Evaluation of Recoil Force on Water Cannon Using Computational Fluid Dynamics and Experimental Data

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Abstract

This paper presents a dynamic analysis of 7.2-kg water cannon from which a water projectile of mass 150 g is fired, taking the energy released from the explosion of a 0.5-inch BMG bullet. In this study, three different exit nozzles were used to eject the water projectiles. The first two nozzles have exit diameters of 15 and 12 mm respectively. The last nozzle has the exit diameter of 12 mm, but it has additional eight 2-mm holes of back flows. The back flows were meant to reduce the recoil force from firing the water projectile. In the computer simulations, performance curves of the nozzles were determined using computational fluid dynamics techniques. In the experiment, the water cannon was allowed to move on a 45^{o} track. The water projectile was fired 45^{o} downward causing the recoil force to propel the cannon upward. The horizontal distance that the cannon travelled before hitting the ground was measured. Using the measured distances and performing the dynamic analysis of the cannon, the recoil force was found to decrease with the nozzle diameter; from 35.92 MN to 22.18 MN when the nozzle's diameters were 15 and 12 mm, respectively. The explosion pressures pushing the water projectiles can be found from the performance curves to be 90.7 MPa. The recoil force was further reduced to 19.40 MN when using the nozzle with back flows. The destructive force also decreased but the reduction was insignificant compared to that of the recoil force. This finding confirms that incorporating back flows yield an effective way to reduce the recoil force.

Keywords*:* water cannon, recoil force, destructive force, water projectile

1. Introduction

Water cannon in this paper, is a military device, being used to shoot a water projectile at an improvised explosive device (IED). It is the large fluid impulse of the water projectile that destroys the IED target. When shooting, there exists recoil force reacting on the water cannon at the same magnitude to that of the destruction force but in the opposite direction.

To install the water cannon onto an explosive ordnance disposal (EOD) robot, appropriate means to reduce the recoil force is needed in order to avoid any damage of the robot's components due to the enormous impulsive recoil force acting on the robot [1].

It has been shown that the water projectile is an impulsive fluid holding high destruction energy. The effective time that the recoil force acts upon the cannon, however, lasts only a few milliseconds [2]. Two well known techniques being used to reduce the recoil force are to delay the effective time of the recoil force by using a mechanical damping [3] or to create a counter recoil force by shooting additional amount of water jets in the opposite direction to the main jet [4]. Both techniques, however, need additional mass loads either in the form of mechanical damping component or as an additional of water and the back flow nozzles onto the EOD robot.

In this work, a new design for the water cannon head is purposed. The design concepts are based on the facts that the effective destruction time is very short due to the impulsive nature of explosion and that there is always excess water loaded in the water cannon. The cannon head, under the new design, has a main nozzle, for shooting the water projectile, in the forward direction. Just before the main exit, several holes are drilled in the way to direct part of the water stream to leave the cannon in the reverse directions, creating counter recoil forces against the recoil force. With this scheme, the water cannon can operate at the reduced recoil force and no additional mass load of water or any mechanical damping system is needed.

Numerical simulations of the flows pass the nozzles with different numbers of the back flow jets using CFD software have been advanced in order to determine the demand curves of such flows. Experiments to determine the operating conditions of the cannon have also been conducted. Effects of the number of back flow jets on the recoil and destruction forces have been analyzed.

2. Methodology

This section presents the research methodology in both numerical and experimental aspects.

2.1 The water cannon

The size and shape of the water cannon are shown in Fig. 1(a). Part 1 is the head of the cannon and part 2 is a chamber for water loading. The mass of the water cannon is 7.1 kg; the chamber and the head are filled up with water of mass 150 g. When firing the water projectile takes the energy released from the explosion of a 0.5-inch BMG bullet. The combustion chamber locates at the end part 2 (not shown in the figure).

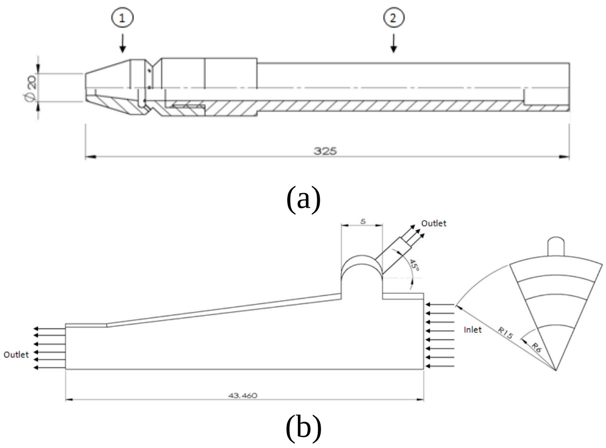


Fig. 1 (a) Water cannon: water cannon head 1, and water chamber 2. (b) Simulation domain with specified inlet, exit and periodic boundaries

We simulate the demand curves of the flow through the head of the cannon using computational fluid dynamics (CFD) commercial software. The mass flow rate at the inlet is varied and the outlets are set at atmospheric pressure. The periodic boundary conditions are used so we only need to simulate one back flow outlet for each simulation. The k-epsilon turbulence model has been used in this work. Fig. 1(b) shows the simulation domain, representing the water inside part 1 of the water cannon .The simulations are for the following cases: the case without back flow, the cases with 8, 16 and 24 2-mm holes of back flows.

