Dual Nozzle Weapon Power Couple Vibration Controller With Delayed Rear Nozzle

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Abstract. Aiming at the problem that the firing accuracy of barrel weapon is affected by the violent vibration during continuous firing, a double-nozzle vibration controller using the energy of gunpowder gas in the chamber is proposed. The synchronous external injection of the double nozzles of the controller is realized by the delayed ejection of the rear nozzles, so as to generate a power couple to balance the recoil flipping torque of the barrel weapon to achieve the stable firing effect of reducing the bore vibration. A double-nozzle vibration controller with a delayed rear nozzle for a chain gun is designed. The rigid-flexible coupling dynamic model of a chain gun with a double-nozzles vibration controller was established considering the two-phase flow of propellant gas in the barrel and airway. The numerical simulation of the muzzle vibration characteristics of the original weapon and a chain gun equipped with a double-nozzles vibration controller is carried out respectively, and the effectiveness of the double-nozzles dynamic couple vibration controller for the continuous firing vibration control of the barrel weapon is verified.

1. Introduction
In the continuous firing process of the gun, the high temperature and high pressure powder gas in the bore will push the projectile to accelerate the movement to the bore, and at the same time it will act on the bore bottom to produce recoil impact force, so the barrel will produce violent vibration; Especially, the muzzle will be disturbed by the recoil torque relative to the support seat, which will seriously affect the firing accuracy of the weapon. Therefore, the vibration control problem of barrel weapon is the key bottleneck problem that restricts the improvement of firing accuracy, and this directly affects the application prospect of conventional weapons.

In recent years, scholars have proposed active and passive vibration control methods, such as servo control, magnetorheological vibration suppression and chamber vibration absorption, in the study of vibration control design [1] and vibration servo control of multiple rocket weapons [2] during the movement of weapon carrying platform. However, these vibration control methods are not fast enough, or the output force is small, or the vibration suppression effect is limited, or the application of conventional weapons is difficult. Liao Zhenqiang [3], Hua Hongliang [4] et al put forward the control technology of nozzle flow pushing back the barrel by using the energy of gunpowder gas in the bore. Through the torque generated by nozzle backthrust perpendicular to the axis of the barrel, the recoil force reversal torque is suppressed and the bore disturbance is controlled, so as to achieve the vibration control effect synchronous with the shooting process. However, in this method, if the number and
position of the nozzle are not set properly, there will be a lateral periodic impact effect on the weapon support, which is not conducive to the vibration control of the weapon support. Jia-sheng li [5] in the revolving barrel weapon vibration control puts forward a couple of stable type fire control idea, but because of the two gases stabilizer independent setting pipe to different positions, so it is difficult to produce transient synchronous control of two equal and opposite, which acts on the tube, in the form of couple will not impact the role of an effect on the body tube pedestal.

In this paper, a dynamic couple vibration control scheme of double-nozzles weapon with delayed rear nozzles is proposed. By using the delayed rear nozzles to synchronously spray the two nozzles, a dynamic couple balancing the recoil torque of the barrel weapon is generated to achieve the stable firing effect of reducing the bore vibration. In order to accurately study the transient synchronicity of the reverse thrust of two nozzles, the flow characteristics of the propellant gas in the barrel, the nozzle and the nozzle were studied by using the two-phase flow theory. In this paper, a rigid-flexible coupling dynamic model of a chain gun firing process with a double nozzle vibration controller is established. By using numerical simulation method of the original weapons and is equipped with double nozzle vibration controller on the muzzle vibration characteristics of a chain gun contrast research, and analyzes the double nozzle dynamic coupling vibration controller the influence law of vibration of the chamber body tube and mouth, double nozzle dynamic coupling vibration controller is verified for barrel weapon continuous firing effectiveness of vibration control.

2. Dynamic Couple Vibration Control Scheme for Dual Nozzle Weapons with Delayed Rear Nozzle

2.1. Vibration control device structure scheme

As shown in Figure 1, the principle of a weapon double-nozzle power-couple vibration control device with a delayed rear nozzle is as follows: The body tube is provided with two upper and lower nozzle, the two nozzle is provided with a rear air vent and through a trachea is connected with the lower nozzle; A leading air hole is arranged at a position in front of the barrel and is directly connected with the upper nozzle.

