of components with relative movement between them when at fire. In some cases they can be complex in a such a way that using C3D10M elements and defining an adequate mesh seeding is not sufficient to avoid the appearance of nodes not lying on the surface and which, due to the small play, lead to the numerical jam of the pistol. Connectors (TRANSLATOR, CYLINDRICAL) are useful tools to ensure the right execution of operations by forcing the relative movement between components. However, their use is limited when the motion develops along a non-standard path (i.e. cam groove-cam pin interaction) or when the contact between sliding components localizedue to vibrations (i.e.: slide frame interaction). In these cases the knowledge of how the interaction evolves through the distribution of some contact quantities (CAREA, CFORCE, CPRESS, CSTRESS) is one of the major contributions that numerical analysis gives to the comprehension of firearm behavior both from the reliability and durability point of view.

4. Cartridge FE Modeling

In order to simulate the operating cycle of a semiautomatic pistol actuated by firing, the modeling of a specific cartridge is required both from the geometric point of view and from the points of view of the materials involved and the loading exerted by gases. The ammunition taken into consideration here is a cartridge in caliber 40 S&W, bullet weight of 155 grs, which is idealized within Abaqus/CAE pistol model as illustrated in Figure 7.

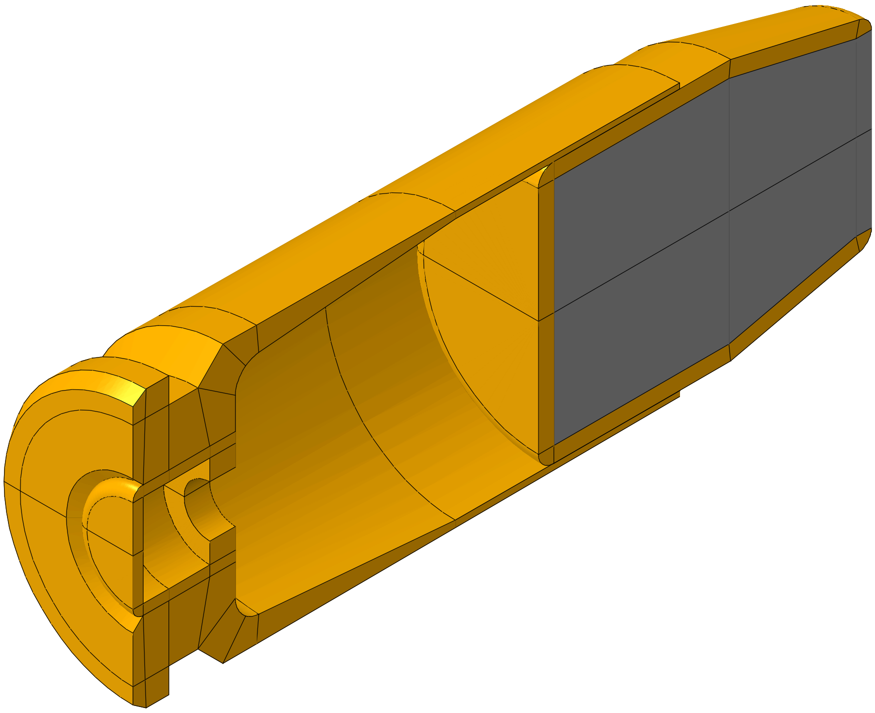

Figure 7. 40 S&W 155 grs Cartridge.

