Numerical Study of a Novel Piston-type Synthetic Jet Actuator with a Quick-return Characteristic

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Abstract. A novel designed piston-type synthetic jet actuator has been developed, which has a quick-return characteristic. When moving to the Top Dead Centre, the piston in high speed route moves faster than the classical one. Compared with classical piston-type SJA, the pressure ratio of the cavity, jet velocity and the jet momentum of the novel SJA increase significantly, which greatly enhances the performance of the actuator. A parametric study has been carried out focusing on the affection in different actuation frequencies and duty cycle. Results show that the performance of the quick-return piston-type SJA is significantly improved.

1. Introduction

Recently, a considerable number of investigations have been carried out in the area of active flow control techniques, and it is a potential field which is beneficial to aerospace, transportation and other fields [1-2]. Synthetic jets have attracted great research interest for the active flow control applications, and the synthetic jet is a jet-like fluid motion formed by the time-periodic, alternative ejection and suction of the fluid through a small orifice bounding a flexible volume cavity. The main structure of the actuator is shown in Figure 1.
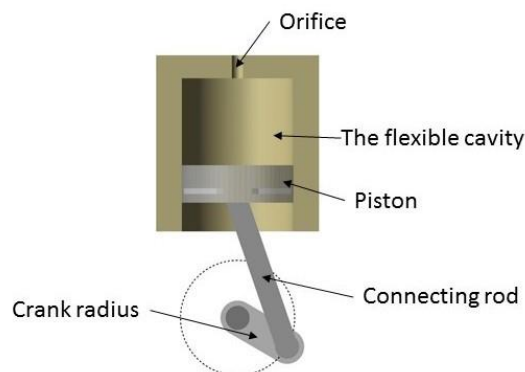

Figure 1. Schematic diagram of synthetic jet actuator driven by piston.

Due to the nature of the zero-net-mass-flux, the synthetic jet is considered as a positive approaching method to the flow control application, involving jet vectoring, flow separation controlling, and boundary layer controlling.

Considerable research has been covered on piston-type SJAs. Georgia Institute of Technology has designed a synthetic jet actuator [3], with the piston diameter 21.2mm, the route 18.4mm, and the volume of the cavity 6.49 cm^3. The max compression ratio was 27.1, and the actuator was set in a normal level of rotate frequency. A conclusion has been drawn that the max velocity of the jet was supersonic in both ejection process and suction process. With the enhancement of the frequency of the piston, the time costed in ejection would be less than that in low level frequency, and the maximum pressure of the cavity would be increased with the minimum of the pressure decreased, the appearance of pressure peak would be put off, which was closer to the t/T=0.5 moment. So, the actuator had to spend more time to breathe more air. The higher the piston frequency was, the more obvious the phenomenon would be. Under the circumstance, the compression ratio (r) was 27.1 with the frequency of the piston 200Hz, the maximum of the pressure up to 6.24atm, the minimum of the pressure 0.22atm, and the peak time t/T=0.5 moment.

From the Figure 2, we could find that the process of suction (the shadow section) cost 71% of a cycle time, leaving about 29% time of the cycle as the ejection process. The reason why the suction time was enlarged and the ejection time was decreased in one period was that the suction was forced by the environment atmosphere's pressure, and the fluid flow wouldn't increase after reaching the critical value. However, ejection was forced by the pressure of the cavity. As a result, the system needed more time to inhale air to meet the requirement of no-mass jet.

Zhang has designed a new piston SJA [4], with the frequency 202Hz, the diameter of the piston 19.5mm's, the 18.6's pressure ration, the maximum pressure was up to the 1.987atm. And with the development of the frequency, the jet velocity would increase, the maximum jet pressure would enlarge in respect with the minimum of the jet pressure decreasing at the same time.

The recently research mostly focus on the performance, including the max jet velocity, the max pressure in the cavity, the total jet mass flow, and the momentum of the jet. Unfortunately, as the things going like the Georgia's, under the high level of the frequency, the jet actuator can't inhale too much air, which doesn't match the mechanical or acoustic resonance phenomenon to get the optimal performance, which is an ideal synthetic jet generator.

This paper proposes a modified mechanical structure, which can enhance the piston's velocity in the ejection process, and the time in outstroke is predicted to be decreased, by putting the piston pin offside the middle line, and shortening the connecting rod length to enhance the quick-return characteristic, aiming at making a significant effect on the ejection velocity and alleviating the shortage of inhaling. The flow-fields are studied by numerical simulation, the effects of actuation frequency and the extent of the quick-return characteristic are also analyzed.

