Load simulation analysis of a new erection system based on the gas-assisted drive erecting scheme

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Abstract. To improve the traditional erecting process with lower velocity and smaller power density, a new erection system is designed based on the hybrid drive of gas and electric cylinder, which could erect quickly without increasing the power of the whole machine. According to the prescribed rotational motion and the rotational differential equation of the erection mechanism, the computational models of the related characteristic parameters in erection process were set up. Taking some parameters of a missile as boundary conditions, the models were simulated in MATLAB, and the parameters were obtained graphically. The results can offer references for the design of a new erection mechanism based on pyrotechnics.

1. Introduction
Erection system is the mechanism of the missile launching vehicle to erect the missile from the horizontal state to the inclined or vertical state[1]. The large inertia erecting system can realize the rapid erection of heavy load and ensure the high mobility and quick response ability of weapon equipment, so it is widely used in military field. In the research of erecting system, there is a great gap between China and foreign countries[2-3]. The erection time of China's active erecting system is 140 s ~ 180 s, while the erection of Russian poplar M-series strategic missiles is completed within 20s. The traditional erecting system in China mostly uses hydraulic as the driving source, which has the advantages of large thrust and large stroke. However, due to the limitation of the energy density of power source and mechanical space size, the hydraulic drive has the problems of relatively slow erection and insufficient energy density. Many domestic research institutes and universities have done a lot of research work on the optimization design of traditional hydraulic erecting mechanism and control system[4-7], which has certain guiding significance to improve the stability and rapidity of the erecting system, but these studies can not fundamentally solve the problem of rapid erection.

In order to complete the erection within 20 seconds, exploring a new driving mode of erecting system becomes a new research direction. In order to greatly improve the erection speed, this paper proposes a gas assisted Missile Erecting System Scheme driven by gas and electric cylinder. The missile can be erected quickly without increasing the whole power of the erecting system. In this paper, the erection load of the gas assisted erecting system is simulated, and the relevant characteristic parameters of the erecting system are determined, which is convenient for the subsequent design of mechanism structure and control strategy.

2. Composition and working principle of erection system
The gas assisted erecting system is mainly composed of gas booster unit and electric cylinder system, and its schematic diagram is shown in figure 1.
1-servo motor, 2-servo motor reducer, 3-safety clutch (torque limiter), 4-brake, 5-driving pulley, 6-driven pulley, 7-trunnion, 8-rolling bearing, 9, 10-screw transmission system, 11-multi-stage electric cylinder block, 12-anti rotation device, 13-pyrotechnics driving unit, 14-rack assembly, 15-gear assembly, 16-pyrotechnics driving unit, 17-electric ignite

Figure 1. Composition diagram of gas assisted erecting system.

The working principle of the gas assisted erection system is as follows: after the erection system is started, the electric ignite ignites to make the gas unit work. In the gas driving unit, the high-pressure gas enters the power cavity through the damping chamber through the damping structure. Under the pressure difference between the power chamber and the damping chamber, making the missile frame hinged with the trunnion rotate at a certain angle to complete the erection of the initial section. After the missile rotates to the angle when the gas unit is finished, the controller of the erecting system controls the clutch to disconnect the gas unit, connect the servo motor, and continue to push the screw. Through the brake and anti-rotation device to prevent the screw from reverse movement under the load, the Missile Erecting is finally realized.

3. Load mathematical model of erecting system

3.1. Analysis of hinge point layout and mechanism elongation of erecting system

There are three different motion states in the process of erecting missile by erecting mechanism, as shown in figure 2. And $O_4$, $O_1$, $O_4'$ are the mass centers of the missile in state 1, state 2 and state 3 respectively. Set $\overrightarrow{O_1O_2} = L_1$, $\overrightarrow{O_2O_3} = L_2$, $\overrightarrow{O_3O_4} = L_3$, $\overrightarrow{O_1O_4'} = L_4$, $O_1'$ is the coordinate origin, the angle between the line $O_1O_3$ and the horizontal line is $\theta$, and the angle between the line $O_1O_2$ and the horizontal line is $\theta_0$.

Figure 2. Different motion states of missile during erection.

Figure 3. Curve of angular velocity of erection with time.
The length of the erecting mechanism in the fully retracted state is $L_{\text{min}}$, and the length in the fully extended state is $L_{\text{max}}$, and the expansion ratio $\lambda$ formula is as follows:

$$
\lambda = \frac{L_{\text{max}}}{L_{\text{min}}}
$$

(1)

$$
L_1^2 - \frac{2L_3}{\lambda^2 - 1} \left[ \lambda^2 \cos(\varphi_0 + \delta_0) - \cos(\varphi_0 + \delta_0 + 90^\circ) \right] L_1 + L_3^2 = 0
$$

(2)

The erecting system is set to go through the erection process of "uniform acceleration uniform speed uniform deceleration", and the erection angular velocity curve is shown in figure 3. The mathematical model of erection angle $\varphi(t)$ changing with time is shown in equation (3).

$$
\varphi(t) = \begin{cases} 
\varphi_1 + w_1(t - t_1) & 0 < t < t_1 \\
\varphi_2 + w_1(t - t_1) + \frac{1}{2}a(t - t_2)^2 & t_1 < t \leq t_2 \\
\varphi_2 + w_1(t - t_1) + \frac{1}{2}a(t - t_2)^2 + \frac{1}{2}a(t - t_3)^2 & t_2 < t \leq t_3
\end{cases}
$$

(3)

Where $\theta(t)$ is the angle between and at time $t$. The formula of $s(t)$ at time $t$ is as follows:

$$
s(t) = L_1(t) - L_2
$$

(4)

By deriving equation (10) to time $t$, the erecting speed of erecting system $v(t)$ can be obtained.