The external profiles of cartridge case and bullet are comply with European (CIP) and American (SAAMI) standards. Their internal profiles have been reproduced by sectioning a physical cartridge and measuring dimensions and geometry using an optical comparatorto magnify their interior.It is worth noting the detail of the primer metal cup in the base portion of the case: its definition is necessary to stop the travel of the firing pin once it is launched by the hammer striking at the beginning of the firing cycle. The crushing action of the firing pin on the metal cup is one of the most severe loading conditions to which the firing pin is subjected and this accounts for my inserting it into the FE model. Moreover, the impact force transmitted between the firing pin tip and the head of the cartridge casewhich is obtained from the analysis will be directly compared with the experimental measuring as an additional parameter in order to validate the firing mechanism within the FE pistol model. As usual the firing mechanism of firearms is studied through a specially designed FE model whose only purpose is to cover the firing pin design and the firing energy required (run down test). However the added value of the FE model of a complete firearm, including the firing mechanism, is evident when you consider the possibility it offers to assess numerically the risk of firing in the case of its being dropped from a certain height (drop test). All the above-mentions are topics that affect the safety and reliability of the man-firearm-ammunition system, which are of great interest within international standards, and to which simulation could give an innovative contribution. After firing pin indentation on the primer, the burning propellant begins with gases acting on the base of the bullet and on the inner wall of the cartridge case. In short a thermodynamic system where one of the boundaries, the base of the projectile, rapidly moves down the tube leaving the cartridge case muzzle, overcoming the opposing action due to the barrel forcing cone, which is essential to attain a well-established gas pressure regime, and finally engraving the rifling which imparts a spin to the bullet around its long axis. These are the subjects of interior ballistics the study of which would require a complete fluid-structure interaction approach. Here we are interested in analyzing just the firearm dynamics and the combustion of powder can be modeled by applying the pulse pressure measured in the powder chamber by a pressure transducer. Figure 8 shows the pressure history considered in the present work: it is that of the individual cartridge having the highest peak pressure within a sample of ten rounds.

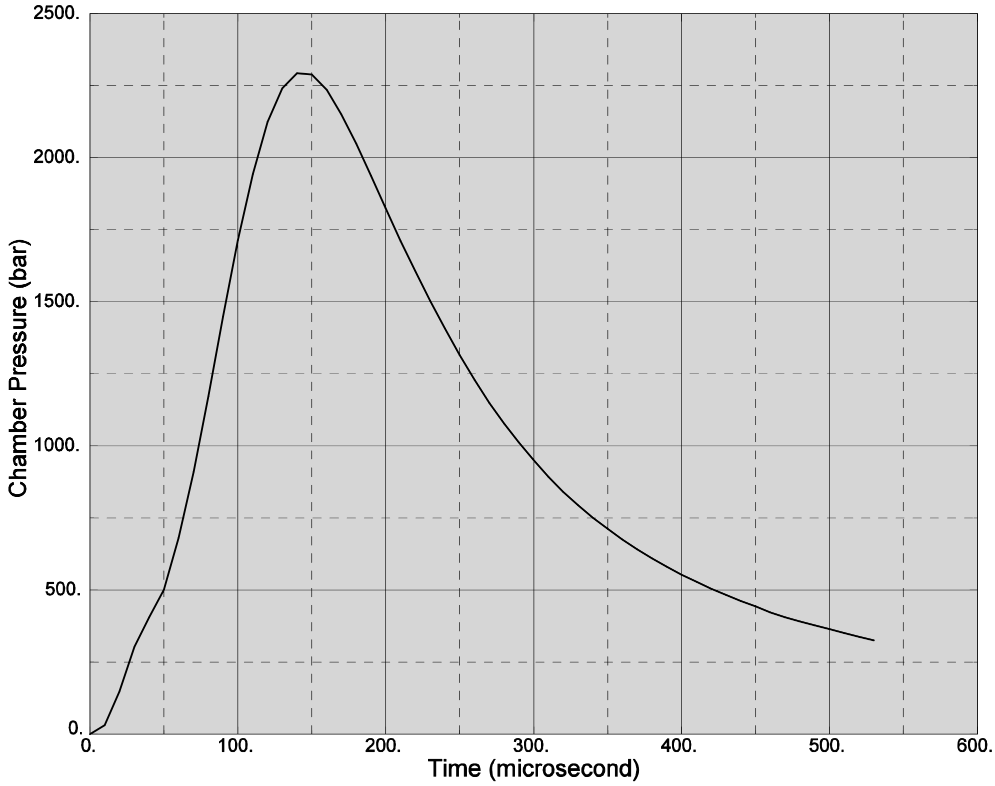

Figure 8. Graph of chamber pressure versus time.