2. Eccentric piston SJA model

2.1 Principle of the quick-return piston-type SJA

The classical piston-type SJA is made up by a crank, a connecting rod, a piston, a cylinder liner, and a jet orifice with the piston pin standing offside the line along which the piston can move away and back. An equation can simulate the motion, (2.1).

$$P_S = \left((r_c + L)^2 - x^2_{offset} \right)^{1/2} - r_c \cos(\theta_c) - \left(L^2 - (r_C \sin(\theta_c) + x_{offset})^2 \right)^{1/2} \quad (2.1)$$

Where P_s is the piston location, r_c is the crank radius, L is the connecting rod length, X_{offset} is the piston pin offset, and θ_c is the current crank angle. Here is the draft model in Figure 3.
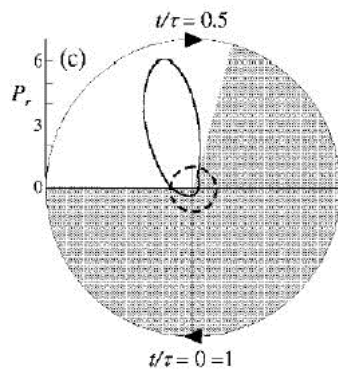
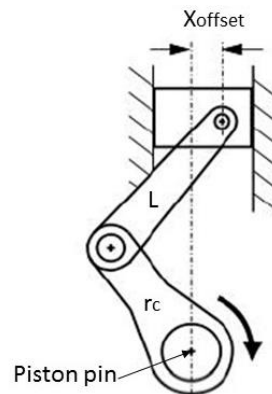**Figure 2.** r=27.1, f=200Hz, draft in polar curve.   **Figure 3.** Eccentric piston-type model.

It is because of the quick-return characteristic that using the slider-crank mechanism, such as the feeder, automatic thread rolling machine is popular in the industry. In the automatic feeder machine, the 'giving material' process which would cost a huge amount of energy is beneficial, so the low-speed route is widely used in it. On the contrary, we try to shorten the back route to save time, as a result, the low-speed route is considered. Taking the quick-return structure is actually fit for the requirement, and the requirement in the piston-type SJA happened roughly as same as the feeder machine. In the common SJA, the time costed in ejection is equal to the suction's in terms of the mechanical structure in theory. In order to enhance the ejection velocity, we put the high-speed route into the ejection process, as the same time, the low-speed route is settled in the suction process. Under this condition, the piston velocity in the back route is a bit slower than the original design, but the time we cost in the inhaling route is more, which is beneficial for the suction route, and the cylinder can inhale much more fluid in a cycle. In conclusion, under the circumstance of constant frequency, the ejection speed is enhanced, which is most important to the performance, and much more fluid was inhaled due to the longer suction time. The quick-return mechanical structure is rather fit for the aerodynamic characteristic.

Three mechanical components, piston pin offset, crank radius and connecting rod length, all have an effect on the quick-return characteristic, and through a branch of examples, we can draw conclusions as followings:

1. Quick-return characteristic occurs due to the offset.
2. It is the crank radius rather than the piston pin offset or the connecting rod length that has a huge affection on the route length as well as the maximum velocity. In order to enhance the velocity, the longer crack radius is expected to be considered.
3. The more approximate the length between the piston pin offset and the crack radius was, the more obvious the quick-return characteristic would be, when the connecting rod length is invariable.
4. The more approximate between the whole length of the piston pin offset as well as the crack radius and the connecting rod length was, the more obvious the quick-return characteristic would be.

In order to explain the phenomenon in more details, we shall set several examples. We designed three cases in table 1.

Table 1. Parameters in different quick-return characteristics.

Name	Piston Pin Offset/mm	Crank Radius (r_c)/mm	Connecting Rod Length (L)/mm	Route/mm (L_c)	Frequency/Hz
Case1	5.87	5.4	14	12.2	200
Case2	5	6.01	30	12.2	200

Case3	0	6.1	30	12.2	200

Here is the reason why to set these examples. First of all, according to a number of samples, we find that the wider the piston pin offset is, the earlier the appearance of the jet velocity peak would be. But, the crank radius would be shortened a little respectively considering the condition of the same route length. Besides, with the reduction of the connecting rod length, the quick-return characteristic is expected to be more apparent with the peak appearing earlier.

An explanation has been given in the Figure 4 bellow. But the article doesn't aim at comparing the different crank radius, different offset or different connecting rod length, and the three above examples are totally different from the extent of the quick-return characteristics.

