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Analyzed and proposed system recoil models to reduce barrel displacement and mitigate recoil efforts

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Abstract: The usual recoil system in modern rapid-fire weapons is the hydropneumatic recoil system. In this system, the recoilable barrel is mounted on rails. However, besides all energy absorption performed by recoil system, a considerable amount of energy is transferred to the armament structure. This paper aims to analyse a simplified recoil system model of a heavy weapon and to propose a new one to reduce the maximum displacement of the armament barrel and the magnitude of the force acting into the armament even after the recoil system works.

Keywords: heavy weapons recoil systems, contact force theory, rigid body dynamics, reduction of mechanical efforts

INTRODUCTION

The present work started in the analysis of recoil systems weapons, in special larger calibers of heavy weapons. The first known recoil system was used is the French Matériel 75mm Mle 1897 Cannon, shown in Fig 1. Since then, all existing recoil mechanisms have the common objective of moderating the loads from the firing applied on the armament support structure, through the prolongation of the resistance time of the forces generated by the gases of the propellants.

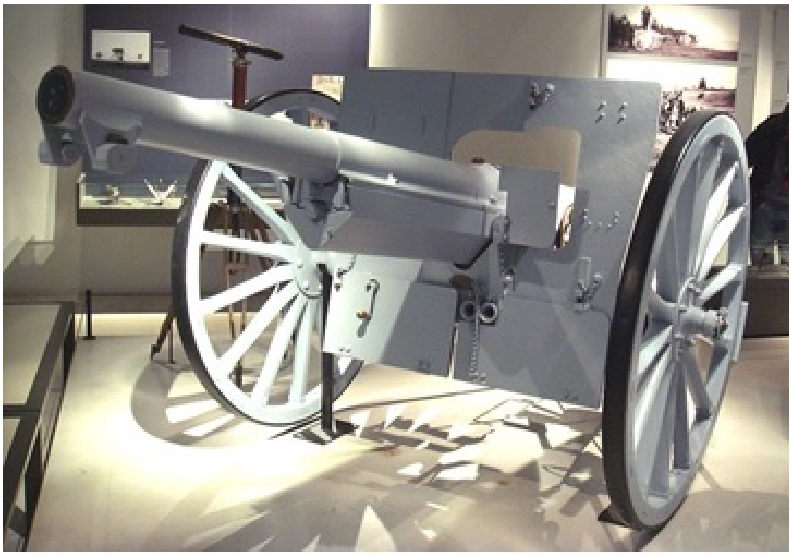

Figure 1 – Matériel de 75mm Mle 1897 French cannon. de Rumania *et al.*

A characteristic present during firing in all weapons is the impulsive profile of the forcing that acts on the recoil mechanism, as can be seen in Fig.2. This is the effort that the recoil mechanisms moderate and the objective of this work is to analyze a simplified recoil system and propose a dynamical system with the aim of mitigating the efforts coming from the recoil at the base of the armament.

Kathe (2001) indicates that the firing of a large caliber gun imparts substantial momentum and kinetic energy to the projectile. An attempt to reduce the efforts over the basements is the use of magneto-rheological dampers, as proposed by Ahmadian *et al.* (2003), however, this implies high costs. Lin *et al.* (2009) develop a dynamic simulation of the recoil mechanism on artillery weapons, specifically apllied on M109 155mm selfpropelled howitzer.

