Double Motor Equipments in Guns Loading Systems

JIRI BALLA
Department of weapons and ammunition
University of Defence
Kounicova 65, 662 10 Brno
CZECH REPUBLIC
jiri.balla@unob.cz  http://www.unob.cz

Abstract: - The paper deals with the possibilities of the ramming device modelling the drive with two DC series excited motors. The mechanical part is described as system with three degrees of freedom and both motors are supply separately. The main characteristics as are speed-torque, rammer velocity, linking of individual parts and change of the characteristics and their influence on the system are discussed. In the future author is going to explore the interaction between projectile and rammer and impacts inside of the mechanical part of the system.

Key-Words: - Double motor, Chain gun, Gatling gun, Electric DC drive, Loading system, Ramming device, Motion equation.

1 Introduction
Modern howitzers, tank gun and mortars are distinguished by the increase of the maximum range, the effect on the targets and the hit probability.
The increase of the hit probability can also be achieved also by the increase of the rate of fire, now by firing of Multiple Rounds Simultaneous Impact (MRSI) effects, for example. One of the tasks which must be completed is cartridge loading since the rate of fire depends on the loading velocity. The MRSI effect is achieved by the coordination of loading system with other gun systems – breech, aiming, fire control system (FCS) etc.
One of the tasks which must be completed is cartridge loading since the rate of fire depends on the loading velocity.
The gun loading is a very difficult operation from the viewpoint of energy consumption by a gun crew. It follows from the following reasons.
The loading work for one round approx 150mm calibre is 2800 J. The human power is limited to 120 W. The lengths of the cartridges are until 1 m and the mass from 15 to 50 kg as shown in Error! Reference source not found. and [2].

Ramming as one of the as of the significant operation is very difficult mainly when loading by hand. Cartridge ramming is an operation which influences on a weapon reliability most importantly on a rapidity of fire and it belongs to the hardest thing before a shot.
The maximum rapidity of fire attainable during loading by hand is two rounds a minute. A mechanization of cartridge ramming was the first step destined for an easement of the loading process. The ramming can start if the breech is opened and the fired cartridge case is ejected from the barrel chamber and from the loading space. After complete ramming of a new cartridge (or its parts) can start following periods of the functional cycle (closing and locking of the barrel chamber and the shot). The ramming difficulties can be explained by means of Fig. 1 representing the forces acting against the projectile movement – see Error! Reference source not found., [2] and [6].

To move the projectile, the ramming force \( F_{zas} \) according to the expression (1) has to be:

\[
F_{zas} \geq G (\sin \lambda + f \cos \lambda).
\]  

(1)

So the magnitude of the resistance against the ramming changes with the angle of elevation and for the calibre around 150mm it is approx. in limits from 85N to 412N without taking into consideration the resistances at the breech closing and the pressing the projectile into the forcing cone. With respect to this fact, the man is able to produce the power 120W and then the velocity of the ramming at the resistance 400N could be 0.3 m.s\(^{-1}\). This could not be sufficient for reliable pressing of the projectile into the forcing cone and release of the extractors catching the breech. The total resistances
against ramming for calibres projectiles 122 mm and 152 mm depending on the elevation angle \( \lambda \) are shown in Fig. 2.

![Fig. 2 Ramming resistance](image)

In Error! Reference source not found. and [6] there are given the recommended values of the ramming velocities at the end of movement when shell is engraved into the forcing cone, see Table 1.

<table>
<thead>
<tr>
<th>ramming velocity</th>
<th>( v_{\text{min}} ) (m/s)</th>
<th>( v_{\text{max}} ) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>unitary cartridge</td>
<td>0.6 – 1</td>
<td>4 – 6.5</td>
</tr>
<tr>
<td>separated cartridge</td>
<td>more than 0.3</td>
<td>1 – 1.4 (charges)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 (projectiles)</td>
</tr>
</tbody>
</table>

Double motor equipments are being used in many technical military applications as are externally powered automatic weapons (Gatling systems, chain guns) or loading systems of guns, see [1], [4] and [5] for example. The reasons can be following: decreasing of whole inertia mass moment and improvement of dynamical properties of drives, location of drives into the limited space in combat vehicles, tanks or aircrafts. In any cases the velocity adjustment to achieve the required of rapidity of fire is possible.

