Study on Flexible cylinder Ejection Accelerator System Dynamics

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Abstract

Based on the drive energy needs of the train collision test bench, a type of flexible cylinder ejection acceleration method is proposed. Under the mode of constant gas flow rate, it can make the high-pressure gas push heavy bodywork to do work in a short distance and time which make the heavy gain higher kinetic energy, and no blasting phenomenon. Take the multilayer cystiform flexible cylinders as the main object of study, and during its deployment process, analyze the flexible cylinder the thrust function distance, catapult energy feature and the continuity of pushing force, etc. The result of study shows: when the flexible airbag is folded and then inflation, its ejection ability is related to its deployment length and capsule number. The more capsule number and the more fully folded, the deployment length and the effective thrust function distance of flexible cylinder is longer and the ejection ability is stronger. At the same time, the thrust of flexible cylinder to ejection bodywork is a continuous and effective process. In the same bodywork quality and different initial pressure situation, by numerical analysis and experimental tests the ejection process of flexible air cylinder, the ejection bodyworks maximum speed distribution curves with of pressure changing are similar. That reflects the flexible cylinder ejection acceleration method is feasible. And through the combined drive of certain parameter characteristics of flexible cylinder 4.6 MJ kinetic energy of the collision can be obtained can be obtained, enabling 60t single full-size vehicle according to EN15227 standard implementation of crash performance tests.

Keywords

Locomotive; Crash test; Flexible cylinder; Ejection technology.

1. Introduction

The test bench collision test is the most direct and effective method to study the passive safety characteristics of locomotive. At present, the collision test system of locomotive mainly adopts the acceleration methods of traction truck, winch or linear motor traction, weight hammer falling, downhill driving, automatic driving, piston pushing and so on.

The energy required for the real vehicle collision test of locomotive is high, and the energy provided by the acceleration system based on those acceleration theories is limited, and there are some disadvantages such as equipment heavier, occupying a large area, high cost and poor repeatability [1][2].

By rapidly releasing the pre-stored energy of the system under controllable conditions, the ejection mechanism can accelerate the speed of dozens of tons of ejection objects to nearly 100 meters (m/s) in a short time and a short distance. According to the different forms of power, there are mechanical, electromagnetic, gunpowder, gas-fired, steam, high pressure gas, hydraulic and other catapult devices [3-6]。Explosive, gas-fired, gunpowder, rocket, steam and other catapult devices do not meet the requirements of locomotive crash test site. The energy provided by the mechanical type catapult devices is less, electromagnetic accelerators will be subject to strong magnetic interference, and the usable ejection acceleration method are high pressure gas type and hydraulic type. The instantaneous release of energy stored in a high-pressure gas, liquid, or vapor-liquid mixture can push the piston in the rigid cylinder to do work, thereby enabling the weight to achieve a higher ejection velocity. It also has the disadvantages of equipment heavier, big noise, difficult manufacturing process of high-pressure gas cylinders, sophisticated equipment and difficult maintenance [7-9]. At the same time, the length, diameter and other parameters of rigid cylinder or hydraulic cylinder will restrict the improvement of its ejection ability.

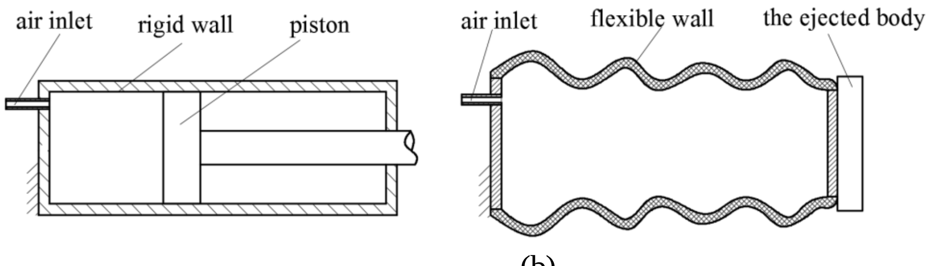
In this paper, a method of ejection acceleration of high-pressure gas expanding in flexible boundary to release energy cylinder is proposed to solve the acceleration problem of locomotive collision test bench.

The flexible cylinder will elongate along with the expansion of the high-pressure gas， and when the gas flow into the flexible cylinder at a constant flow rate, The high pressure gas can work on the heavy object in a short distance and time, making it obtain high kinetic energy. The characteristics of ejection energy of the flexible cylinder with a curved capsule structure are studied.