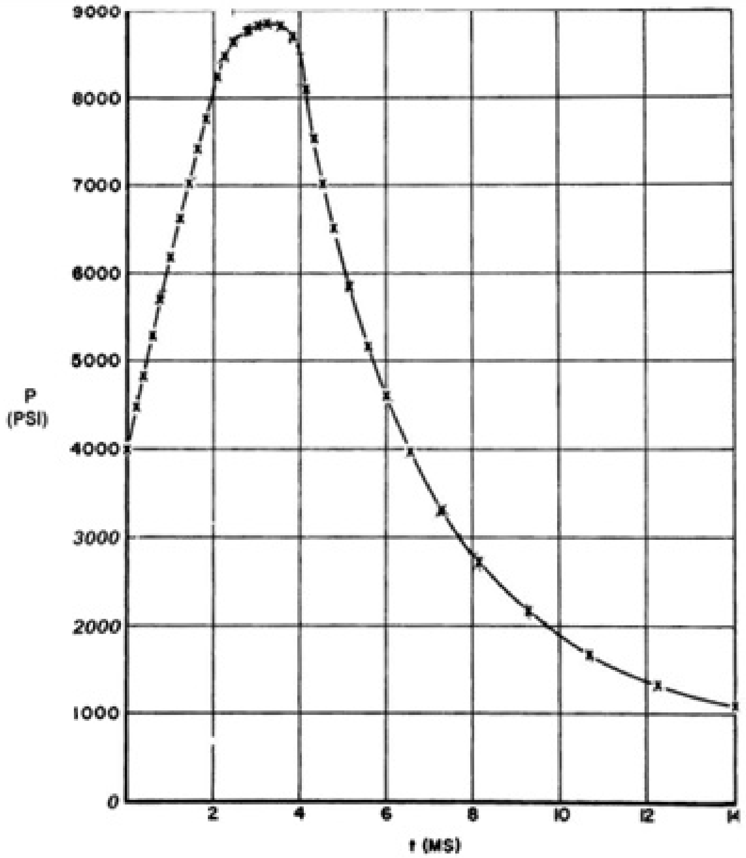

Figure 2 – Howitzer 105 mm theoretical internal pressure curve. (AMCP-706-150, 1965)

ANALYZED AND PROPOSED MODELS

In this section, we will present both simplified and proposed models. The proposed model is expected to mitigate the recoil force produced by a shot.

Analyzed Model

Most recoil mechanisms can be represented by a simplified model, as shown in Fig. 3. This model consists of a barrel, which represents a cannon barrel, with mass M, whose only degree of freedom considered is in the horizontal direction, along the coordinate x_M. An impulsive force $F(t)$ is applied at one end of the barrel and at the other end, on the wall P where the barrel is fixed, the connections are made by a spring with stiffness k and a damper with coefficient of damping c .

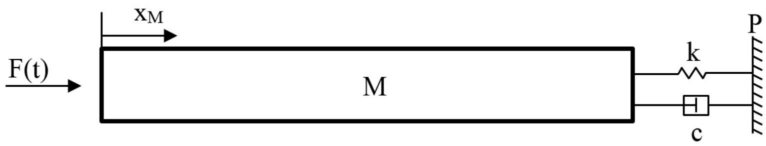

Figure 3 – Simplified model

Thus, the equation of motion of the simplified model is

$$\mathbf{M}\ddot{\mathbf{x}}_M(t) + \mathbf{c}\dot{\mathbf{x}}_M(t) + \mathbf{k}\mathbf{x}_\mathbf{M}(t) = \mathbf{F}(t) \quad (1)$$

The damping coefficient c is defined as (Polach and Hajžman, 2010)

$$\mathbf{c} = 6239 \text{ N}\cdot\text{s/m, if } \dot{\mathbf{x}}_M(t) > 0$$
$$\mathbf{c} = 14050 \text{ N}\cdot\text{s/m, if } \dot{\mathbf{x}}_M(t) < 0 \quad (2)$$

the stiffness constant k is considered 27500 N/m (Hassaan, 2014).

The impulsive force $F(t)$ in Eq. 1 can be understood as an initial velocity (v_0) of the mass M. So, Eq. 1 is transformed into the homogeneous equation

$$\mathbf{M}\ddot{\mathbf{x}}_M(t) + \mathbf{c}\dot{\mathbf{x}}_M(t) + \mathbf{k}\mathbf{x}_\mathbf{M}(t) = 0 \quad (3)$$

where the initial conditions are $x_M = 0$ and $\dot{x}_M = v_0$. The initial velocity v_0 can be derived by conserving momentum when a shot is fired. The mass of the projectile is considered to be 6,86 kg, the mass of the barrel (M) is 5600 kg and the projectile exit velocity after the propellant burning is 564 m/s. Therefore, v_0 is worth 0,7 m/s.