Finally during malfunction of the one drive the second one is able to operate with decreasing power. Only the two drives are usually used in weapon application in contradistinction to non-military area where more than two motors actuate the machine. The main issue of these drives follows from a proportional distribution of powers among individual drives can cause an overloading one of them and an inconsonance of angular velocities driving motors brings along a danger of an oscillating process.

In the next paragraphs will be discussed the series excited drives which are very often used in the weapons applications which are suitable due to they work in short time with breaks ensuring their cooling when do not operate.

### 2 Problem Formulation

The often arrangement of the twin-motored drives using DC motors is represented in Fig. 3. The torques of both motors act on the first wheel in the transmission linking the gear box. The elastic shafts rotating with angular velocities \( \phi_1, \phi_2 \) have own torsion rigidities \( k_1, k_2 \), damping torsion coefficients \( b_1, b_2 \) and mass moments of inertia \( I_1, I_2 \). The driven part has the inertia mass moment symbolized by \( I_3 \). This part is being loaded by the \( M_Z \) load torque.

![Fig. 3 Twin drive scheme](image)

The mechanical part can be written by using of the Lagrange equations of the second order:

\[
\frac{d}{dt} \left( \frac{\partial E_K}{\partial q_j} \right) - \frac{\partial E_K}{\partial q_j} = -\frac{\partial E_p}{\partial q_j} - \frac{\partial R_d}{\partial q_j} + Q_j. \tag{2}
\]

The expression (2) describing the dynamic model with the three degrees of freedom has been determined as follows.

The kinetic energy of the system is:

\[
E_K = 0.5I_1\phi_1^2 + 0.5I_2\phi_2^2 + 0.5I_3^{\text{red}}\phi_3^2 \tag{3}
\]

where \( I_1 \) ... inertia mass moment of 1\textsuperscript{st} motor shaft, \( I_2 \) ... inertia mass moment of 2\textsuperscript{nd} motor shaft, \( I_3^{\text{red}} \) ... variable reduced inertia mass moment of the other part depending on the mass loading.

The potential energy and dissipative function are given as:

\[
E_p = 0.5k_1 (\varphi_3 - \varphi_1)^2 + 0.5k_2 (\varphi_2 - \varphi_3)^2 \tag{4}
\]

where
$k_1, k_2$ – rigidities of the motor 1 and 2 shafts.

The dissipative function is

$$R_0 = 0.5b_1 (\phi_3 - \phi_1)^2 + 0.5b_2 (\phi_2 - \phi_3)^2$$  \hspace{1cm} (5)

where

$b_1, b_2$ – damping factors in the linking between the motor 1 and 2 shafts and gearbox.

Very often substitute the dissipative function by damping of every degree of freedom only by one force anyhow in Error! Reference source not found., [7] or Error! Reference source not found..

The mechanical and electrical system is described with helping the Fig. 4 and following equations.

![Fig. 4 Mechanical and electrical parts](image)

The mechanical part equations follow from (2) and they can be written, see [2], Error! Reference source not found., Error! Reference source not found.,

\[ I_1 \frac{d \phi_1}{dt} = M_{M_1} + k_1 (\phi_2 - \phi_1) + b_1 (\phi_3 - \phi_1), \]  \hspace{1cm} (6)

\[ I_2 \frac{d \phi_2}{dt} = M_{M_2} - k_2 (\phi_2 - \phi_3) - b_2 (\phi_2 - \phi_3), \]  \hspace{1cm} (7)

\[ I_3^{\text{red}} \frac{d \phi_3}{dt} = 0.5 I_3^{\text{red}} (\phi_3 - \phi_1) + k_2 (\phi_2 - \phi_3) - b_2 (\phi_2 - \phi_3) - b_1 (\phi_3 - \phi_1) - M_Z. \]  \hspace{1cm} (8)

The torques of motors are given

\[ M_{M_1} = K_{MS_1} i_1^2, \]  \hspace{1cm} (9)

\[ M_{M_2} = K_{MS_2} i_2^2, \]  \hspace{1cm} (10)

where $K_{MS_1}, K_{MS_2}$ are the electromechanical constants.

The load torque is

\[ M_Z = F_{\text{ra}} i_G, \]  \hspace{1cm} (11)

where $i_G$ is total transmission ratio from load to the part 3 representing of shaft having $I_1$ mass moment of inertia, gear box, rammer and projectile.