Case 1 is obvious for the quick-return characteristic, the case 2 is a slight quick-return example, and the case 3 is the contrast example. The Figure 4 below reflect piston velocity on the direction of motion. Data about velocity are all counted from the bottom-dead-center (BDC). When the curve moving to the 'piston velocity is equal to 0' straight line again, the piston is on the top-dead-center (TDC). The maximum velocity in case 1 is 47% higher than case 3, and the case 2 is just 4.8% higher than case 3. Besides, the minimum velocity in case 1 is nearly equal to the case 2 and 3. If the velocity in the suction process is slightly smaller than the non-quick-return SJA's, the energy costed in suction process is projected to be saved a little. Furthermore, what we should focus on is the duty ratio, we can easily find that, in the case 1, the suction time is totally enhanced, and it takes 58.3% of a cycle time. What's more, the trend of the curve is fit for the a wide arrange of frequency. From the 100Hz to the 200Hz, the max and the min velocity is expected to increase, and the duty ratio is predicted to be constant.
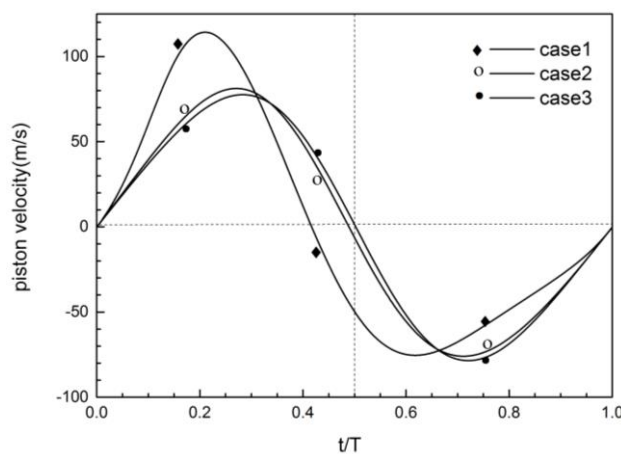

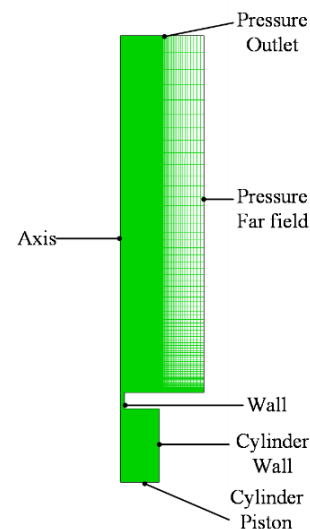**Figure 4.** Plot of the piston velocity.

Figure 5. Computational domain and boundary definition.

Another phenomenon appears in the above Figure 4. The peak in case 1 is earlier than case 2 and case 3. A reasonable explanation can be given that the more quick-return characteristic is, the earlier the peak appears.

2.2 Measurement and the parameter definition

The computational domain of the piston-type SJA flow-field is shown in Figure 5. The cylinder wall is set to adiabatic wall, and the environment flow-fields are set as pressure far field and pressure outlet, in which 1atm pressure is given, and a normal temperature air is also used.

A simple cylinder flow channel (L_c=12.2mm in length) with a constant round cross section (r=9.75mm in radius) is considered in this paper, the 2D axisymmetric section is also shown in Figure 5. The jet direction domain is 90 mm long and the round cross section radius is 21 mm. The nozzle outlet diameter (d) is 3 mm, the thickness is two times of the d (6mm). The actuation frequency (*f*) is

tested every 50 Hz from 100 Hz to 200 Hz, corresponding to the ability of the novel SJA in the experiment. The crank radius and the connecting rod length are flexible. The movement of the piston is simulated by a cylinder dynamic mesh. Specifically the piston wall is defined as a movement wall. The mesh growth of the piston wall is based on smoothing and remeshing methods of mesh deformation. The crank angle step size is 0.1°.

Viscous flow-fields of SJAs are simulated by finite volume method of CFD software Fluent [5]. Conservation equations are solving coupling with the method of density based method. An implicit algorithm with second-order spatial accuracy is used to solve the Navier–Stokes equations for steady flow-fields. The jet flow in the present investigation is unsteady, turbulent, and compressible. Density is calculated based on the ideal gas law. Gravity is neglected.

In order to analysis the performance of the quick-return piston-type SJAs, the seven cases are devised in table 2.

Table 2. Parameters in different cases.

Name	Offset/mm	Crack radius (r_c)/mm	Connecting rod length (L)/mm	Route (L_c)/mm	Frequency/Hz
Case1	5.87	5.4	14	12.2	200
Case2	5	6.04	30	12.2	200
Case3	0	6.08	30	12.2	200
Case4	5.87	5.4	14	12.2	150
Case5	0	6.08	30	12.2	150
Case6	5.87	5.4	30	12.2	100
Case7	0	6.08	30	12.2	100

The table 2 includes diversity of factors, and all of the data are in the same route and pressure ratio (5.8). Case 1 ,4 and 6 are all the obvious forms, Case 2 is the unapparent forms, and Case 3, 5and 7 are all the non-quick-return forms.