2.2. Dynamics analysis of the water cannon

Experimental setup has been advanced to obtain parameters to be used in the analyses of the dynamics of the water cannon upon the firing of the water projectile. In the experiment, the water cannon were allowed to move on a 45° track. The water projectile was fired 45° downward causing the recoil force to propel the cannon upward.

The analysis of the motion is divided into 2 time periods: the propulsion and the projectile motion periods. The horizontal distance that the cannon travelled before hitting the ground was measured. Fig. 2 shows the free body diagram of the water cannon and the flows.

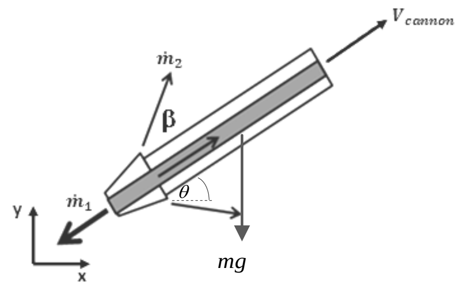


Fig. 2 Free body diagram for dynamics analyzes of the water cannon.

Dynamics equations describing the flow during the propulsion period are

$$\frac{d^2x}{dt^2} = \frac{\dot{m}_1 v_e \cos\theta - ((\dot{m}_2 v_e \cos\beta)\cos\theta)}{(m_o - \dot{m}t)} \quad (1)$$

$$\frac{d^2y}{dt^2} = \frac{\dot{m}_1 v_e \sin\theta - ((\dot{m}_2 v_e \cos\beta)\sin\theta)) - (m_o - \dot{m}t)g}{(m_o - \dot{m}t)} \quad (2)$$

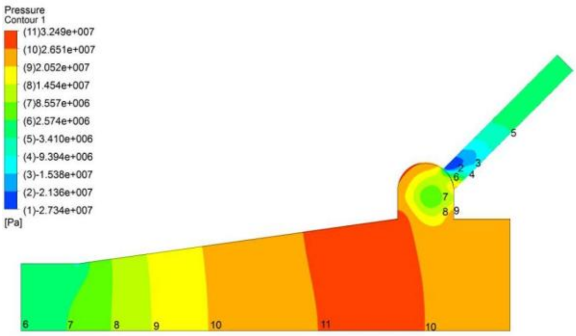
Where x and y are displacement of the cannon, $\dot{m}_1$ and $\dot{m}_2$ are mass flow rates at the main and at the back flows, respectively. The mass flow rate $\dot{m}$ is the total mass flow rate at the entrance plane of the head of the cannon and m_0 is the initial mass of the cannon and the water within.

The angle β is the angle between the back flow and the cannon axis. The angle θ is the angle between the cannon axis and the horizontal plan. The values of the angles β and θ are set to be constant at 45°.

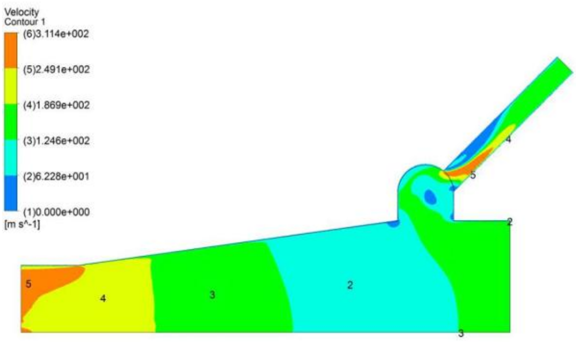
3. Simulation Results and Discussions

In this study, three different exit nozzles were used to shoot the water projectiles. The first two nozzles have exit diameters of 15 and 12-mm, respectively. The last nozzle has the exit diameter of 12-mm, but it has eight additional 2-mm holes of back flows.

Fig.3 shows the simulation results for the case of the exit diameter being 12 mm with 24 back flow holes of 2-mm diameter. It can be seen from the simulation results that the average inlet pressure, forward and backward specific z-momentums are 25 MPa, 247.88 m/s and 160.29 m/s respectively. These values are further used for calculating the destructive and the recoil forces.



(a) Pressure contour



(b) Velocity contour

Fig.3 The simulation results of water cannon

3.1. Effective time of the shooting

Experimental results showed that for the case of 12-mm and 15-mm exit without back flow the measured horizontal distances before the cannon hit the ground are 8.5 and 9 m, respectively. Solving the dynamics Eq. 1-2 for the effective (propulsion) time and mass flow rate of the 12-mm nozzle were 3 ms and 50.8 kg/s and or the 15-mm nozzle, being 1.9 ms, 79.52 kg/s.