The measuring of pressure has been conducted in the powder chamber (drilled cartridge case) by means of electromechanical pressure transducer. According to CIP standards, reference standard pressure barrels for pistols and revolvers has a length of 150 mm. The measuring device has been positioned at a distance of 10.50 mm from the breech face.

Table 2. Cartridge fundamental data (Proof House).

Barrel pressure length	150	mm
Time to bullet exit	530	μs
Peak pressure @10.50 mm from breech face	2293	Bar
Bullet velocity @1.0 m from the barrel muzzle	417.5	m/s
Impulse at time to bullet exit	4.20	N s

5. Preloading of Set of Springs

The intended assembly of the PX4 pistol takes into account 14 springs of two different types: the helical cylindrical compressive spring (e.g. hammer spring) and the torsion spring (e.g. trigger spring). They play a fundamental role within the operating cycle of the pistol and their idealization into the FE model of pistol deserves great attention. Initially modeling springs were made by using connectors. However, this approach showed some limits in describing torsion springs when the interest is in capturing the force transmitted through the legs on the involved component in the presence of finite-sliding contact. For this reason a true FE modeling of springs has been preferred, above all for its ability to capture the stress regimes to which they are subjected by virtue of pulse loading due to firing. The first step was to try an FE modeling of the wire only by using beam elements. In some cases this approach turned out to be weak in capturing the real contacts with contiguous components and the final choice has been to model springs by using C3D8R solid elements. It is a demanding choice because it entails the development and the solution of a specific Abaqus/CAE model designed to preload each spring, where very tricky numerical questions like contact and buckling arise. For instance, the case of hammer spring preloading is discussed. It is a helical cylindrical compression spring of round wire, with closed and ground ends, a ratio between the free lengthand the mean diameter greater than ten. Figure 9 indicates the pistol components which interact with the hammer spring: they are the hammer, the hammer spring guide and the hammer spring cap.

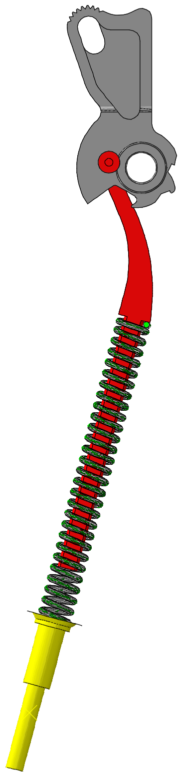

Figure 9. CAE model for the hammer spring preloading study.

The hammer spring must be preloaded to permit its insertion inside the pistol with the hammer into the full-cocked position, which is the initial configuration assumed for the analysis of the firing cycle. Contact pairs are defined between the lower spring end and cap; between the upper spring end and the rod; between the coils with themselves (surface-to-surface, finite sliding, friction coefficient of 0.10, contact control with automatic tolerance of 0.0001). The problem history has been divided into two static stress analysis steps: in the first the installing of the hammer spring inside the pistol is accomplished by pushing the spring cap upwards. In the second step the hammer spring reaches its final configuration by pulling the hammer backward completely into its firing position, driving down the hammer spring rod which in turns compresses the hammer spring. The final ratio between the final deflectionand the free length immediately suggests that an unstable behavior of the spring is likely. In the first step the buckling is avoided by applying some boundary conditions to the nodes along a very narrow strip following the direction of spring axis (the author did not manageto solve in an effective way the finite-sliding contact between the coils and the spring rod by using the static, general procedure: static, riks procedure will be examined). The second step removes the interior boundary conditions on the spring and introduces the contact with the spring rod. The obtained solution indicates that the ALLSD component in the energy balance is under control. Figure 10 shows the stress distribution at the end of the preloading.