2. Problem Description

2.1 Flexible Cylinder

The cylinder or the hydraulic cylinder of the high-pressure gas type and the hydraulic type catapult device is rigid, which can bear certain pressure without deformation, moreover it will not distort in the launching or the catapult process. As shown in fig. 1(a), the barrel of air cylinder is fixed, and when the high-pressure gas in the cylinder pushes the piston to move in a straight line to the right, the position of the piston moves relative to the cylinder boundary (rigid wall), while the length and shape of the air cylinder remain unchanged. The magnitude of the piston doing work to the ejection object is related to the effective working area of the high-pressure gas, the pressure of air and the displacement of the piston.



(b)

Fig. 1 the cylinder constraints

Compared with the rigid boundary air cylinder, the boundary of the flexible cylinder is made of flexible materials, which is called the flexible wall. The shape and length of the whole flexible cylinder will change during the progress of ejection work is done.

In figure 1(b), the flexible wall of the flexible cylinder can be folded and withstand a certain pressure of high-pressure gas.

The flexible cylinder is folded and then filled with compressed air at a constant air flow rate, which will make the volume and length of the flexible cylinder increase. In the process of flexible cylinder deployment, on the contact area between the air cylinder and the ejection object, the force generated by compressed air will make the ejection object accelerate motion. In this process, the length of the air cylinder increases dynamically, and the shape of the flexible wall also changes. As long as the strength of the flexible wall is sufficient, the phenomenon of gas blasting and rigid impact of components will not happen which often occur in the rigid air cylinder. Similar to the rigid cylinder, the magnitude of the flexible boundary air cylinder doing work is except in related to the effective action area and air pressure, but the effective acting distance of the high-pressure air also is an important influencing factor. But in the same space, compared to the rigid cylinder, the compressed air effective acting distance of the flexible cylinder is longer, and the kinetic energy of ejection object obtained is higher.

2.2 Flexible cylinder ejection acceleration system

The components of the flexible cylinder ejection acceleration system of the locomotive collision test bench studied in this paper include gas-tank, flexible cylinder (whose shape is similar to the curved sac of air spring and easy to fold), limit device, ejection vehicle body and track, etc. The left side of the flexible cylinder is provided with an opening as an air inlet, which is connected with the air filling tank, and the right side of the flexible cylinder is sealed and in contact with the ejection vehicle body. The collision test ejection system of locomotive is shown in figure 2.

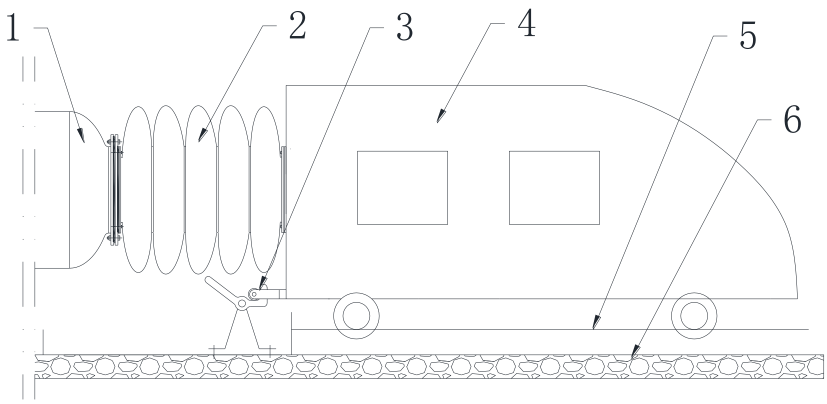


Fig. 2 the ejection acceleration system of flexible cylinder

1-air filling tank; 2-flexable cylinder; 3- limit device; 4- ejection vehicle body; 5- track; 6-the foundation;

Firstly, the ejection vehicle body is pushed to the left, the flexible cylinder is folded and contracted to a certain length, and the limit device is used to fix the catapult body. Then the compressed air is filled into the flexible cylinder with a constant air flow. When the air pressure in the cylinder reaches the set value, the limit device is controlled to unlock the ejection vehicle body. Under the action of compressed air, the flexible cylinder gradually deploys and pushes the catapult body to do accelerated motion until the flexible cylinder is fully deployment.

