

Programmable Firing System of Pyrotechnic Shells

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Abstract

The project is intended to propose a programmable firing system of pyrotechnic shells. The introductory chapter provides a review of currently used methods of launching and their drawbacks. I have worked out in detail the firing system using ProEngineer software. It is a system of eight rotating barrels and chambers and an autonomous control unit.

Key words: Automatic Firing System. Micro Memory Card. Programmable Logic Controller. ProEngineer. Barrels. Firing System.

Introduction

My project is intended to design a programmable firing system of pyrotechnic shells. In particular, I focused my attention on consumer pyrotechnics used in fireworks displays as well as those used for military purposes, primarily for illuminating terrain. My endeavour was directed to devise a mechanism ready to fire shells immediately after being loaded and programmed. I intended to come up with a lightweight device that would be safe and easy to operate. Currently employed firing systems, excluding Carousel automatic ammunition loader systems, consist of a great number of mortars, fuses, detonating fuses, time delay fuses, binders, control units which make their installation and preparation for firing a lengthy process. Therefore, I decided to devise a mechanism that can be easily transported and be ready for firing within minutes. The device presented is capable of automatic loading and firing as programmed, and ejecting fallout, empty cases or unexploded shells into a container.

1. Current Techniques Employed in Firing Pyrotechnic Shells

Nowadays, the mortar system is one of the widely employed consumer mechanism to fire pyrotechnic shells. Firing is controlled by a control unit which sends an impulse to an electric igniter. In addition, there are carousel – based systems used only in Disneylands. Carousel – based mechanisms are less common and completely different from the prevalent systems. Carousel – based mechanisms use compressed air and special electric igniters. As they are not economical, I will not deal with them any longer.

1.1 Types of pyrotechnic shells

Firework bombs and mines are widely used in consumer pyrotechnics. Pyrotechnic bombs can be of cylindrical or round shape and they can also be combined with mines. Parachute flares are appropriate to military purposes.

Pyrotechnic bombs (Fig. 1) are made up of stars, a lift charge and a time delay fuse. They can be of spherical or cylindrical shapes. Dimensions are given in inches (1 inch = 2,54 cm), and they are usually graded such as 2“, 2,5“, 3“, 4“, 5“, 6“, 8“, 10“, 12“, 18“, etc.

Similarly, pyrotechnic mines (Fig. 2) also contain stars, however they explode directly out of the launch tube. Pyrotechnic mines are sometimes combined with bombs.

Parachute flares (Fig. 3) have a structure similar to bombs, however they contain an illuminating compound instead of stars and a parachute to slow descent.

Granulated black powder burst by a fuse is utilized to lift shells out of mortars. Upon lifting, a time delay fuse gets ignited and initiates burst charge upon reaching the required altitude.