Figure 4 shows mass M displacement along 10 s of simulation. It is observed that the maximum displacement occurs in 0,61 s and the maximum displacement value is 22,15 cm (0,2215 m).

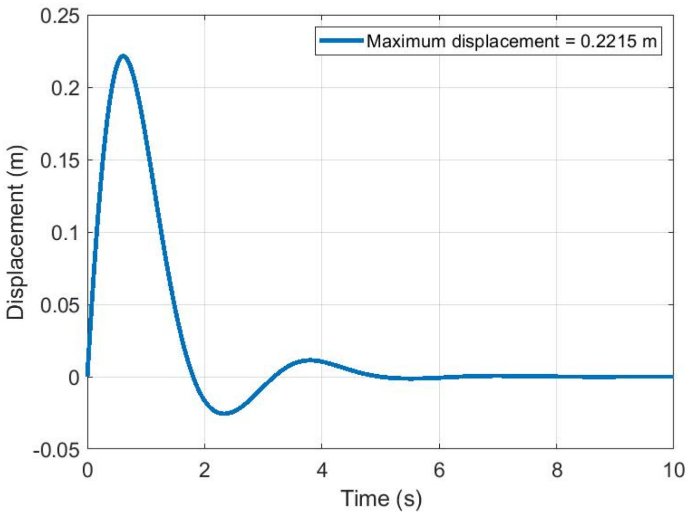

Figure 4 – Mass M displacement

Proposed Model

The new model proposed to improve the simplified recoil mechanism is presented in Fig 5. A system of on board mass m is attached to the barrel. The degree of freedom that describes the motion of the mass m is x_m, as shown in Fig 5. It is assumed that the mass m can move along the horizontal without friction and mass m is initially at a distance defined as *gap* from the wall A at one end. At the other end, the mass m is connected to a spring-damper with stiffness and damping coefficients k_r and c_r, respectively. An impulsive force $F(t)$ is applied to the barrel of mass M which initiates the motion of the system, similar to simplified model.

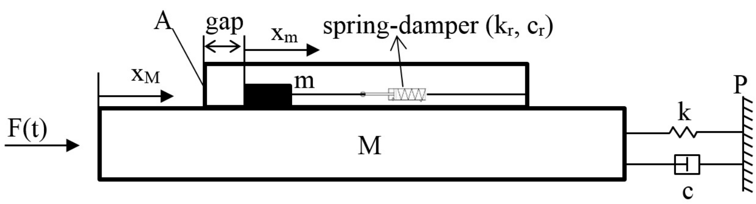

Figure 5 – Proposed Model

The equations of motion of the proposed model system are presented in Eq. 4. It is observed that due to the contact between the mass m and the wall A, which is considered solidary to the barrel of mass M, there is also a contact force F_{ct}. So the equations of motion are:

$$\begin{aligned} \mathbf{M}\ddot{\mathbf{x}}_M(t)+\mathbf{c}\dot{\mathbf{x}}_M(t)+\mathbf{c_r}(\dot{\mathbf{x}}_M(t)-\dot{\mathbf{x}}_m(t))+\mathbf{k}\mathbf{x_M}(t)+\mathbf{k_r}(\mathbf{x_M}(t)-\mathbf{x_m}(t))-\mathbf{F_{ct}}=0 \\ \mathbf{m}\ddot{\mathbf{x}}_m(t)-\mathbf{c_r}(\dot{\mathbf{x}}_M(t)-\dot{\mathbf{x}}_m(t))-\mathbf{k_r}(\mathbf{x_M}(t)-\mathbf{x_m}(t))+\mathbf{F_{ct}}=0 \end{aligned} \tag{4}$$

The initial conditions are: $x_M(0) = 0$, $\dot{x}_M(0) = v_0$, $x_m(0) = 0$, $\dot{x}_m(0) = 0$.