To determine the motors torques, the $i_1, i_2$ currents have to be set using the differential equations of the first order:

\[ L_1 \frac{di_1}{dt} + R_1 i_1 + U_{b1} = U, \]  \hspace{1cm} (12)

\[ L_2 \frac{di_2}{dt} + R_2 i_2 + U_{b2} = U \]  \hspace{1cm} (13)

where

$U$ – supply voltage [V],

$R_1, R_2$ – resistance of armatures [Ω],

$L_1, L_2$ – inductance of armatures [H],

$U_{b1}, U_{b2}$ – electromotive forces (emf) [V],

$U_{b1} = K_{ES_1} \phi_1$,  \hspace{1cm} (14)

$U_{b2} = K_{ES_2} \phi_2$,  \hspace{1cm} (15)

$K_{ES_1}, K_{ES_2}$ – electromagnetic constants of both series excited motors.

Since equations describing the system are nonlinear they have to be solved numerically. The analytical solution is possible only in the several special cases as it is mentioned in [7], Error! Reference source not found., Error! Reference source not found.,

The system of the five differential equations (6), (7), (8), (12) and (13) has been solved using by the Runge-Kutta integration method of 4th order together with the other additional equations.

The suitable integration step has been chosen as 0.0001s for the specific purpose. It corresponds to known condition between the minimal integration step and the maximal considered frequency $f_{\text{max}}$ of the undamped system as it is recommended in Error! Reference source not found., Error! Reference source not found., Error! Reference source not found., Error! Reference source not found.,

\[ \Delta t_{\text{min}} = \frac{1}{\pi f_{\text{max}}}. \]  \hspace{1cm} (16)

But in case of the mass moment of inertia change and during impacts the integration step has to be cut down hundred times.

The oncoming results have been gained with comparison of calculations and measurements on the medium calibre loading device [2] when the software was debugged.

### 3 Results

The results of calculation are presented onward. The numerical values of the input parameters belonging to the system were obtained from technical specifications and drawings. Due to very large numbers of inputs only the most important there are mentioned hereto. First of all, the significant values for the case when both motors have the identically characteristics, see Table 2.

The power supply voltage changes according to the instantaneous value of both currents and it is modelled by the equation

\[ U = U_0 - k_i (i_1 + i_2) \]  \hspace{1cm} (17)
where $k_i$ is a factor obtained from the technical experiments on the piece and depending on the instantaneous currents consumption when the device operates. The variation of voltage during ramming time is drawn in the Fig. 5.

The inputs belonging to the electric drive were chosen according to the design of the piece and they were corrected with respect to the technical experiments.

Table 2 Drive inputs (same characteristics of both motors)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{MS_1}$</td>
<td>0.0081 N.mA$^{-2}$</td>
</tr>
<tr>
<td>$K_{MS_2}$</td>
<td>$K_{MS_1}$ N.mA$^{-2}$</td>
</tr>
<tr>
<td>$K_{ES_1}$</td>
<td>0.005 V.s.A</td>
</tr>
<tr>
<td>$K_{ES_2}$</td>
<td>$K_{ES_1}$ V.s.A</td>
</tr>
<tr>
<td>$I_1$</td>
<td>0.00014 kg.m$^2$</td>
</tr>
<tr>
<td>$I_2 = I_1$</td>
<td></td>
</tr>
<tr>
<td>$U$</td>
<td>24 V</td>
</tr>
<tr>
<td>$M_Z$</td>
<td>0.11 N.m</td>
</tr>
<tr>
<td>$R_1$</td>
<td>1.19 $\Omega$</td>
</tr>
<tr>
<td>$R_2 = R_1$</td>
<td></td>
</tr>
<tr>
<td>$L_1$</td>
<td>0.0098 H</td>
</tr>
<tr>
<td>$L_2 = L_1$</td>
<td></td>
</tr>
<tr>
<td>$k_1$</td>
<td>6782 N.m.rad$^{-1}$</td>
</tr>
<tr>
<td>$k_2 = k_1$</td>
<td></td>
</tr>
<tr>
<td>$b_1$</td>
<td>0.0022 N.m.s$^{-1}$</td>
</tr>
<tr>
<td>$b_2 = b_1$</td>
<td></td>
</tr>
</tbody>
</table>

The speed-torque characteristic is drawn in Fig. 6 from the beginning of the operation. The current/time history curve of the first DC motor is in Fig 7. It depends on the ratio of the armature inductance and the resistance values. The resultant velocity of the rammer is portrayed in the Fig. 8. It is clear that the rammer acts onto projectile during all period and that is accelerated to the maximal value.