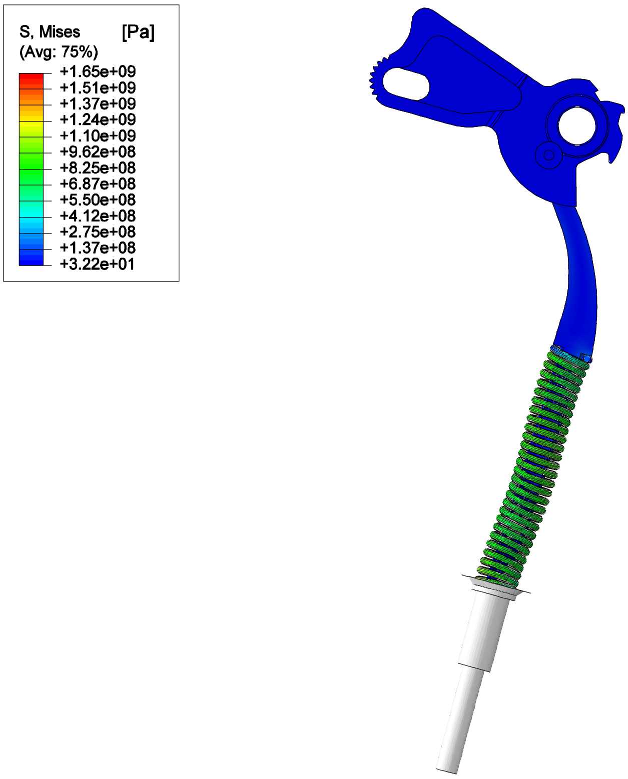

Figure 10. Hammer spring at full cocked position.

The same approach here discussed for the case of the hammer spring has been applied to preload all of the springs involved in the PX4 pistol. Figure 11 shows the Abaqus/CAE model of the set of springs. The deformed parts are then imported into the Abaqus/CAE model of the complete pistol by using the IMPORT option (INITIAL STATE).

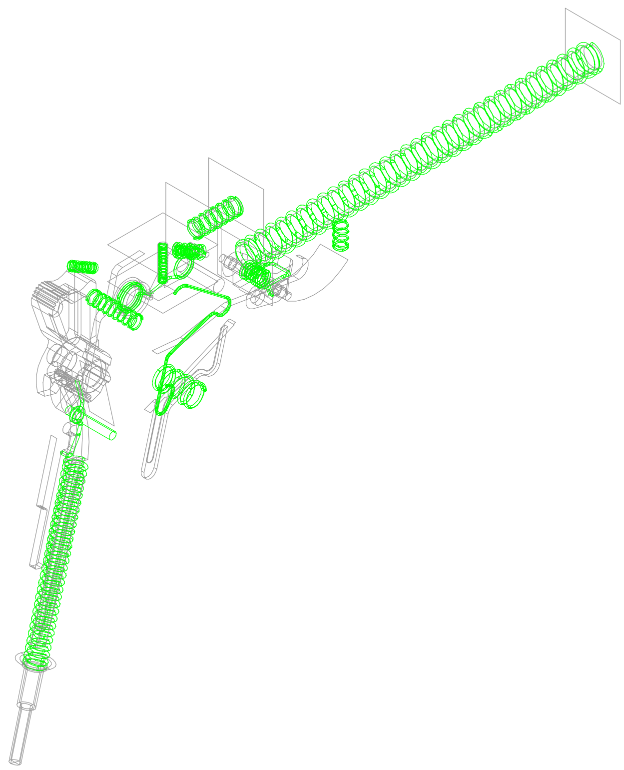

Figure 11. CAE model for the preloading of the set of pistol springs.

6. Shooter-pistol reaction modeling

The operating condition of firing a pistol held by hand is simulated in the model by connecting the pistol grip to the shooter via a BUSHING connection with appropriately defined connector elasticity and connector damping. The shooter, who we assumed is fixed in the space, is idealized as the first node of a connector element. The nodes on the surface which identifies the pistol grip are coupled, using a kinematic coupling constraint, to a reference node located in the center of the hand, which is the second node of the connector element. Figure 12 shows the scheme employed in the present work to enforce a kinematic linkage between the shooter and the pistol.