![Figure 1. Structure diagram of weapon power couple vibration control device.](image)

When the gun is fired, the projectile will accelerate along the barrel to the bore under the thrust of high temperature and high pressure powder gas. When the projectile moves to the rear vent, part of the gunpowder gas in the bore will be exported from the rear vent and then through the airway from the lower nozzle at high speed, thus generating a counter-thrust to the barrel upward. The projectile continues to move to the bore under the push of gunpowder gas. When it moves to the front guide hole, there will also be part of the gunpowder gas in the bore ejected from the upper nozzle to produce a downward counter-thrust to the barrel. Due to the delay effect of the nozzle, the relative distance between the two nozzles, the relative position of the front and rear vents and the length of the nozzle can be reasonably designed to make the gunpowder gas ejector from the front and rear nozzles at the same time. When the two counter-thrust forces are equal in size and opposite in direction, the two synchronous counter-thrust forces will form a transient force couple on the barrel, so as to achieve the purpose of not only offsetting the recoil flipping torque of the barrel weapon, but also producing no additional force on
the support frame of the barrel. The barrel weapon can also achieve the effect of stable shooting under the effect of periodic strong impact when shooting continuously.

2.2. Two-phase flow model for vibration control devices

The dynamic couple vibration control device with double nozzles uses part of the gunpowder gas burned in the bore, so the interior ballistic parameters of the weapon system must be changed after installing this device. According to the internal ballistic theory of two-phase flow, when the position of the guide hole is close to the bore bottom, because more gunpowder and gas are diverted, the nozzle recoil thrust will be larger, and the bore pressure will be smaller and larger, so that the muzzle velocity of the projectile will also be more affected. Therefore, the position of the air vent on the body tube should not be too close to the position of the chamber bottom, so as to ensure that the muzzle velocity of the projectile does not drop much and that the powder particles have basically finished burning when the air vent is derived. To sum up, in order to obtain more accurate calculation results in physical sense, the following mathematical model is established in this section, and the following assumptions are made in order to obtain a more reasonable mathematical model:

(1) The powder particle group is treated as a kind of quasi-fluid with the characteristics of continuous medium, that is, it conforms to the basic assumption of two-fluid model of two-phase flow.

(2) The flow of gunpowder and gas in the bore and the airway is regarded as one-dimensional unsteady flow. There is no influence of powder particles in the airway, that is, solid-phase flow is not considered, only single-phase flow of powder gas is considered.

(3) High temperature and high pressure propellant gas is treated as isentropic flow when it passes through bifurcated and curved pipes.

(4) The viscous dissipation of the gas and the heat loss to the bore wall are neglected.

Interior ballistic model of two-phase flow in the bore: According to the conservation of mass, momentum and energy of the gas phase and the solid phase, the interior ballistic mathematical model of two-phase flow in the bore is as follows:

\[
\frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} = \begin{bmatrix} H - J \\ H - J - K \end{bmatrix}
\]

The projectile passes through the rear hole

The projectile passes through the leading hole

\[
U = \begin{bmatrix} A\phi \rho g \\ A(1-\phi)\rho p \\ A\phi \rho p \\ A(1-\phi)\rho s u_p \\ A\phi s \left( e_g + \frac{u_g^2}{2} \right) \end{bmatrix}
\]

\[
F = \begin{bmatrix} \frac{A\phi g \rho g u_g}{\rho g} \\ \frac{A(1-\phi)\rho p u_g}{\rho p} \\ \frac{A\phi p \rho p u_p}{\rho p} \\ \frac{A(1-\phi)\rho s \rho p u_p}{\rho s} \\ \frac{A\phi s \rho s u_p}{\rho s} \end{bmatrix}
\]

\[
H = \begin{bmatrix} A\rho s + m_g \\ A\rho p + m_p + u_p u_g - f_i + p \frac{\partial A}{\partial \rho g} \\ A(f_i - m_p u_p) + p \frac{\partial A(1-\phi)}{\partial \rho p} + \tau_p (1-\phi) \frac{\partial A}{\partial \rho p} \\ A\rho p + \frac{\partial A}{\partial \rho p} \\ A(m_p + \rho_p u_p^2 + m_p u_p - Q_s) - p \frac{\partial A}{\partial \rho p} \end{bmatrix}
\]

\[
J = \begin{bmatrix} A\rho g \\ A\rho p \\ 0 \\ A\rho p u_p \\ 0 \end{bmatrix}
\]

\[
K = \begin{bmatrix} A\rho g \\ A\rho p \\ A\rho p u_p \\ A\rho p u_p \\ A\rho g \left( e_g + \frac{p}{\rho g} + \frac{u_g^2}{2} \right) \end{bmatrix}
\]