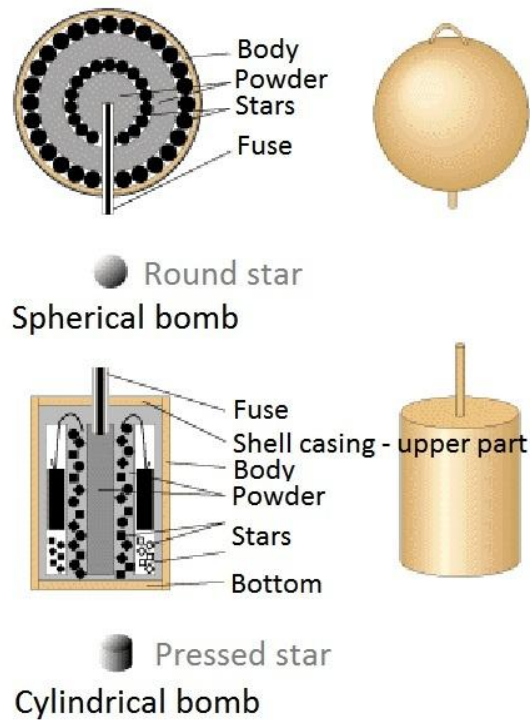


Fig. 1 Pyrotechnic shells

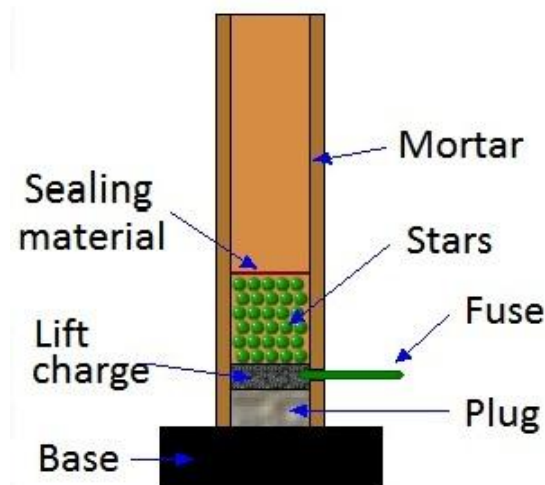


Fig. 2 Pyrotechnic mine

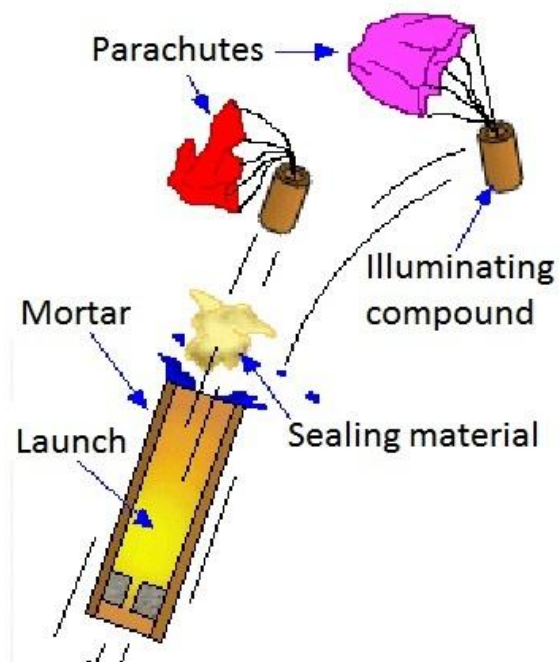


Fig. 3 – Illuminating flare

1.2 Mortars

Mortars (Fig. 4) are employed to launch shells of various sizes. Mortars can be made of paper, steel, plastic or fiberglass. Fireworks mortars are assembled into wooden or steel racks.



Fig. 4 – Mortars

1.3 Firing systems

Autonomous firing systems, containing a programmable unit controlling individual shots as programmed or shots synchronized to music are used to fire fireworks. Mutual communication is provided by radio signals, certain models are fitted with a floating code. Figure 5 shows the Firemaster device by Parente company.



Fig. 5 Firemaster

1.4 Accessories to launch fireworks

Electric igniters, fuses, incendiary cords, time delay fuses (e.g. Piroclock) and electric cables are utilized to launch shells, and they can all be used once.

1.5 Preparing for and controlling shell launching

We will place lift charge tubes into mortars, lead fuses and connect them to the time delay fuses. All fuses belonging to one subset of mortars will gradually be connected to the time delay fuse. Electric igniter, connected to the time delay fuse, will be connected together with the igniters of the entire set to the sequencer that is in charge of controlling the launch of the respective entire set of mortars. All sequencers of the respective block will be connected to the so called „child“ of the Firemaster. All „children“ communicate with their „mother“ by means of the radio signal with a floating code (Fig. 6).

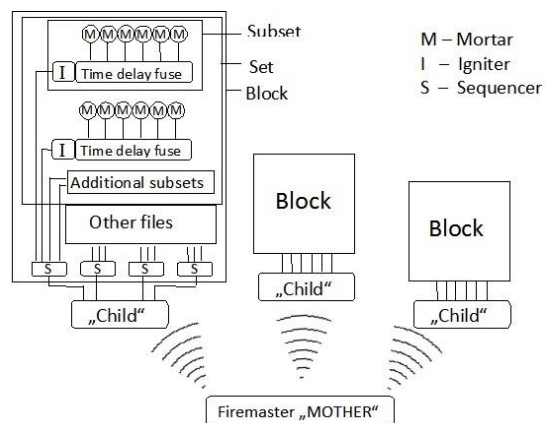


Fig. 6 Connection diagram

Then, firing sequence is pre-programmed and the program imported with a cable to the control unit. Single shots can be fired manually by means of a wireless system from the main control unit. This mechanism provides a precise timing of firing and almost an unlimited number of shells to be fired at an arbitrary frequency of firing, but transport takes a lot of effort (it is necessary to carry a great number of mortars, racks and other material), assembly and preparation are lengthy (may take several hours) and audience must be kept off the shooting site during assembly and setting off fireworks.

2. Design of the Firing System of Pyrotechnic Shells

The system comprises eight rotating barrels and chambers, a magazine, a container for fallout, empty cases and unexploded ammunition, a feeding device and an ejector. I used ProEngineer software to design the AFS – 3 system (Automatic Firing System).

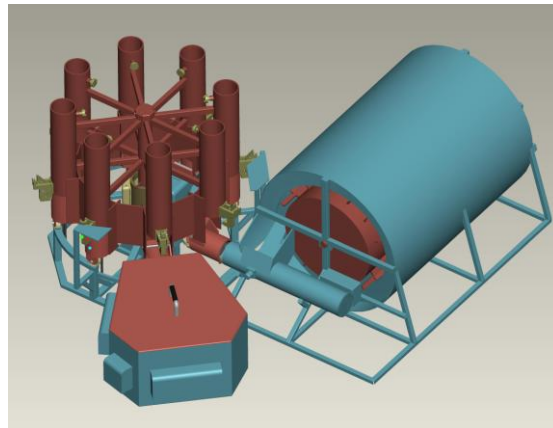


Fig. 7 AFS-3 – View

The system comprises a set of barrels and a block of contacts rotating around its own axis mounted on a base. A magazine together with a feeding device and a fallout container are attached to the system laterally. There are eight chambers which can be tilted by 90°, pressure sensors and barrel locks attached to the set of barrels. The base is fitted with a control unit and an ejector. Electric motors drive barrels, a drum and a feeding device piston. Chamber guide wheels allow chambers to be tilted.

The Automatic Firing System is capable of firing up to six shells simultaneously, even during barrel rotation.

2.1 Base

The base (Fig. 8) is welded from rectangular profiles, band steel and a steel tube. The centre is designed to assemble and guide laterally the set of barrels. The base is fitted with rails to guide the chamber guide wheels.