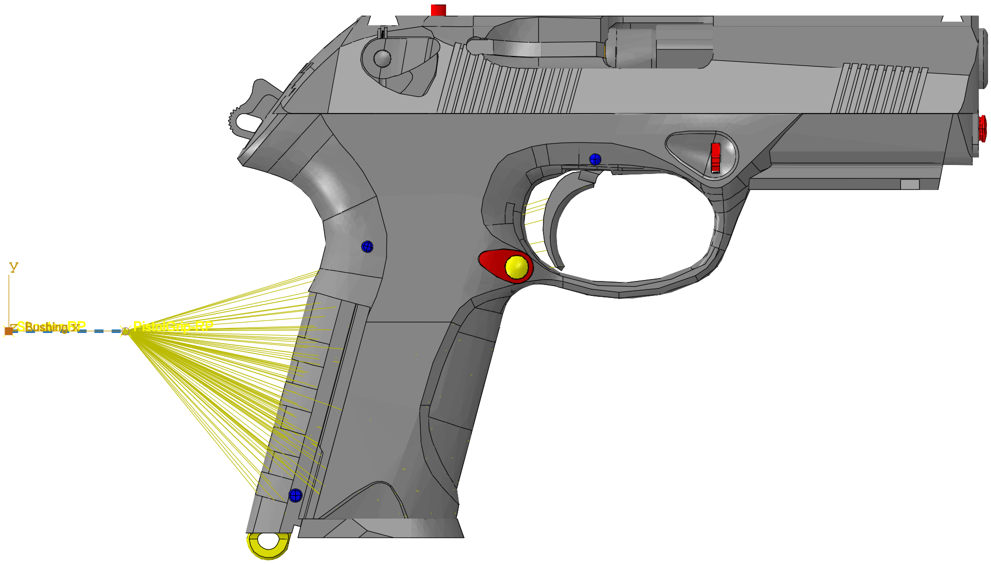

Figure 12. Shooter-pistol BUSHING connection.

Although this is a purely qualitative representation of the real biomechanics involved in the firing, the described constraint allows us to avoid fixing the receiver to the ground, which is a too severe condition from a durability point of view.

7. Solution over the entire cycle of firing

The analysis of the firing cycle, the duration of which is about 60 milliseconds, has been carried out using Abaqus/Explicit. The simulation requires a very large number of increments since the stable time increment (2E-09 s) is much smaller than the total duration of the event. The analysis has been run in double precision. The stability limit has been increased by using mass scaling with a target time increment of 2E-08 s, resulting in a mass increasing by about 1.50 percent only. The model involves a large number of contacting bodies and the general contact is used to define contact interactions. Coulomb friction is assumed for the mechanical behavior, with a friction coefficient of 0.10 for the entire domain. A small amount of friction (Coulomb coefficient of

0.01), simulating a certain degree of lubrication, is applied in the contacts between the barrel chamber and the cartridge case and between the slide and the barrel in proximity of the muzzle. The values used in these analyses are standard values and have been chosen to provide good correlation with the experimental data.The analysis has been divided into three steps: the first step with duration of 8.50 milliseconds describes the hammer falling from the completely cocked position into the decocked position, the launching of the firing pin and the primer cup indentation. The loading is represented by the release of hammer spring internal energy, which has been stored during cocking, caused by the hammer disengagement from the sear. The second step analyzes the condition of free recoil covering the time period from the instant at which the chamber pressure starts to rise until the bullet leaves the barrel muzzle (approximately 500 microseconds). The external loading is given by the chamber pressure-time curve for the specific cartridge here considered. Initially the curve acts inside the powder chamber and on the base of the bullet. With the powder burning progression the bullet moves down the barrel and extends the portion of the barrel bore to which the gas pressure is applied. In order to include this mechanism within the analysis, the time variation of bullet travel has been determined by interior ballistics computations. A user subroutine correlating the pressure-time and the bullet-travel time data permits the automatic updating of the region of gas pressure application on the barrel bore at each analysis increment. While the bullet is accelerated, the thrust exerted by gases on the breech via the base of the cartridge case pushes the slide backwards and takes the barrel with it by means of the locking device. After the bullet leaves the muzzle the action of gases is completely removed from the model: in other words the analysis ignores the effect of the residual pressure on the velocity of the recoiling parts. The third step with a duration of 50 milliseconds considers the sequence of events which take place after the bullet's exit: the unlocking of the barrel from the slide as a result of barrel rotation caused by the action of the central block tooth on the barrel cam groove; the extraction of the spent cartridge case from the barrel; the barrel stoppage against a shoulder of the central block, which determines the first significant stress distribution into the frame; the slide motion up to the end of the recoil stroke, with the ejection of the cartridge case; the striking of the slide spring box against the front portion of the central block and its reversed motion under the influence of the recoil spring; the return motion of the slide, which grasps a fresh cartridge from the magazine and pushes it into the barrel chamber, and the locking of the barrel to the slide by its counter-rotation. The final model has a size of approximately 3.70M DOF. Figure 13 shows the deformed configuration of the pistol at different stages of the firing cycle when the extraction, the ejection, the slide striking against the central block and the feeding occur. The calculation leads to the functional diagram of Figure 14 showing how the velocity of the moving parts (i.e. the barrel and the slide) with respect to the frame vary with time for the complete cycle. The barrel strikes the central block at 7.0 m/s after 1.50 milliseconds from the moment the gas pressure starts to rise in the powder chamber. The central block is struck by the slide after 10 milliseconds with a relative velocity of 5.0 m/s. The simulation captures remarkably well the actual velocity of the recoiling parts obtained by analyzing the images taken with a high-speed camera. The analysis also covers the important point which is the determination of the forces exchanged between the various parts. The time variation of the loads applied on the slide breech face via the base of the cartridge case and on the locking surfaces are shown in Figure 15.