The coupling between part 1 or 2 and 3 is represented with the spring link in Fig. 9 and they are denoted as $M_{13}$, $M_{23}$.

Both linking moments are same since inputs are same as well and it is the theoretical case. But during service very unusual stages can occur: the different characteristics of drives or malfunctions when one of the motors is excluded from the function and that becomes
load of the second one. It is very important to know what happens foremost in military technologies when the system reliability is on the first place. The influence of the drive different characteristics on the behaviour of the system is explained furthermore. The drive characteristics have been chosen according to experts group having knowledge and experience in this branch, see Table 3. The results of this second case are presented next. The ramming velocity as one of the most important characteristics changes negligible.

Table 3 Drive inputs (different characteristics of both motors)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{MS_1}$</td>
<td>0.0081 N.mA$^{-2}$</td>
</tr>
<tr>
<td>$K_{MS_2}$</td>
<td>0.0088 N.mA$^{-2}$</td>
</tr>
<tr>
<td>$K_{ES_1}$</td>
<td>0.005 V.s.A</td>
</tr>
<tr>
<td>$K_{ES_2}$</td>
<td>0.005 V.s.A</td>
</tr>
<tr>
<td>$I_1$</td>
<td>0.00014 kg.m$^2$</td>
</tr>
<tr>
<td>$I_2$</td>
<td>$I_1$</td>
</tr>
<tr>
<td>$I_3$</td>
<td>0.00017 kg.m$^2$</td>
</tr>
<tr>
<td>$U$</td>
<td>24 V</td>
</tr>
<tr>
<td>$M_Z$</td>
<td>0.11 N.m</td>
</tr>
<tr>
<td>$R_1$</td>
<td>1.19 Ω</td>
</tr>
<tr>
<td>$R_2$</td>
<td>1.1 Ω</td>
</tr>
<tr>
<td>$L_1$</td>
<td>0.0107 H</td>
</tr>
<tr>
<td>$L_2$</td>
<td>0.0098 H</td>
</tr>
<tr>
<td>$k_1$</td>
<td>6782 N.m.rad$^{-1}$</td>
</tr>
<tr>
<td>$k_2$</td>
<td>$k_1$</td>
</tr>
<tr>
<td>$b_1$</td>
<td>0.0022 N.m.s$^{-1}$</td>
</tr>
<tr>
<td>$b_2$</td>
<td>$b_1$</td>
</tr>
</tbody>
</table>

The course of the 1st motor current $i_1$ is not too different comparing with Fig. 7. Due to the the change of the electromechanical and the time constant the current value at the beginning of the operation is greater but without substantial effect on the final rammer velocity which is necessary to obtain the suitable engraving of the projectile driving band into the forcing cone in the barrel. Nevertheless the mechanical and electrical system is able to ensure reliable operation at the end of ramming. The greater value at the beginning of the operation achieves the 1st motor and after the transient performance the both motor drive the system with the same torque, see Fig. 10. At the end of this part the overall exclusion of the motor from the drive due to malfunction has been discussed. The change of the ramming velocity has been studied.

Fig. 8 Rammer velocity

Fig. 9 Elastic links between motors and part 3

Fig. 10 Motor torques – different characteristics
The non-operating motor is the load for the operating one and it is interesting how the ramming device works. The maximal ramming velocity attains at 70% of the nominal as it is given in Fig. 11 and the elastic links between motors and part 3 are depicted in Fig. 12.

During this simulation the maximum electrical power reached the value of 350W.

Fig. 11 Ramming velocity – one DC motor out of order

![Fig. 11 Ramming velocity – one DC motor out of order](image1)

Fig. 12 Elastic links during malfunction of the one motor

![Fig. 12 Elastic links during malfunction of the one motor](image2)

During this simulation the maximum electrical power reached the value of 350W.

4 Conclusion

The results given in the figures reflect a good coincidence with the real piece which was explored according to presented theory. The theory was verified on the other examples of weapons patterns as it is published in references [2], [7].

The procedure used in this article has been applied in the Czech research institutes and in the University of Defence in Brno as additional teaching material for students of weapons and ammunition branch.

In future is supposed to study the influence of rammer stiffness (e.g. linking between rammer and projectile will be elastic and system will have over one degrees of freedom) and the influence of the mass change throughout the ramming device operation together with the engraving of the projectile into the forcing cone.

References:


Acknowledgement
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