2.3 Mathematic model

Constant air intake flow is the inflating method in the process of flexible cylinder folding and then inflating deploy. During the process of ejection, the constant air intake flow in the cylinder can maintain the relatively stable thrust force. The inflatable flow rate of the flexible cylinder is controlled by the flow valve of the air inlet. When the flexible cylinder is fully deploying ejection, the air supply is stopped. In this process, it changes with time which the pressure p of the high-pressure gas in the flexible cylinder and the effective force F acting on the ejection vehicle body. But the effective action area A of the high-pressure gas is a constant value, and the moving speed of the flexible cylinder right sealing end is equal to of the ejection vehicle body.

The inflation deployment process of the flexible cylinder in constant air intake flow can be regarded as two stages:

In the first stage, the volume of the flexible cylinder remains unchanged to V_0 and gas is filling, until the gas pressure in the flexible cylinder is p_1, and the time taken is set as t.

In the second stage, ignoring the gas leakage, the gas mass in the flexible cylinder remains unchanged, and the flexible cylinder deploy. At time t, the volume of the flexible cylinder increases to V; meanwhile, the gas pressure in the flexible cylinder is reduced to p.

(1) Calculate the pressure p_1 in the flexible cylinder at time t: at this time, after the gas flowing into, the volume of the flexible cylinder is not changed to V_0; the gas flow is Q, the volume of the gas flowing into the flexible cylinder is V=Qt, and the pressure increases from p_0 to p_1:

$$p_1 = p_0 + \Delta p \tag{1}$$

$$\Delta p = \Delta V T_i \frac{\rho R}{M V_0}(1-\xi) \tag{2}$$

$$\xi = \frac{M V_0 p_0 + \rho R T_i \Delta V}{\rho R T_i (V_0 + \Delta V)} \tag{3}$$

Put (3) into equations (2) and (1) to get:

$$\Delta p = \frac{\rho R T_i}{M V_0}\left(\frac{V_0 \Delta V}{V_0 + \Delta V}\right) - \frac{P_0 \Delta V}{V_0 + \Delta V} \tag{4}$$

$$p_1 = \frac{p_0 V_0}{V_0 + Qt} + \frac{\rho R T_i Q}{M}\frac{t}{V_0 + Qt} \tag{5}$$

In the formula, p_0 and V_0 are the initial pressure and volume of the flexible cylinder before deployment respectively. Q is the gas flow into the flexible cylinder; T_i is the gas temperature in the flexible cylinder, and here is room temperature T; ρ is the density of gas; M is the molecular mass of air; R is the ideal gas constant.

(2) When the pressure increases to p_1, the gas mass in the flexible cylinder is constant, the volume of the flexible cylinder increases to V, and the pressure decreases to p. According to the ideal state equation，can get:

$$\frac{pV}{T_2} = \frac{p_1 V_0}{T_1} \tag{6}$$

$$V = V_0 + x \cdot A \tag{7}$$

Where, x, p and V are the deployment length, air pressure value and volume of the flexible cylinder at time t.

$$x = \int_0^t \left(\int_0^t \frac{p \cdot A - \mu m g}{m} dt \right) dt \tag{8}$$

$$A \cdot \left[\int_0^t \left(\int_0^t \frac{p \cdot A - \mu m g}{m} dt \right) dt \right] + V_0 = \frac{p_1 V_0}{p} \tag{9}$$

Equation (9) can also be written as:

$$p = \frac{p_1 V_0}{A \cdot \left[\int_0^t \left(\int_0^t ? \frac{p \cdot A - \mu m g}{m} dt \right) dt \right] + V_0} \tag{10}$$

The second derivative of both equations (10) sides with respect to time:

$$\frac{P \cdot A - \mu mg}{mV_0} = \frac{p_1^{''} p^2 - (p_1 p'' + 2 p_1^{'} p') p + 2 p_1 p^{'2}}{p^3} \tag{11}$$

Since p_1 is a function of time t, can get:

$$p_1^{'} = \Delta p^{'} \quad p_1^{''} = \Delta p^{''}$$

$$p_1 = \frac{p_0 V_0}{V_0 + Qt} + \frac{\rho R T_i Q}{M} \frac{t}{V_0 + Qt}$$

$$\begin{cases} p_1^{'} = -\dfrac{V_0 Q \left(M p_0 - \rho R T_i\right)}{M \left(V_0 + Qt\right)^2} \\ p_1^{''} = -\dfrac{2 V_0 Q^2 \left(M p_0 - \rho R T_i\right)}{M \left(V_0 + Qt\right)^3} \end{cases} \tag{12}$$

In combination with (9) and (10), the differential equation of the pressure in the flexible cylinder can be solved to obtain p. According to formula (8), the energy and speed of the test vehicle body at each moment under the inflating mode of constant air intake can be obtained.

$$E = \int_0^t Ftx(t)dt = \int_0^t A \cdot Ptx(t)dt \tag{13}$$

$$v = \sqrt{\frac{2\int_0^t A \cdot Pxdt}{m} - \mu mg \int_0^t xdt} \tag{14}$$

Where, μ—coefficient of kinetic friction; m—mass of ejection vehicle; g—gravitational acceleration; *v*—the speed of ejecting the car body at time t， t∈(0， T), T is the thrusting action total time of the flexible cylinder [10].