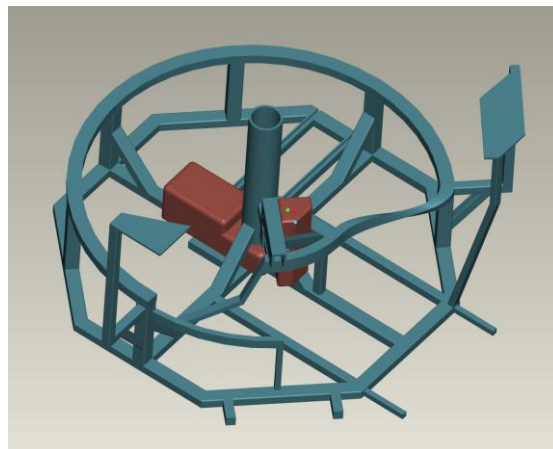


Fig. 8 – Base

The rails serve to tilt the chambers and to support and guide the set of barrels. In addition, they transfer the force generated by firing to the base through the guide wheels. There are two segments attached to the base serving to lock and unlock the chamber locks. The base is equipped with a drive unit propelling the set of barrels. The system is driven by an electric step motor with bevel gear drives. Mesh on the set of barrels is inside the central tube. The step motor provides for the correct range of motion of the set of barrels. An ejector located in the central part of the base is driven by a single reduction worm gear unit. There are fastenings located on the sides of the ejector to fix a magazine and a fallout container. There are guides on the bottom which serve to grip or eject the control unit for the programming purposes. Excluding the guides, the surface of the entire structure is coated with a protective paint. Polished guides must be greased with a lubricant of high viscosity on a regular basis.

2.2 Electric motor

The set of barrels is driven by an electric step motor with bevel gear drives. I have chosen the barrel caliber of 100 mm and the speed of revolutions of the set of barrels of $n_2=4 \text{ min}^{-1}$. I made an analysis in the ProMechanica module and the resulting torque needed to make the set of barrels spin is $M_{k1} = 30,65 \text{ N.m}$. Following the data, I selected a suitable electric motor L31RFD (Fig. 9) manufactured by Danaher Motion company. It is an eight pole step motor using the voltage of 12V. The holding torque is $M_{k1} = 4,8 \text{ N.m}$. The requirements related to the electric motor will vary with any change of barrel calibers and the material employed. The required speed of the set of barrels represents another important aspect.

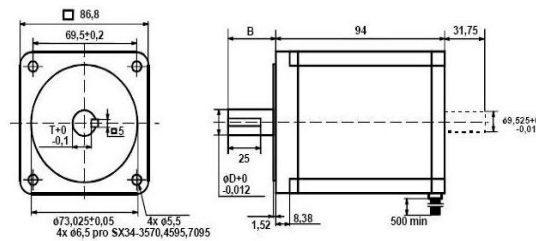


Fig 9 – L31RFD step electric motor

2.3 Gear unit

We will calculate the required parameters using the electric motor specifications and the torque requested. I have selected the gear ratio of $i=10$. We will calculate the main shaft torque:

$$M_{k2} = M_{k1} \cdot i \cdot \eta = 4,8 \cdot 10 \cdot 0,96 = 46,08 \text{ N.m}$$

$\eta = 0,96$ – efficiency of the bevel gear drives

I selected a suitable GKR03-63 (Fig. 10) gear unit manufactured by Lenze company. It is a bevel gear unit having the gear ration of $i=10$ that will transmit the torque of $M_{k2} = 54 \text{ N.m}$.



Fig. 10 - GKR03-63 gear unit

The gear unit is located in the central part of the base so that the motor input shaft is in the horizontal position; the output shaft is in the vertical position going upwards. Upon mounting the set of barrels on the base, the connecting piece located on the central bracket will fit together with the output shaft hollow. Gear unit specifications vary with the barrel caliber changes, material used, electric motor parameters and the requested speed of the set of barrels.

2.4 Set of barrels

The set of barrels contains eight barrels made of steel attached to the structure produced of rectangular profiles and band steel.

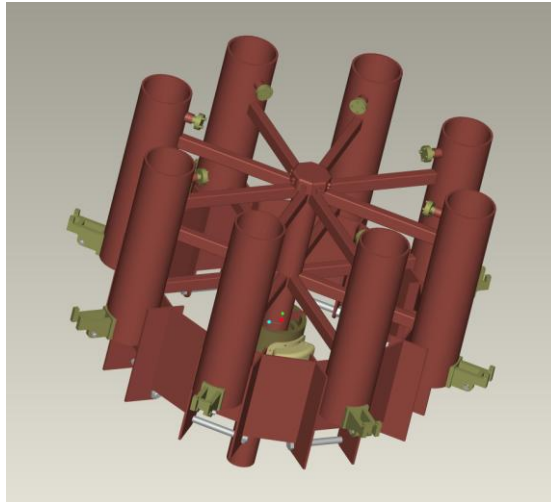


Fig. 11 - Set of barrels

The central part is made up of a closed steel tube and a connecting piece that will fit together with the output drive shaft hollow. There are chamber locks located on all barrels. There are fastenings located on the latter ends of barrels to screw on pressure sensors. A glow control unit is placed on the upper end of the central tube from which cables lead to the pressure sensors, glow plugs and the block of contacts. It is not necessary to mount the set of barrels in bearings as there are low forces generated in fastenings and relatively low revolution speeds are employed. The entire weight of the set of barrels as well as the force generated by firing are transmitted by the chambers through guide wheels to the base. The central tube has solely a centering function. The structure is welded, coated with a protective and heat resistant paint.