Figure 13. Deformed configurations at various times of the firing cycle.

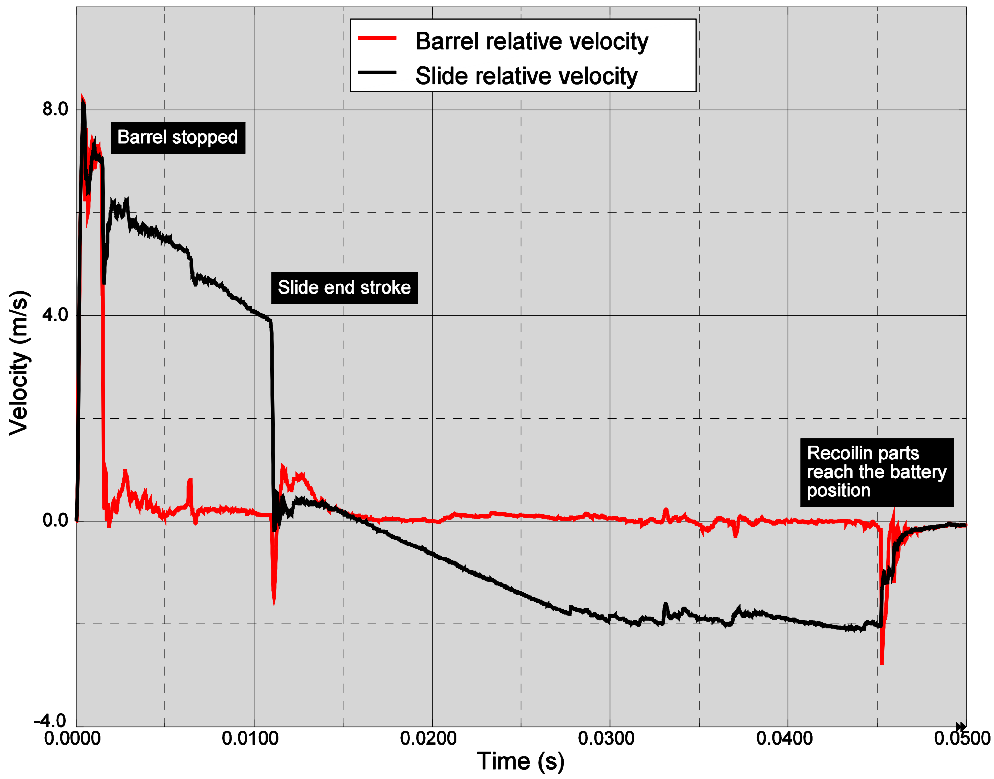

Figure 14. Velocity history of the recoiling parts with respect to the frame.