$$
v(t) = \frac{L_1 L_3 \sin \theta(t)}{\sqrt{L_1^2 + L_3^2 - 2L_1 L_3 \cos \theta(t)}} \cdot \dot{\theta}(t)
$$

(5)

3.2. Analysis of heavy moment and wind load of erecting system

The weight moment formula $M_{GC}(t)$ of the erection system is as follows:

$$
M_{GC}(t) = G_c L_4 \cos \varphi(t)
$$

(6)

The wind load moment acting on the missile $M_{WC}(t)$ at time $t$ is as follows:

$$
M_{WC}(t) = \int \frac{1}{2} \rho \left[ \frac{H}{H_1} \right]^a v(H_1) C_{L} R_{H} \beta x \sin \varphi(t) dA(t)
$$

(7)

Where $C_{L}$ is taking 0.8, $R_{H}$ is taking 1.13, $\beta$ is 1.22 - 1.75, $\rho$ is the air density under a certain temperature, which is 1.293 kg/m$^3$; $v(H_1)$ is the average wind speed is 15 m/s, $a$ is taking 0.16.

3.3. Analysis of erection force of erection system

The moment acting on the erection system is as follows:

$$
J \cdot \varphi(t) = - [M_{WC}(t) + M_{GC}(t) + M_{\rho}(t) + M_{f}(t)]
$$

(8)
The erection force formula of the erection system at time $t$ is as follows:

$$F_p(t) = \frac{J \cdot \dot{\varphi}(t) + M_{wc}(t) + M_{gc}(t)}{L_p(t)}$$  \hspace{1cm} (9)

4. Load simulation analysis of erecting system

Based on the above mathematical model, the calculation program is written by MATLAB, and the calculation flow is shown in figure 4.

![Flow chart of MATLAB simulation calculation.](image)

Figure 4. Flow chart of MATLAB simulation calculation.

Suppose that the weight of a certain type of missile is 42000 kg, the length of a certain type of missile is 13 m, the diameter of a certain type of missile is 2.25 m, the erection angle of a certain type of missile is $0-90^\circ$, $x$ is 7 m, $y$ is 0.66 m, O3 is 1.125m, Y3 is 1.125 m, and $\varepsilon$ is 0.00174, according to these parameters, through formula (1) - formula (8) and simulation calculation, the elongation, extension speed, weight moment, wind load moment and erection force of the erecting mechanism can be obtained. The simulation results are shown in figure 5 - figure 9.

![Variation curve of elongation of erecting mechanism with time.](image)

Figure 5. Variation curve of elongation of erecting mechanism with time.

![Curve of extension speed with time.](image)

Figure 6. Curve of extension speed with time.

![Variation curve of gravity moment with time.](image)

Figure 7. variation curve of gravity moment with time.

![Variation curve of wind load moment with time.](image)

Figure 8. variation curve of wind load moment with time.

![Curve of erection force with time](image)

Figure 9. Curve of erection force with time.
According to the results of simulation, the conclusions are as follows:

First, it can be seen from figure 5 that when the erecting angle changes from 0° to 90°, the telescopic length of the erecting mechanism is extended from 0 mm to 3203 mm, and the erection time is 20 s.

Second, it can be seen from figure 6 that when the erection time of the gas assisted erection system is 5s, the extension speed reaches 0.5 m/s, and the corresponding erection angle is 15° to form an inflection point on the curve. When the erection time is 8.5s, the extension speed reaches the maximum value of 0.54 m/s, corresponding to the erection angle of 36%. When the erection time is 15 s, the erection speed is up to 0.5 m/s. The second turning point is 0.44 m/s, and the corresponding erection angle is 75°. The simulation results can provide the basis for the control strategy design of the erecting mechanism.

Thirdly, it can be seen from figure 7 that when the erection time is 16 s and the erection angle is 80.4°, the direction of the heavy moment changes, and the erection mechanism changes from compression to tension. At this stage, the gas assisted erection system needs to provide tension rather than thrust.

Fourthly, it can be seen from figure 8 that the wind pressure and effective area of the wind load on the erecting mechanism increase with the increase of the erection angle, and the wind load torque increases obviously. When the erecting mechanism erects the missile in place, the wind load torque reaches the maximum, and the wind load torque is about $3.7 \times 10^5$ N·m.

Finally, it can be seen from figure 9 that in the case of downwind, the erecting force of the erecting mechanism needs to provide $1.58 \times 10^6$N when the erection time is 0 s. With the increase of time, the erecting thrust of the erecting mechanism gradually decreases. The erecting force of the erecting mechanism changes from thrust to tension at 15.6 s. And with the increase of time, the erecting force of the erecting mechanism gradually increases. The erecting force provided by the erecting mechanism is about $3.63 \times 10^5$ N at 20 s. In the case of upwind, the erecting force of the erecting mechanism needs to provide $1.58 \times 10^6$ N when the erection time is 0 s. With the increase of time, the erecting force of the erecting mechanism gradually decreases. The erecting force of the erecting mechanism changes from thrust to tension at 15.9 s, and then with the increase of time, the erecting force of the erecting mechanism gradually increases. When the missile is in place at 20 s, the erecting force provided by the erecting mechanism is about $3.12 \times 10^5$ N. The vertical force curve of the erecting mechanism provides the basis for the control strategy.

5. Conclusion

A new erection system is designed based on the hybrid drive of gas and electric cylinder, which could erect quickly without increasing the power of the whole machine. The force of gas assisted Missile Erecting System is analyzed, and the mathematical models of hinge point layout, mechanism elongation, gravity distance, wind load moment and erection force are established. Taking some parameters of a missile as boundary conditions, the models were simulated in MATLAB, and the parameters were obtained graphically. The results can offer references for the design of a new erection mechanism based on pyrotechnics.

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