2.5 Chamber

A chamber (Fig. 12) is welded from steel tube and band steel. The chamber fastening is made of band steel having an opening to grasp the set of barrels.

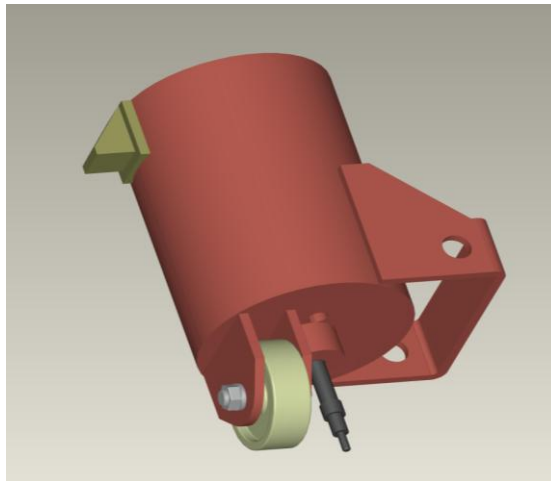


Fig 12 - Chamber – view

A glow plug is screwed in the central part of the chamber bottom, cables from there are led to the glow control unit. A wheel is placed on the roller bearing and screwed to the bracket. The chamber is moving as the wheel moves forward along the rails, thus tracing their shape. The wheel serves to move the chamber and support the set of barrels. There are two openings on the bottom to house and guide the piston of the ejector located inside the chamber. The piston moves up and down. There is a lock tooth on the upper part of the chamber. The chamber is coated with a heat resistant paint.

2.6 Chamber locks

Locks (Fig. 13) are meant to lock chambers to keep them from opening during firing and to keep powder gases from escaping. A lock is made up of a carrier and a lever located on the barrel and a lock tooth located on the chamber. There are two coil – springs with locking function on each lock.

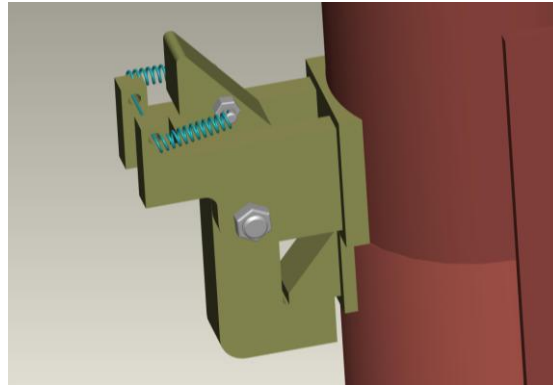


Fig. 13 – A chamber lock

Unlocking (Fig. 14) is a process during which the set of barrels rotate while the segment pushes away the lever, thus unlocking the lock. Coil – springs return the lever to its original position.

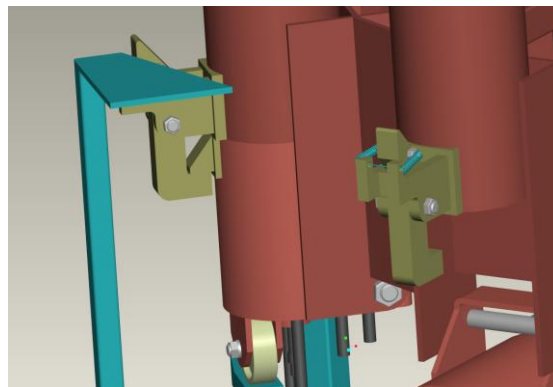


Fig. 14 – Unlocking

Locking (Fig. 15) is a process during which the set of barrels rotate while the segment pushes away the lever which reaches its outermost position, thus keeping the lever from colliding with the chamber. Then, the chamber turns to vertical position, the segment will release the lever and the coil - springs will perform the locking function.

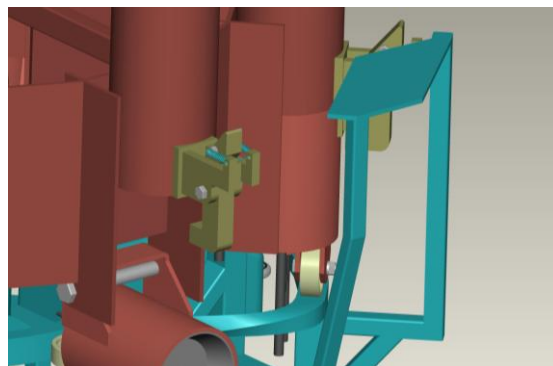


Fig. 15 – Locking

2.7 Pressure sensor

A pressure sensor (Fig. 16) makes the system register firing. It contains a body which is screwed into the fastening on the barrel, sealing and cover. These components are screwed together with four screws. A cable is connected to one of the screws and led to the glow control unit.