Where: \(A\) is the cross-sectional area inside the barrel bore; \(\rho_g\) and \(\rho_p\) are respectively the gas phase density and solid phase density in the bore; \(u_g\) and \(u_p\) are respectively gas phase velocity and solid phase velocity.
velocity in the bore; \( e_g \) and \( e_p \) are the relative internal energy of gas and solid in the bore; \( \phi \) is the voidage in the bore; \( p \) is the pressure of gunpowder gas in the bore; \( \tau_p \) is the inter-particle stress of gunpowder in the bore; \( m_c \) and \( m_{ign} \) are the gas formation rates of propellant and ignition propellant, respectively. \( \phi \) is the voidage; \( p \) is the pressure of gunpowder gas in the bore; \( \tau_p \) is the inter-particle stress of gunpowder in the bore; \( m_c \) and \( m_{ign} \) are the gas formation rates of propellant and ignition propellant, respectively. \( u_{ign} \) is the mass flow per unit volume of gas phase flowing into the airway from the bore; \( u_{gb} \) is the velocity of gunpowder gas flowing into the airway from the bore; \( p_r \), \( \rho_g \) and \( e_g \) are respectively the pressure at the guide hole, gas phase density and gas relative internal energy; \( m_{gb} \) is the mass flow per unit volume of gas phase flowing into the airway from the bore; \( u_{ign} \), \( u_{gb} \), \( p_r \), \( \rho_g \) and \( e_g \) are respectively the pressure at the guide hole, gas phase density and gas relative internal energy [8,9].

3. Computational Simulation

According to the internal ballistic theory of two-phase flow, the backthrust of the upper and lower nozzles is inconsistent because the gas pressure of the rear nozzle is greater than that of the front nozzle. Therefore, adjust the aperture of the guide hole to make the aperture of the back guide hole slightly smaller than that of the front one, so that the flow rate of the powder gas and the reverse thrust in the two nozzles are equal. Adjusting the length of the nozzle plays a delay role, so that when the gunpowder gas passes through the lower nozzle, the projectile just accelerates to the leading nozzle and the gunpowder gas is eject from the upper nozzle. Finally, Matlab programming is used to numerically solve the size of the nozzle's reverse thrust at different distances between the front and rear nozzle, as shown in Table 1:

| Distance of rear hole /mm | Distance of leading hole /mm | Diameter of rear hole /mm | Diameter of leading hole /mm | The impulse of upper nozzle/(N·s) | The impulse of lower nozzle/(N·s) | Reduction rate of muzzle velocity/% |
|--------------------------|-----------------------------|---------------------------|-----------------------------|----------------------------------|----------------------------------|-----------------------------------|
| 1400                     | 1600                        | 12                        | 14                         | 57.3                             | 58.7                             | 1.24                              |
| 1400                     | 1800                        | 12                        | 16                         | 54.2                             | 57.4                             | 1.51                              |
| 1400                     | 2000                        | 12                        | 18                         | 51.9                             | 56.9                             | 1.72                              |

It can be seen from the table that adjusting the diameters of the front and back guide holes can effectively balance the difference of the reverse thrust impulse of the upper and lower nozzle caused by the different positions of the front and back guide holes, and achieve the basic consistency of impulse on the premise that the initial velocity of the projectile decreases little. By calculating and changing the length of the nozzle, the reverse thrust loaded by the upper and lower nozzle to the weapon system can be implemented simultaneously, so as to achieve the purpose of force couple, so that the nozzle can achieve the effect of delay.

4. Dynamics Simulation

4.1. Muzzle Vibration Characteristic Curve of Ordinary Chain Gun

The launch dynamics model of a 30mm chain gun was established and imported into Adams. The chain gun did not consider the muzzle brake and used the original buffer spring, and the barrel, test frame and buffer seat were flexibly treated. Then, the internal ballistic data of two-phase flow without vibration control device is imported into Adams model. The original radio frequency of the gun was 300rpm/min, and the simulation time was set as 1s, that is, the gun fired 5 times continuously. Through the dynamic simulation of the gun model by Adams, the muzzle transverse vibration characteristic curve of the weapon system under the condition of 5 consecutive firing is obtained, as shown in Figure 2 below:
Figure 2. Muzzle vibration characteristic curve of ordinary chain gun.