The maximum displacements of the mass M for the proposed model are shown in Fig. 6, for the variation of the *gap* from 0 to a maximum value and for some masses m. Remembering that the objective is to analyze the displacement of the mass M, his value is observed on the ordinate axis in Figure 6.

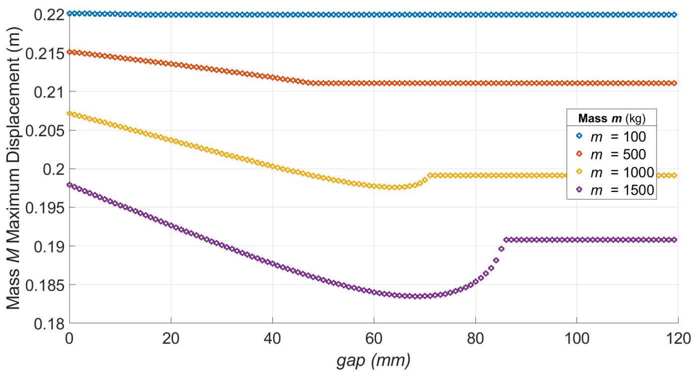

Figure 6 – Mass M maximum displacement with gap variation

We can observe that the maximum displacement of the armament barrel is significantly reduced as the embarked mass m is increased and also there is a minimum displacement for a specific gap between mass m and the wall fixed in barrel M.

Contact Force

The impact between mass m and wall A causes a sudden change in the velocity of mass m. These velocity changes are a function of the contact force, F_{ct}, existing in Eq. 4. Several contact force models are presented in literature, first studied by Hertz (1882) and most recently by Kuwabara and Kono (1987) and Hunt and Crossley (1975). In this paper we will use the Hunt-Crossley model, in which is introduced an alternative model for energy dissipation that includes a nonlinear damping term (hysteresis) and, thus, the contact force F_{ct} is given by Eq. 5:

$$\begin{aligned} \mathbf{F_{ct}}(\delta,\dot{\delta}) = -\mathbf{k_c}\delta^{\mathbf{n_c}} - \mathbf{c_c}\delta^{\mathbf{n_c}}\dot{\delta} \\ \mathbf{F_{ct}}(\delta,\dot{\delta}) = -\mathbf{k_c}\delta^{\mathbf{n_c}}(1+\lambda_\mathbf{c}\dot{\delta}), \text{where } \lambda_\mathbf{c} = \frac{\mathbf{c_c}}{\mathbf{k_c}} \end{aligned} \tag{5}$$

Where δ is the deformation of the contact region defined as $x_m - (x_M + gap)$, $\dot{\delta}$ is the deformation rate given by $(\dot{x}_m - \dot{x}_M)$, k_c is the contact stiffness, c_c is the damping and λ_c is a proportionality coefficient. The exponent n_c depends on the geometric features around the contact surface.

It should be noted that the contact force F_{ct} will only act on the system when the values δ and $\dot{\delta}$ are negative. For $\delta > 0$, the contact force is zero, that is, there is no contact between the mass m and the wall A of the system.

The parameters used to simulate the contact force are similar to the values used by Aguiar (2006). In addition to these, other parameters are listed in Tab. 1.

Table 1 – Values used for the system with mass m.

Parameter	Value
Stiffness (k_c)	$2.1{\cdot}10^8\ N/m$
Non-linearity factor (n_c)	1.3
Damping ratio(λ_c)	0.6
k_r	$13000N/m$
c_r	$3675\ N \cdot /m$

Figure 7 shows the contact force profiles for proposed model and Fig. 8 shows the details for the most effective impacts. All figures are for gap equal to zero. One can see that the peak force is 98.03 kN.