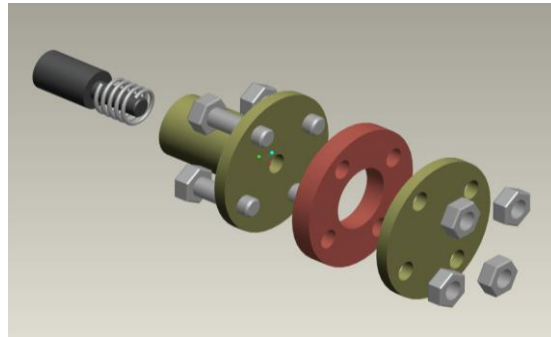


Fig. 16 – Pressure sensor

There is a small piston inside the pressure sensor. Upon firing, the piston is pushed back by escaping powder gases and its overlapping end touches the cover. Then, a signal is sent to the control unit. Upon firing, the control unit makes a request to stop glowing. Upon lessening the pressure, the coil – spring pushes the small piston to its original position. It is not necessary to utilize too strong coil-springs as the sensor is sealed and the air within the sensor serves as air suspension counteracting the powder gas forces. The small piston must be greased with a high viscosity lubricant that can withstand very high temperatures. The body is coated with a heat resistant paint.

2.8 Glow plug

I made use of a common glow plug (Fig. 17) used in diesel engines. The plug gets 12V input which initiates the granulated black powder within 1,2 seconds since starting glowing. The glow plug increases the temperature of the lift charge until the critical point is reached and detonation occurs. Even though delayed firing is considered a drawback, it can be corrected by time sequence programming of single shots. It is an advantage that glow plugs can be used repeatedly and no other material is required.

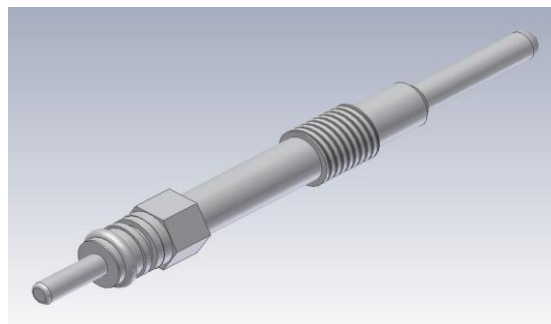


Fig. 17 – Glow plug

2.9 Block of contacts

The block of contacts (Fig. 18) serves to transmit signals from the stationary unit to the rotating unit. The block of contacts is located on the central bracket of the base. It is made up of a central part made of hard plastic. The central part together with a steel mat are mounted on the base (Fig. 19). Steel and plastic rings are alternately slipped over the central part. The former act as a contact on which contact blades are moving, the latter function as insulation between them. There are hollows under the rings to lay cables from individual contacts to the mat opening from which they are led to the control unit. The block of contacts also contains a casing. Upon mounting, the casing is secured with a safety ring and two screws. The block casing can freely revolve around its own axis.

A carrier, blades and cables leading through the cover opening to the glow control unit are attached to the casing. There is a cover placed over the contacts and screwed to the casing. There are two segments located on the central part of the set of barrels that must be positioned into two hollows on the upper end of the casing. The segments transmit rotational motion to the casing with the contacts. The central part, insulation rings, safety ring, block casing, blade carrier and contact cover are produced of hard plastic. Contact rings and blades are made of sheet steel. No components must be lubricated, excluding the casing bottom getting in contact with the steel mat. In addition, no surface coat is needed as the entire block is sealed with plastic elements.

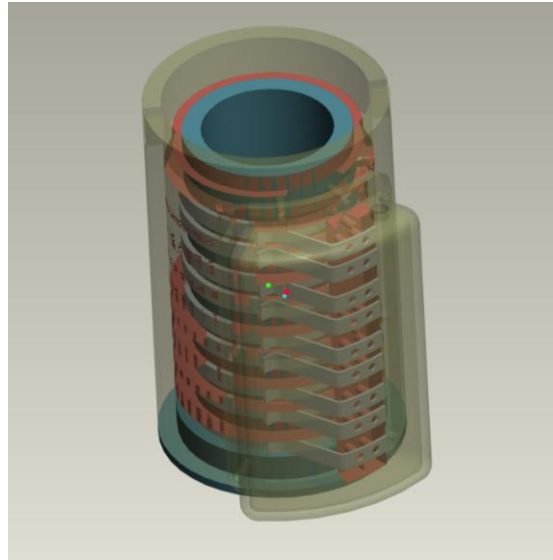


Fig. 18 – Block of contacts

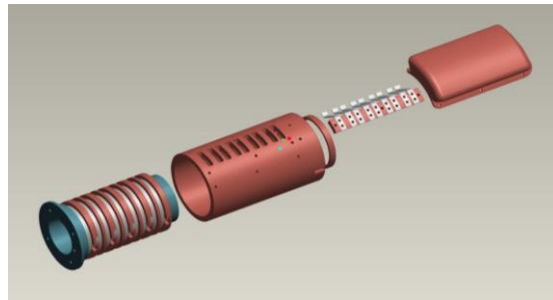


Fig. 19 – Block of contacts – components

2.10 Magazine

Magazine (Fig. 20) is a welded structure made of rectangular profiles containing an external drum made of thick sheet steel. There is a helix fixed internally and its purpose is to guide shells in the magazine. There is an internal drum (Fig. 21) with longitudinal framing mounted on internal bearings. The internal drum revolves around its own axis. Two brackets are used to fasten the magazine to the base. On the front piece, a body of the feeding mechanism is fixed. On the rear part, the drive unit and loading mechanism are mounted. Electric motor with the single reduction worm gear unit provides the required drive. An optical gate is to ensure the correct range of motion of the internal drum. The magazine is refilled from the rear side. Upon feeding a shell into the loading area, we will press the switch, the internal drum will turn by 24° and will keep feeding the magazine with shells until it is full. Next, the control unit will send a loading signal. Then, the internal drum will turn by 24° while ejecting a shell that will slip down to the loading device area and the feeding device will insert the shell into the chamber. The surfaces of the external drum and structure are coated with the protective paint.