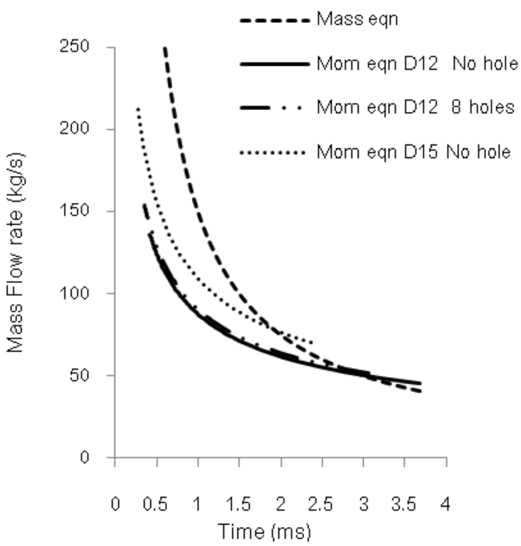


Fig. 4 Graphical solutions

Note that the graphical technique has been employed to find the solutions (see Fig. 4).

For the case with back flows, the back flow velocity appeared as an additional unknown. The CFD techniques were used as auxiliary equation to determine the velocity. It was found that the effective time and the mass flow rate for the case of eight back flow jets were 2.6 ms and 54.08 kg/s, respectively.

It can be concluded that decreasing the exit areas prolongs the effective time. This also delays the transport processes and decreasing the recoil forces as well (see section 3.3).

3.2. Performance curves

The simulation of the demand curve, together with the experimental results of the operating points of the water cannon, defines the performance curves of the water cannon.

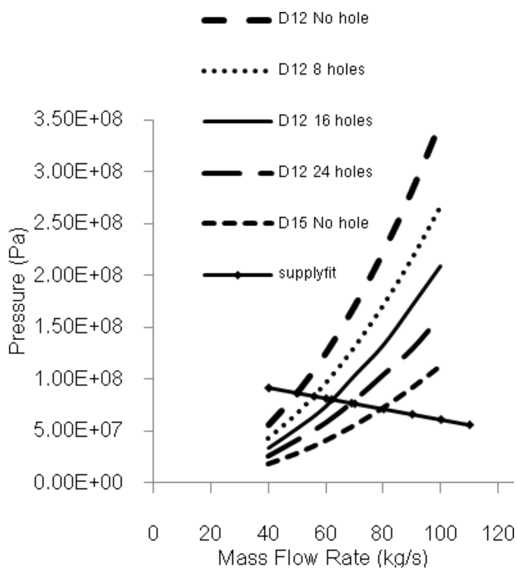


Fig. 5 Performance curves of the cannon

Since the experimental data are limited at the present time then the three exiting points were used as the only data, being fitted by a linear equation to obtain the supply curve for the water cannon. Fig.5 shows the performance curves of the water cannon.

3.3. Destruction and recoil forces

This sub-section shows the calculation of the recoil forces when the number of back flow nozzles varies. Using the measured distances and performing the dynamic analysis of the cannon, the recoil force was found to decrease with the nozzle diameter; from 35.92 MN to 22.18 MN when the nozzle's diameters were 15 and 12 mm, respectively. For the cases without back flows, the recoil force is equal to the destruction force.

When considered the cases with back flows, the recoil forces reduced with the number of back flow jets. The destruction force, however, remained approximately constant (see Fig. 6). The increasing amount of the exit flow power is due the water mass was pushed out of the cannon at in a shorter effective time.

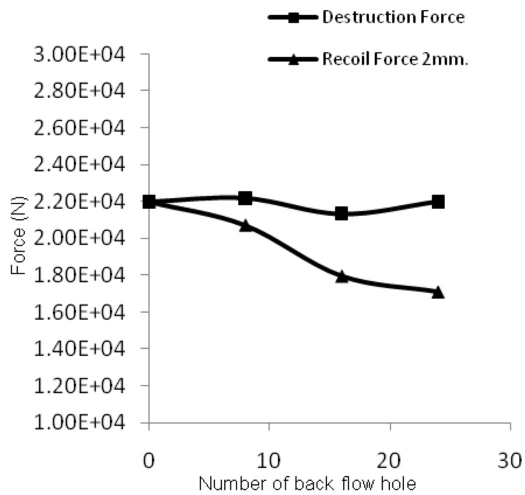


Fig.6 Destruction and recoil forces

4. Conclusions

Recoil force acting on the water cannon can be reduced by creating back flow jets in the direction opposite to the water projectile. With the new design, the counter recoil force increases with the number of the back flow jets while the destruction force remains relatively unchanged. The size of the main and the back flow jets are needed to be enlarged such that higher destruction and counter recoil forces could be obtained.

5. Acknowledgement

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6. References

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