3. Analysis of ejection deployment process of flexible cylinder

3.1 The simulation model

The pushing model of flexible cylinder is shown in figure 3. The left end of the flexible cylinder is fixed on the rigid wall, and the ejection vehicle body is simplified into a mass block, which can only move in the Y direction. The process of the flexible cylinder folding and then inflating to deploy to make vehicle body ejected is as follows:

0 to t1 time period: the right end of the flexible cylinder is in contact with the ejection vehicle body, and external forces are applied on the vehicle body to make the flexible cylinder fold until the length shorten to y1, and lock the vehicle body. At the same time, fill the air into the flexible cylinder at a constant air inflow rate. at t_1 moment: the external force applied on the ejection car body disappears; t_2 to t_3 time period: The flexible cylinder gradually deploys and pushes the ejection vehicle body to accelerate movement along the Y direction. At this time, the air inflow filled in the flexible cylinder is still constant. At t_3 moment: the flexible cylinder has been fully deployed, and the air inflow rate becomes 0, and then the ejection vehicle body uniformly decelerated movement under the action of friction.

In figure 3, y_0 is the free length of the flexible cylinder， y_1 is the length of the flexible cylinder after folding and shortening, y_2 is the length of the flexible cylinder in the process of deployment, and y_3 is the length of the flexible cylinder after fully deployment. The system simulation parameters are shown in table 1.

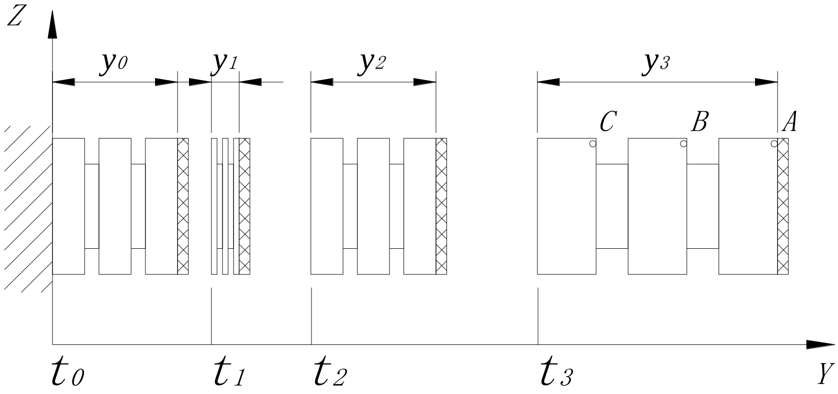


Fig. 3 The length of flexible cylinder varies with time during the inflatable ejection process

Table 1 system simulation parameters

Density kg/m3		Elasticity Modulus	Shear Modulus	Poisson's ratio
The ejection body	7850	EA: 3e11		PR: 0.3
Rigid wall	7850	EA: 3e11		PR: 0.3
The flexible cylinder	1000	EA: 2e10 EB: 2E10 EC: 2E10	GAB: 1.53E10 GBC: 1.53E10 GCA: 1.53E10	PRBA: 0.35 PRCA: 0.35 PRCB: 0.35

3.2 Simulation of the process of flexible cylinder inflating and deploying

The acceleration capability of the flexible cylinder to the ejection body is closely related to elements such as length, the contact area with the ejection body and internal pressure.