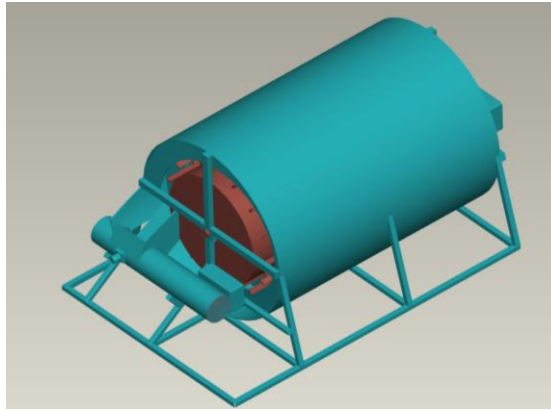


Fig. 20 – Magazine

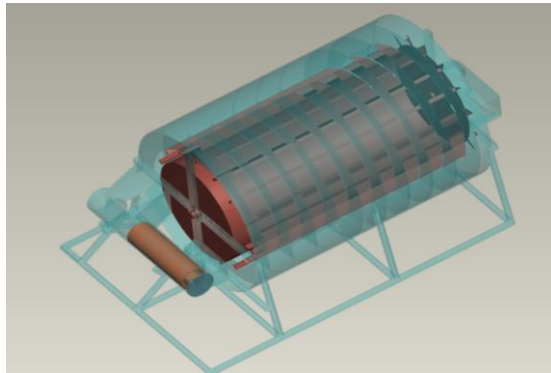


Fig. 21 – Magazine – View

2.11 Feeding device

Feeding device (Fig. 22) is meant to feed a shell from the loading device area to the chamber. The feeding device is made up of a body made of a steel tube with a movable piston, a gear unit, and a driving unit. Electric motor with a single reduction worm unit makes the feeding device function. There are end switches located on the piston trajectory starting and ending points to ensure its correct range of motion.

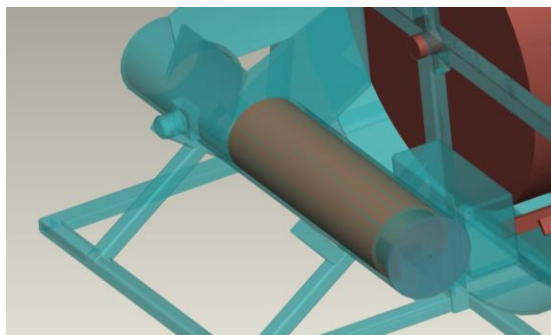


Fig. 22 – Feeding device

Torque is transmitted from the shaft arrangement of the gear wheel to the roller chain attached to the piston. There are gear wheels fixed inside the shafts. Gear wheels are linked together with a chain (Fig. 23) fastened to the piston. Upon receiving a request to start loading, the electric motor will make the wheels in mesh start rolling. Upon rolling, the chain will push the piston to the front. As soon as the piston reaches the end of its stroke, it will return to its original position. There is an optical sensor mounted on the feeding device body indicating whether there are any shells in the loading device area. For the smooth operation of the piston, it is necessary to grease the piston with a high viscosity lubricant. The surface is coated with protective paint.

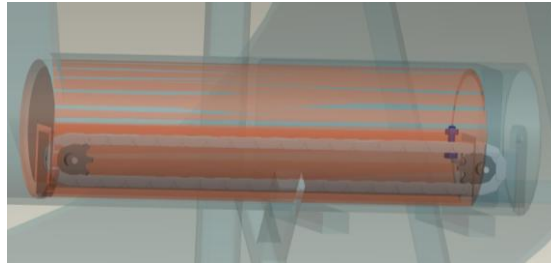


Fig. 23 – Feeding device in detail

2.12 Ejector

The function of an ejector (Fig. 24) is to throw out empty cases, fallout or unfired cartridges. The ejector is attached to the base. There are two gear wheels clamped inside the ejector connected with a roller chain. Electric motor with a single reduction worm unit makes the ejector function. There are end switches located on the trajectory starting and ending points to ensure the correct range of motion. In principle, the drive of the ejector is similar to that of the feeding device. There is a runner attached to the chain which is being pressed by the chain and meshes the ejector piston segments, thus making the piston reach its extreme position (Fig. 25). Following ejecting and turning to the position in front of the loading device, the piston is pushed to its original position by the following shell. Empty cases, fallout or unfired cartridges are thrown into the fallout container. Gear wheels, chain and piston guide units must be greased with a high viscosity lubricant. Surface finish is not needed.