4.2. Muzzle vibration characteristic curve of a chain gun with a double-nozzle power-couple vibration controller with a delayed rear nozzle

Equipped with weapons dynamical coupling type pipe body vibration control device of a 30 mm chain gun in the launch dynamics model and imported into Adams, the nozzle sleeve and body pipe hoop with a body with a fixed connection, respectively with the laval nozzle and airway nozzle sleeve and the guide hole at a fixed connection, other structure are consistent with the normal chain gun, The barrel, test frame and cushion seat are also flexible. In combination with the third quarter of the numerical simulation results and the joint simulation of Adams software, the numerical simulation in the third quarter to get one set of top and bottom reverse thrust nozzle and the bottom of the bore pressure data and import to the Adams model, and load up and down in the bottom of the chamber and the corresponding position of the nozzle, through AKISPL function to set the values the triggering time of the sensor to control. The simulation conditions were also consistent with those before the device was loaded. The original radio frequency was 300rpm/min, and the simulation time was set at 1s, that is, 5 consecutive shots were fired. In the end, the muzzle vibration characteristic curve of chain gun with double-nozzle power-couple vibration controller with delayed rear nozzle obtained by simulation calculation is shown in Figure 3 below:

Figure 3. Muzzle vibration characteristic curve of a chain gun with a double-nozzle power-couple vibration controller with a delayed rear nozzle.
By comparing Figure 3 with Figure 2, it can be seen that in the simulation results of continuous firing for 5 times of chain gun with double-nozzle power-couple vibration controller equipped with delayed rear nozzle, the lateral vibration line displacement of muzzle decreases from the original (-8.5mm, 8.1mm) to (-6.9mm, 4.9mm). The muzzle lateral vibration velocity increases slightly below the horizontal line, by about 40%. The angular displacement and velocity of muzzle transverse vibration decreased significantly from the original (-6.5mrad, 7.1mrad) and (-1.5rad∙s⁻¹, 1.6rad∙s⁻¹) to (-0.71mrad, 0.73mrad) and (-0.31rad∙s⁻¹, 0.35rad∙s⁻¹). The reduction range is above 75%. Thus concluded that after installed the latency of nozzle double power coupling type vibration controller chain gun nozzle mouth vibration in the process of continuous firing chamber under delay synchronization under the action of aerodynamic force couple, in the height direction of the line displacement and angular displacement and angular velocity have obvious decrease, which has more significant effect in above the horizon of the part. This is because the effect of the reverse couple is to counteract the muzzle jump caused by the recoil torque of the weapon, so the decrease above the horizontal line is more pronounced. At the same time, there is a good consistency between the timing of nozzle reverse thrust couple action and the motion of the projectile, and no exciting phenomenon will occur because of asynchronism.

5. Conclusion
In this paper, a double-nozzles dynamic couple vibration control scheme using part of the propellant gas in the bore with a delayed rear nozzle is designed, and on this basis, the mathematical model of weapon firing is established by using the two-phase flow theory of gas-solid two-phase flow in the bore and the gas phase transient flow in the airway. Through dynamic simulation, the muzzle vibration characteristic curve of a 30mm chain gun was obtained under the condition of double-nozzle dynamic couple vibration controller with delayed rear nozzle. By comparing with the initial chain gun, the effectiveness of the device on muzzle vibration of the weapon during continuous firing is analyzed, which lays a foundation for the research on the theory and method of nozzle air flow backthrust vibration. The following conclusions can be drawn:

(1) The nozzle with a time delay of dual nozzle power accidentally in the bore type vibration controller by diverting some of gunpowder gas from the expansion of the high-speed jet nozzle, and adjust the length of the airway to produce a continuous synchronization of power and the projectile accidentally, by adjusting the position of air guide hole and area to achieve the basic under the premise of not reduce muzzle velocity, effectively reduce the effect of the muzzle vibration, So as to improve the firing accuracy of weapon system.

(2) The two-phase flow theory can better describe the change of the flow field in the bore of the weapon system and the combustion phenomenon of gunpowder in the bore, so that the weapon system has more accurate interior ballistic data and research process in the firing process.

(3) The double-nozzles dynamic couple vibration controller with delayed rear nozzles can suppress the lateral linear displacement, lateral angular displacement and lateral angular velocity of the muzzle by 40% and 75%, respectively. It shows that the structure has good vibration suppression effect in the continuous firing of the gun.

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