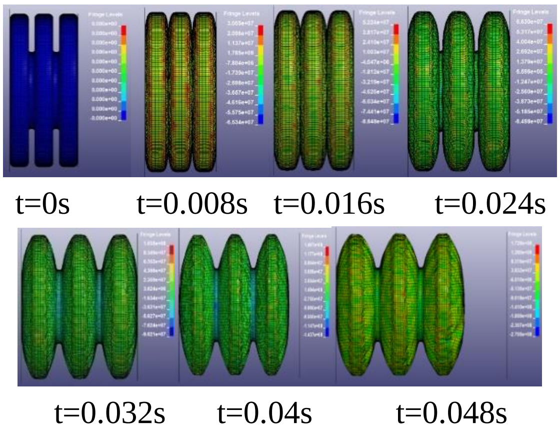


Fig. 4 states at each moment of the process of flexible cylinder inflating and deploying

In figure 4, when t=0s, the ejection vehicle body contacts the flexible cylinder, and external forces are applied on the ejection body. The ejection body moves to the left until t=0.01s, which is the folding and shortening process of the flexible cylinder. With the gas filled into, the internal air pressure of the flexible cylinder increases. At t=0.01s, the external force is removed. The ejection vehicle body, subjecting to the thrust generates from high-pressure gas in the flexible cylinder and the friction resistance on the ground, accelerates in a straight line along the Y direction until the flexible cylinder is fully deployed. After the flexible cylinder is fully deployed, the ejection vehicle body is separated from its right end face, and the ejection vehicle body only does decelerated movement under the frictional resistance. There is no blasting in the process of flexible cylinder deployment.

4. Calculation results and analysis

4.1 The thrust force act distance of the flexible cylinder

In the process of ejection, the length of the flexible wall of the flexible cylinder changes with the expansion of the gas, and the constraint effect of the cylinder on the gas does not change. At the same time, through the flexible cylinder, the thrusting act of the high-pressure gas on the ejection vehicle body still exists and act durablly.

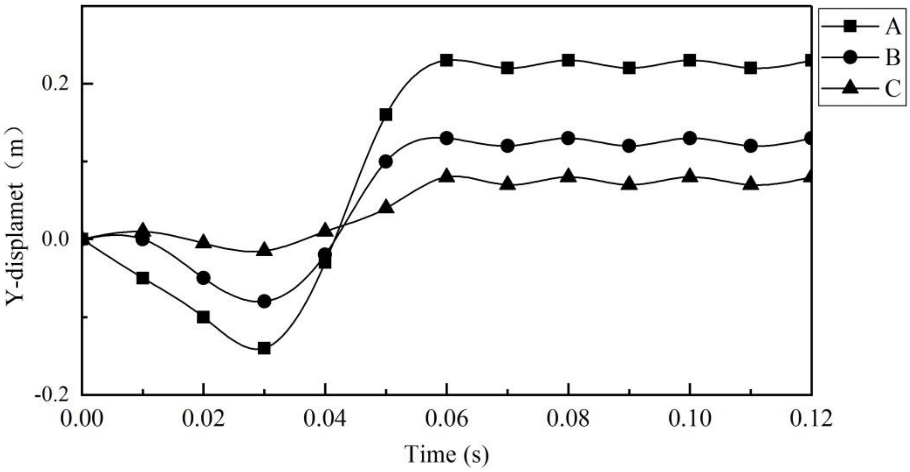


Fig. 5 the force act distance of flexible wall air cylinder deploying

The deployment length of the flexible cylinder is represented by the displacement of the center point at the right end of the flexible cylinder. Under the same ejection conditions, as shown in fig. 5, the three curves of A, B and C are the variation law of the displacement of the center of the right end of the three curved capsules, the two curved capsules, and the single curved capsule with time respectively. The negative displacement in the range of 0 ~ 0.04s represents the displacement of the center point at the right end when the cylinder is folding and shortening. In the period after 0.04s, the curve represents the displacement of the center point at the right end when the cylinder is deploying.

It can be seen that the flexible cylinder which owns three curved capsules has the largest fold shortening length-0.15mm and the longest deployment length-0.25m. The two curved capsules take second place-0.09m and 0.15m.The single curved capsule is shortest-0.025m and 0.08m. It reflects that the deployment distance of flexible cylinders with different curved capsule number is greatly different in the case of folded and filled air. The more the curved capsule number is, the more the folding length is, and the larger the deployment distance is. And within the allowable range of strength, if the gas pressure continues to rise, the deployment length of the flexible cylinder will further increase.

4.2 The energy characteristics of the ejection vehicle body

During the ejection process of flexible cylinder deploying, the energy obtained from the ejection vehicle body is an important index of the ejection acceleration system of flexible cylinder. The amount of the ejection vehicle body energy is related to many factors, such as thrust action distance, air pressure, effective action area of flexible cylinder, material and structure shape of the flexible cylinder, etc., among which, the action distance, air pressure and effective action area are the key factors. Figure 6 shows the kinetic energy changing curves with time of the ejection body in the direction of acceleration movement, under the conditions of constant air inflow rate and effective thrust acting area, when the flexible cylinder with different number of curved capsules is inflated and deployed. The number of curved capsules for A_2, B_2 and C_2 is 1, 2 and 3 respectively.