Fig. 24 – Ejector

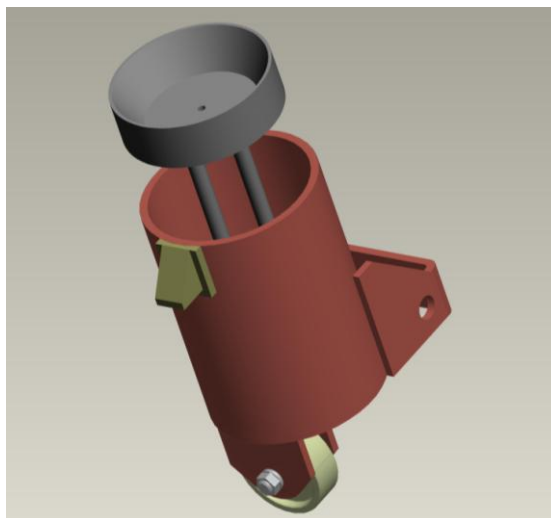


Fig. 25 – Piston of the ejector

2.13 Fallout container

The fallout container (Fig. 26) serves to store empty cases, fallout or unfired cartridges. It is a welded structure made of thick sheet steel which is attached with two brackets to the base. Any fallout is carried to the container through an opening on the front side. A cover fastened in four points occupies the uppermost position of the fallout container.

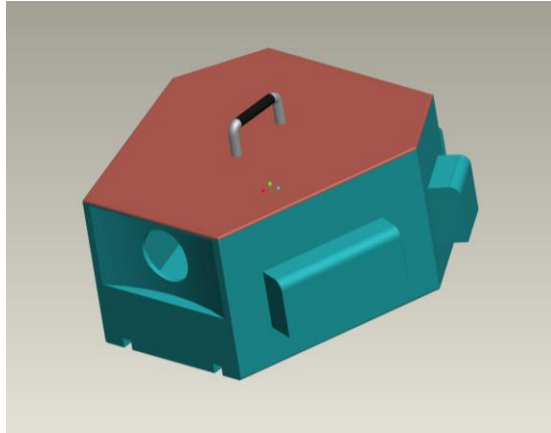


Fig. 26 – Fallout container

There are openings on the sides and their function is to lead out powder gases in case of potential delayed detonation. For safety purposes, the opening covers lead the gases down to the ground. The container must be dimensioned so that multiple and simultaneous firing of shells does not damage or open the upper cover. The container has a protective coating both on the inside and outside.

2.14 Control unit

The main control unit (Fig. 27) is positioned on the guide rails on the bottom of the base.

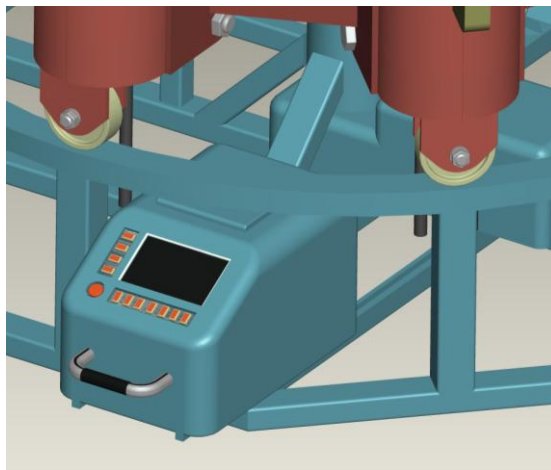


Fig. 27 – Main control unit

The main control unit comprises a body with all the control elements. The main control unit is cable-connected with the drive unit of the set of barrels, magazine, feeding device, ejector optic sensor and the glow control unit through the block of contacts (Fig 28). The glow control unit is positioned on the upper part of the set of barrels and serves to control the glow plugs. The main control unit receives signals from the pressure sensor and requests the glow start and glow end. Firing is initiated by a remote control with a floating code. In case several firing systems are employed, they are not coupled and each firing system uses a control unit of its own. Synchronized firing occurs if receivers of all systems work with an identical floating code and are simultaneously commanded to start firing by the main remote controller. Potential differences in launch start or sequence of firing must be taken into consideration in the course of programming the control units.

An unlimited number of systems can be used simultaneously. The core of the main control unit is the Programmable Logic Controller (PLC). The power source can be a battery, generator or direct connection as the system is fitted with a transformer.

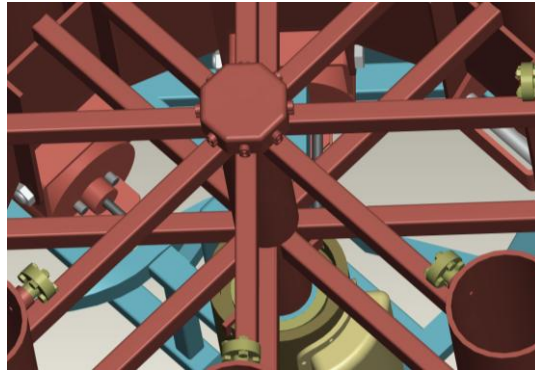


Fig. 28 – Glow control unit

2.15 Programmable Logic Controller

The Programmable Logic Controller (PLC) is a computer of relatively small dimensions used to make processes automatic in real time. Its most frequent applications include controlling machines or production lines. Cyclic run is a typical feature of programmable logic controllers. Unlike general – purpose computers, PLC peripheral devices are directly adapted and linked to control technological processes. Most of the peripheral devices are digital inputs/outputs as well as analogue inputs/outputs serving to process continuous (analogue) signals. Additional modules of peripheral devices which can be connected to PLC are known as function modules (e.g. positioning module, communication module, communication processors to collect and transmit data, etc.). Designs and applications of function modules vary with particular tasks assigned and manufacturers. SIEMENS company presenting SIMATIC Programmable Logic Controllers for sale ranks among the leading manufacturers.