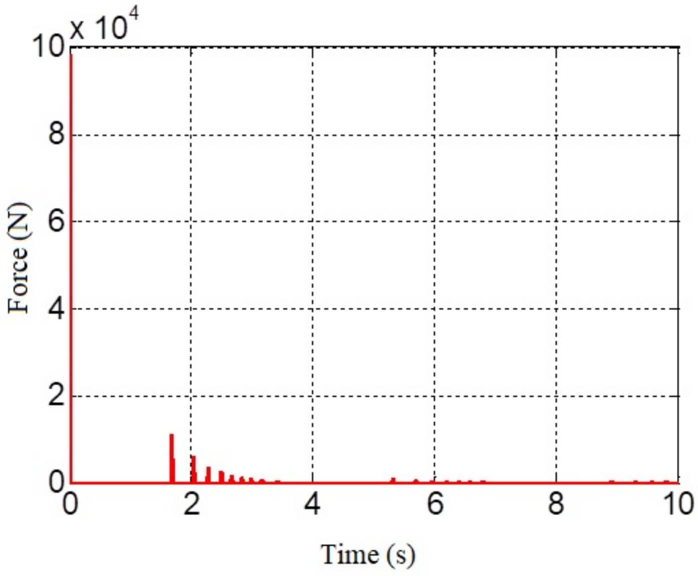

Figure 7 – Contact Force

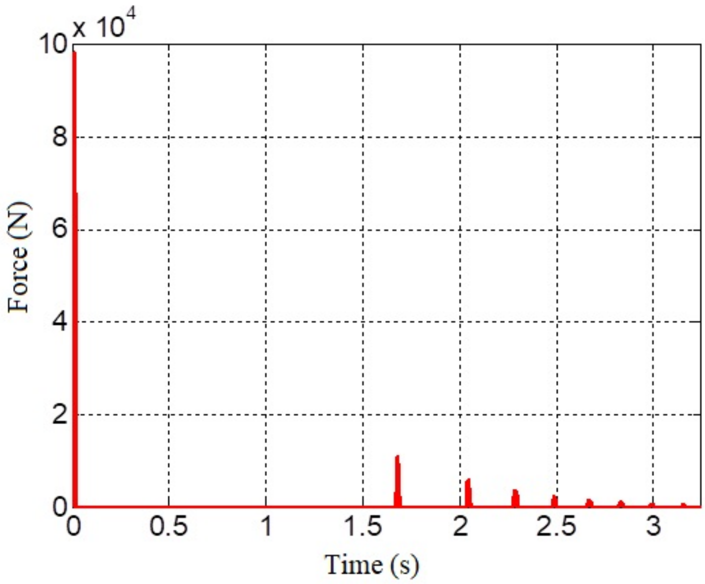

Figure 8 – Detailed Contact Force

ANALYSIS OF THE REACTION FORCE AT THE ANCHOR POINT

The force exerted on the system's anchor point (wall P, Fig. 3 and 5) is one of the critical points of the dynamics of the recoil system, as this force will be transmitted to the armament support. For the simplified model, Fig. 3, the anchoring force, F_{AN}, over time is given by Eq. 6 and shown in Fig. 9. It is observed that the maximum force is 6950 N

$$\mathbf{F_{AN}} = \mathbf{k x_M} + \mathbf{c \dot{x}_M} \tag{6}$$

As depicted in Fig. 4, where the maximum displacements of mass M with gap variation was analyzed, the behavior of the maximum anchoring force is analyzed in Fig. 10. It is observed that for mass m equal to 100 kg, the maximum