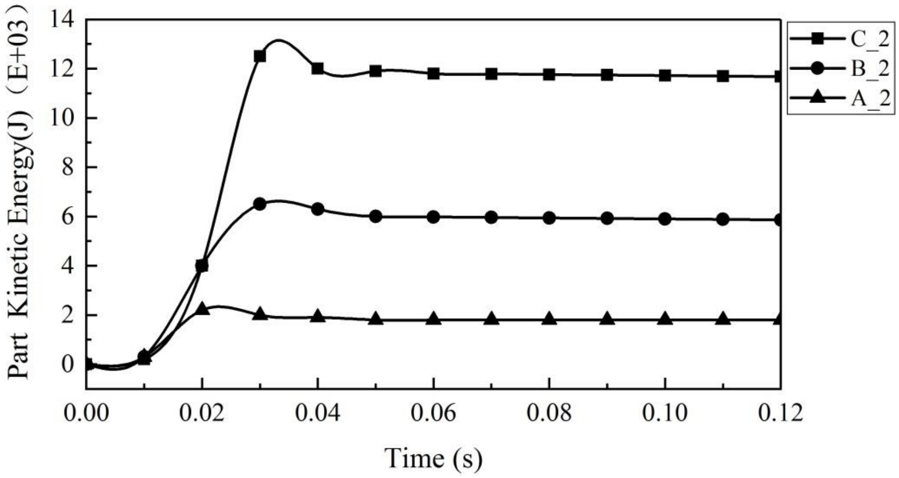


Fig. 6 kinetic energy curves of ejection vehicle body in the inflated and deployed process of flexible cylinder with different number of curved capsules

It can be seen from fig.6, in the process of flexible cylinder with different number of curved capsules deploying and pushing the ejection vehicle body to accelerated movement, the kinetic energy obtained by the ejection vehicle body changes in a similar way with time. Moreover, both of them tend to be stable after 0.04s, but there is an obvious difference in the maximum kinetic energy value obtained and the time taken to reach the maximum kinetic energy value. The flexible cylinder with three curved capsules makes the ejection vehicle body gain the maximum kinetic energy about 12.3 KJ, and the time taken is about 0.035s; The flexible cylinder with two curved capsules makes the ejection vehicle body gain the maximum kinetic energy about 6.3 KJ, and the time taken is about 0.027s; The flexible cylinder with single curved capsules makes the ejection vehicle body gain the maximum kinetic energy about 2.2KJ, and the time taken is about 0.018s.

The flexible cylinder with three curved capsules has the longest pushing action time and the most outstanding ejection acceleration ability. Combined with fig. 5, it can be shown that the more the number of flexible cylinder's curved capsules, the more the folding and shortening, the longer the inflatable deployed length and the effective action time of high-pressure gas, and the greater the kinetic energy obtained of ejecting the vehicle body.

4.3 The continuity of the pushing action process of the flexible cylinder

The left end of the flexible cylinder is fixed with the rigid wall and the right end is in contact with the ejection body, hence it can finish to catapult and accelerate.

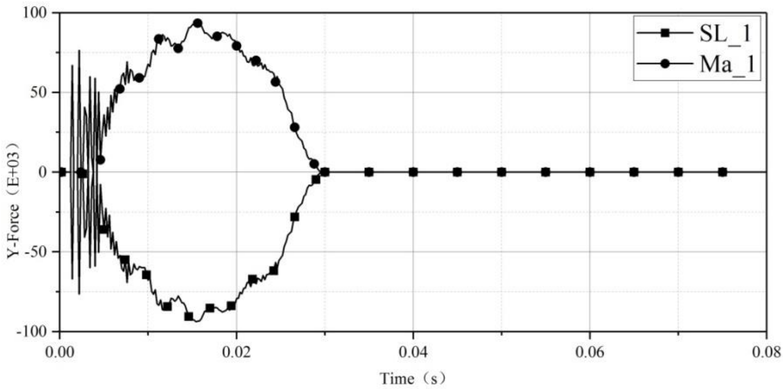


Fig. 7 the force variation curves of flexible cylinder and ejection body

Figure 7 shows the change curve with time of the force of the flexible cylinder and the catapult body. Sl_1、Ma_1 are the change curves with time of the force on the main body (cylinder) and the object (ejection vehicle body) respectively. The continuous curve can judge that the pushing action of flexible cylinder on the ejection body is a continuous and effective process.