Fig. 29 – SIMATIC S7-300 Programmable Logic Controllers

STEP 7 software is employed to program SIMATIC logic controllers (Fig. 29). Micro Memory Card (MMC) is used to import the program to the controller. It is possible to store the entire project data on a Micro Memory Card which makes the program maintenance and update easier.

2.16 Preparation for firing

Preparing the system for firing means to program the control unit according to the selected timing and to fill the magazine with shells in the required sequence. The magazine is filled from the rear side. Upon inserting a shell into the loading area, we press the switch. The internal drum will turn by 24° and will make the shell enter the magazine. We continue loading the same way until the magazine is full. For effortless transportation, disassemble the system into four components, such as the base, set of barrels, magazine and fallout container. Then, place the base in a specified location and insert the set of barrels. Make sure that the grooves of the drive unit output shaft and block of contact segments click together in the correct position.

Use a connecting piece to connect the cable harness of the block of contacts to the glow control unit. Next, unlock manually the locks of two empty chambers which were locked during the transport. After that, attach the magazine to the brackets and secure. Then, connect the cable harness of the magazine to the control unit. Next, equally attach the fallout container and secure. Then, connect the control unit to power source and switch it on. Upon system start-up, check on the functionality of all systems. By pressing the „Prepare for firing“ button, the loading process starts. Upon completion of loading, the system is ready to start firing shells.

2.17 The process of operating

Upon starting the loading process, the magazine drum turns by 24° and ejects a shell that slips down to the loading device area. The optical sensor registers the correct position of the shell and sends an impulse to the feeding device to feed the shell into the chamber. Simultaneously, the control unit determines the position of the first barrel by means of the light gate and sets the barrel in front of the feeding device. Then, the shell casing bottom is pierced by the glow plug. As a result, the glow plug is surrounded by the lift charge. At the same time, the ejector piston is pushed back to its original position. Upon feeding the shell, the set of barrels will turn by 45°, thus lifting the loaded chamber to vertical position and locking the chamber lock. Simultaneously, the feeding device piston will return to its original position. The process is continued until six barrels are loaded. Thus, the system is ready for firing.

After sending an impulse to start firing, the glow plug will start glowing the lift charge and the initiation will start in approximately 1,2 sec. The shell is expelled out of the barrel the pressure sensor registers firing. Then, the pressure sensor sends an impulse to stop glowing and to make the set of barrels turn. This motion will unlock the chamber, tilt the chamber horizontally, position it in front of the fallout container where the ejector piston will eject the residues of cases and fallout. If, for any reasons, no shell is launched in three seconds since the glow start, the control unit will register the shell as unexploded and glowing will be stopped. It will take another two seconds for the control unit to send a request to twist the set of barrels and the unexploded shell will be thrown into the fallout container. Smothering residues may make the shell explode inside the magazine, yet the magazine is adjusted accordingly and there is no danger threatening. Other shells are paralelly being loaded in the course of firing. Up to six shells may be launched simultaneously, even during the movement of the set of barrels. Upon ending the firing sequence or upon receiving an impulse from the optical sensor indicating no shells are present in the magazine or upon the unit indicating there are no shells present in the barrels, firing is automatically ceased. Firing can be stopped anytime manually by pressing the emergency button. Firing can be performed in a manual or automatic mode. In automatic mode, the control unit is controlled by the firing sequence programmed, however firing must be started manually. In the manual mode, each launch is started by pressing a controller button while the controller indicates the actual number of chambers ready to launch shells.

2.18 Shells

It is possible to use shells of single type, such as round shells (Fig. 30) as well as cylindrical shells. To make individual shells compatible, small adjustments are necessary. Those slightly adjusted do not contain any fuse for initiation purposes and their central part is thinner to allow piercing by glow plugs.

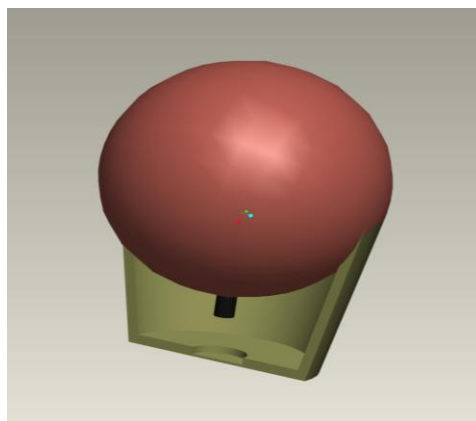


Fig. 30 – Round bomb – cross – section

3. Conclusion

My project is intended to propose an autonomous system capable of automatic firing of pyrotechnic shells. I have designed a system able to load chambers with shells automatically and launch them according to the programmed sequence. I consider my project to be novel in applying the glow plug to initiate the lift charge as no other material such as fuses, igniters or cables that can be used once are needed compared to the current systems in use. In the first place, my design takes into consideration safety, functionality, effortless transportation and easy operation.

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