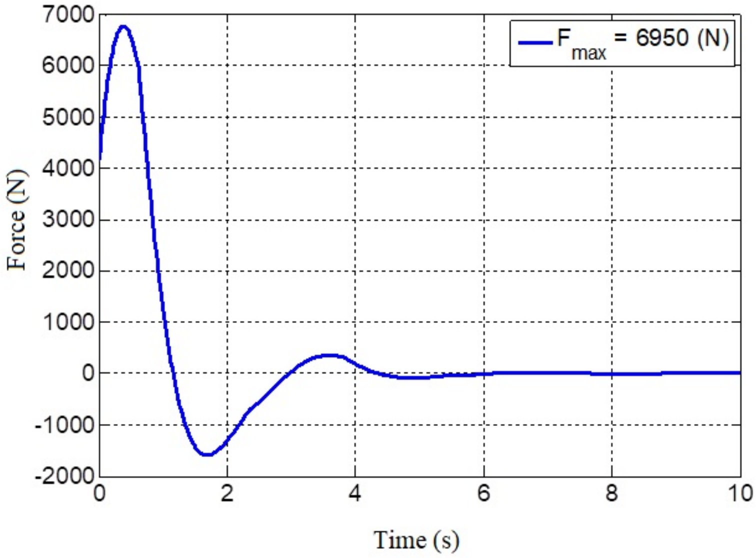

Figure 9 – Mass M maximum displacement with gap variation

anchoring force starts with a value of 6891 N for a gap of 0 mm and there is a small reduction reaching a minimum value of 6884 *N* in a 15 *mm* gap, keeping this value for all other gap values.

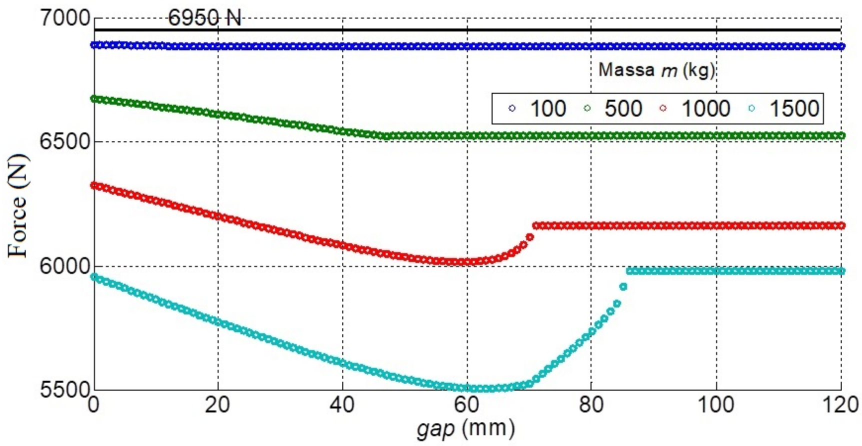

Figure 10 – Mass M maximum displacement with gap variation

For the mass *m* of 500 *kg*, the maximum anchoring force has a value of 6673 *N* for a gap of 0 *mm* and for values greater and equal to a gap of 44 *mm*, the anchoring force is 6523 *N*. Anchoring force for a gap of 0 *mm* is 6324 *N* for the mass *m* of 1000 *kg*. For a gap of 59 *mm*, the anchoring force reaches a minimum value of 6014 *N*. For a mass *m* of 1500 *kg*, the initial value of the anchoring force is 5955 *N* and for a gap of 62 *mm*, this force is 5504 *N*, lowest value reached. A summary of these values is given in Tab.2.

Table 2 – Maximum anchoring force for masses m.

Mass m (kg)	Lowest anchoring force (N)	Gap (mm)
100	6884	greater than 15
500	6523	greater than 44
1000	6014	equal to 59
1500	5504	equal to 62
100	6891	0
500	6673	0
1000	6324	0
1500	5955	0

CONCLUSIONS

This paper was supposed to analyse a simplified recoil system model of a heavy weapon and to propose a new one to reduce the maximum displacement of the armament barrel and the magnitude of the force acting into the armament even after the recoil system works. Both goals were achieved: the maximum displacement of the armament barrel was reduced in proposed model (0.2215 m) compared to simplified model (0.175 m), and the maximum anchoring force was also reduced from 6950 N to 5504 N from simplified model to proposed one.

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