In the period of (0, 0.005s), the elastic modulus of the flexible cylinder is small, and the air pressure inside the cylinder fluctuates greatly. The ejection vehicle body is pushed less by high-pressure gas, and the external force is applied on the ejection vehicle body and makes it to fold and shorten, which is finally reflected as violent acceleration fluctuation.

In the period of (0.005s, 0.02s), the internal part of the flexible cylinder is suffered action by high-pressure gas and starts to deploy. The contact surface between the right end of the cylinder and the ejection vehicle body generates a large contact force. The force on the right end of the cylinder and the ejection car body is equal and opposite. Ma_1 curve reflects that the pushing force acting on the ejection vehicle body increases rapidly in a short time, so its acceleration and velocity sharply in this stage.

In the period of (0.035s, 0.002s), the pushing force shows a trend of downward fluctuation, mainly because the volume of the flexible cylinder increases rapidly with the deployment of the flexible cylinder and the air intake flow is constant, so that the pressure inside the flexible cylinder and the driving force on the contact surface decreases. But the thrust still makes the ejection vehicle body accelerate movement.

The downtrend can be improved by reducing the radius of the curved capsule and increasing the air intake flow.

4.4 Flexible cylinder ejection acceleration experiment

The flexible cylinder ejection acceleration test bench is composed of gas storage tank, flexible cylinder, ejection vehicle body, track and connecting parts. The site is in the laboratory, and the ejection body is placed on two long i-shaped tracks separated by a certain distance. The flexible cylinder and gas storage tank are connected with flange structure and sealed. Limit device is the use of the electromagnet gains and loses electricity to control the limit of the ejection vehicle body and release. The gas storage tank, flexible cylinder and limit device are all assembled on the track, as shown in figure 8.

Fig. 8 ejection acceleration test bench of flexible cylinder

The flexible cylinder ejection acceleration test bench can control the air flow rate and gas pressure of the high-pressure gas tank. In the inflation, deployment and ejection process of the flexible cylinder, an acceleration sensor is installed on the ejection vehicle body to obtain the acceleration and velocity in X, Y and Z directions at a point. The multi-signal integrated measurement and control system is composed of pressure sensor, flow sensor, acceleration sensor and electromagnetic controller, which can finish the signal acquisition and control of the ejection acceleration system of the flexible cylinder.

The maximum velocity obtained by ejecting vehicle body is affected by the initial pressure P in the cylinder, the acting length L of thrust, the effective acting area A of the high-pressure gas, and the mass m of the ejecting vehicle body. However, the test bed shown in figure 8, on the one hand, the end of the cylinder is made into a rigid plane, so the effective working area A of the high-pressure gas is constant. On the other hand, the length of the cylinder is not easy to change due to the limitation of installation conditions. The length of the fully deployed is less affected by the air pressure, and the limit device makes the length of the flexible cylinder after folding and shortening constant. Therefore, the cylinder action length L is also regarded as constant.

During the experiment, the variable that can be controlled is the initial pressure P and the ejection vehicle body mass m. In order to simplify the experiment and verify the numerical analysis model, the mass of the ejection vehicle body is not changed during the experiment, which is set as 60.25kg. The initial air pressure before the ejection of the cylinder was designed to change from 0.12 to 0.21MPa and in increments of 0.01MPa, and the maximum speed of ejecting vehicle body under each pressure was recorded.