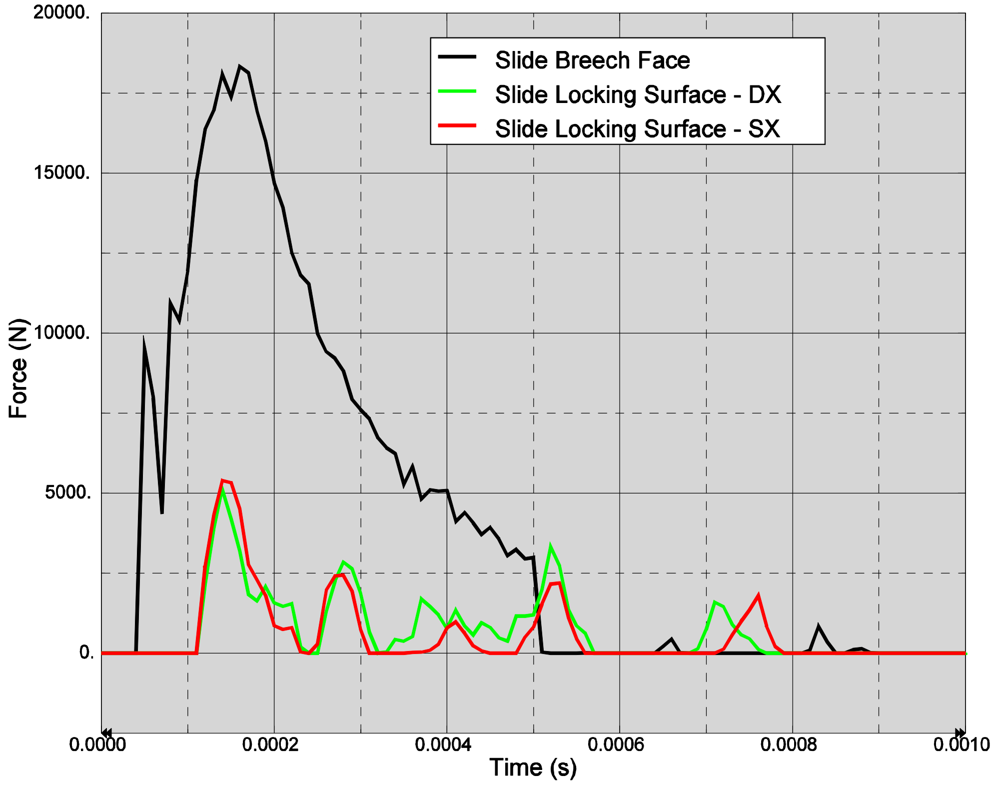

Figure 15. Breech face and locking device force histories for the first millisecond.

8. Final Remarks

The FE analysis of a single entire firing cycle for a semiautomatic pistol has been discussed. The main numerical aspects are: the modeling of the complete pistol; the static preloading of a number of components, typically springs, which involves quite difficult numerical questions (finite-sliding contact, buckling); the solution over the entire operating cycle, from the hammer falling to the feeding of a fresh cartridge. The satisfactory correlation between results and measurements in terms of velocity of the recoiling parts indicates as reasonable the simplifications which have been made and which regard: the engraving of the bullet into the rifling, which has been ignored, having modeled the barrel bore as a smooth bore; pressure distribution along the barrel, which is considered uniformly distributed between the breech face and the base of the bullet at any generic instant of time; the gas pressure loading, once the bullet has left the muzzle, has not been taken into consideration; heating, which is neglected because the work considers one single shot;

friction, which has been modeled with the basic Coulomb approach, and the reaction of the shooter on firing, described not from a biomechanical point of view but quite simply by means of a connector. Starting from the load histories based on the analysis which was carried out over the whole firing cycle, it is now possible to estimate the fatigue life of the most stressed components (i.e. springs, locking device, firing device, extracting device, etc.) which are repeatedly subjected to pulse loading over time (shakedown, ratcheting, low-cycle fatigue).

9. References

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