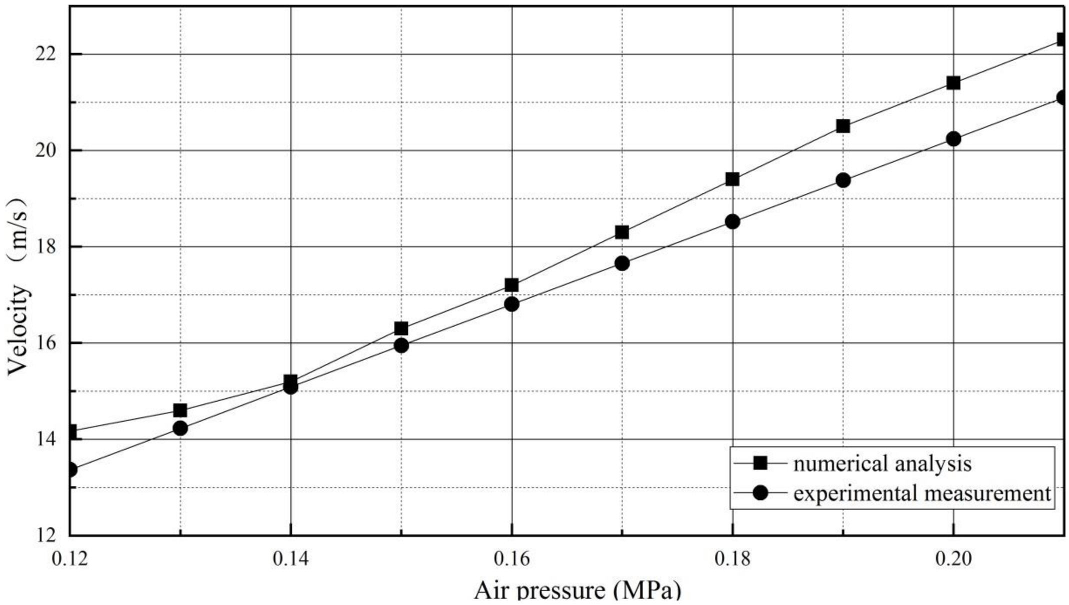


Fig. 9 the maximum ejection body velocity comparison between the numerical analysis and the experimental measured

With the constant mass of the ejection body, figure 9 shows the comparison between the theoretical and measured maximum ejection body velocity of the flexible cylinder at different initial pressures. The results show that the theoretical results of the proposed method are close to the simulation results, On the whole, the data measured in the experiment were slightly larger than that in the simulation analysis, mainly because the elastic modulus of the flexible cylinder material used in the experiment was relatively large. It can be seen that the model used in the numerical analysis is correct and reasonable.

By combining theoretical and experimental analysis, If 6 flexible cylinders with effective diameter of 0.5m and free length of 4m and number of 27 curved capsules are connected in parallel， At the initial pressure of 2MPa and maintaining a constant air intake flow, it can provide energy up to 4.6MJ, enabling a 60t object to achieve a speed of 36km/h. Therefore, it is feasible to realize a train carriage crash test with standard EN15227.

5. Conclusion

In this paper, a flexible cylinder ejection acceleration method is proposed based on the large driving energy requirements of the rail locomotive real crash test. High-pressure gas releases energy inside the flexible boundary and does work on the ejection object to make it obtain high kinetic energy is obtained in short distance and time. Through theoretical formula calculation, simulation model analysis and experimental verification, the ejection acceleration method of flexible cylinder with curved capsule structure was studied, and the following conclusions were drawn:

The ejection ability of flexible cylinder after folding, shortening, being inflated and deploying is related to its deployment length. If the flexible cylinder has more enough folding and more curved capsules, in the process of cylinder deployment, the effective action distance of the cylinder on the ejection body will be longer, and its ejection acceleration ability and pushing force action time will become more prominent. In the process of simulation and experiment, the phenomenon of flexible cylinder blasting did not appear.

The high pressure gas produces a pushing force on the contact surface between the right end of the flexible cylinder and the ejection vehicle body. This pushing force action is a continuous and effective process. However, in the later stage of the deployment and ejection of the flexible cylinder, the driving force presents a downward fluctuation trend. The fluctuation can be reduced and the pushing force can be increased by reducing the radius of the curved capsule and increasing the air intake flow.

Under the condition of the same vehicle body mass and different initial pressure, the maximum velocity of the ejection body was measured by the flexible cylinder ejection acceleration test bench, and compared with the maximum velocity obtained by numerical analysis. The velocity distribution curves obtained by the two methods are close; hence the flexible cylinder ejection acceleration method is feasible. Combined with theoretical and experimental analysis, If 6 flexible cylinders with effective diameter of 0.5m and free length of 4m and number of 27 curved capsules are connected in parallel，At the initial pressure of 2MPa and maintaining a constant air intake flow, it can provide energy up to 4.6MJ, enabling a 60t object to achieve a speed of 36km/h. Therefore, it is feasible to realize a train carriage crash test with standard EN15227.

The research of this paper has reference significance to realize the ejection technology of heavy-duty and high-energy collision test bed by making use of high-pressure gas ejection acceleration method.

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