3. Comparison of the computational results

3.1 Analysis of the quick-return characteristic impact under 200Hz.

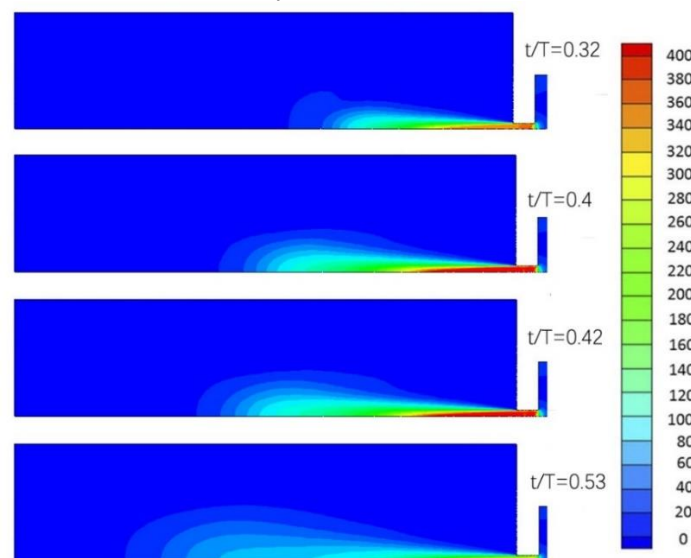*3.1.1 Flow image about the main calculation field under the 200 Hz.*

Figure 6. Jet image at different moments.

The picture above contains 4 images in the condition of case 1, they are different from diversity of velocity at diverse moment in a cycle. The first image is at the t/T=0.32 moment, the piston is moving towards the TDP, and the jet flow is gathering. The second image is at the t/T=0.4 moment which is actually under the maximum pressure of the cavity in the ejection process, and this phenomenon is expected to be discussed in the following paragraphs. And the third image is at the t/T=0.42 moment when the piston is at the TDP. The last one is at the t/T=0.53, the piston is moving away the TDP, but the jet flow is still expanding.

3.1.2 Comparison of the velocity in the X axis direction under the 200Hz
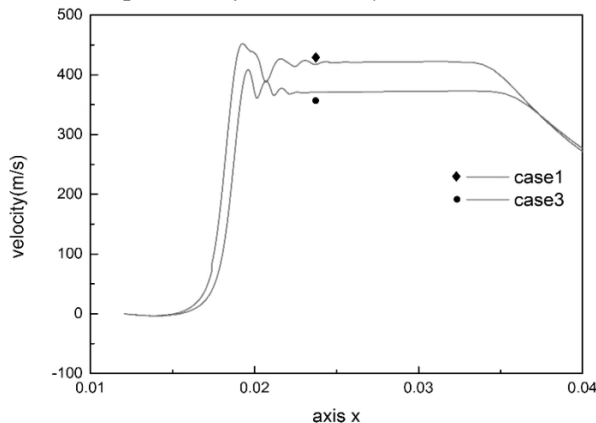

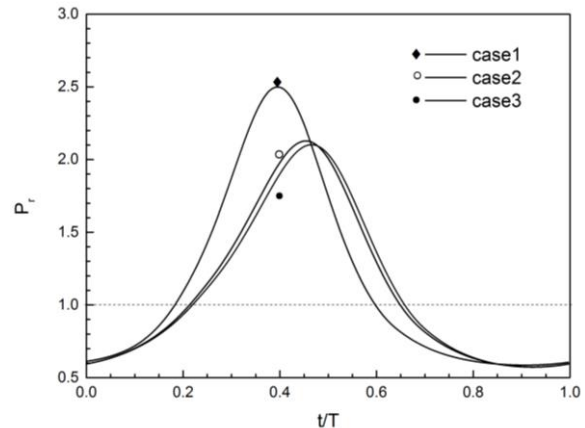**Figure 7.** Velocity in the x-axis direction under the 200Hz.

Figure 8. Pressure ratio in 200Hz.

The positive direction of the x-axis is considered as the jet flow direction. A visual survey can be concluded that the jet flow thrown from the nozzle has a slight supersonic, and the weak shock wave shows in the curve in Figure 7. Besides, the velocity in case 1 is higher than that in case 3, but the depth of the centre jet flow has not formed, because the jet haven't expanded.

3.1.3 Comparison of the pressure under the 200Hz. First, what we should know is the definition of the pressure ratio, which is actually the outcome of the environment pressure divided by the pressure of the cavity. Under the frequency of 200Hz, we can see that (**Figure. 8**), the case 1 takes an advanced phase position, and the peak of the pressure in case 2 is slightly ahead than the case 3, the control group. Besides, the peak of case 1 is 2.5, the peak of case 2 and 3 are 2.13 and 2.1, so the apparent quick-return characteristic facility has a priority in pressure ratio.
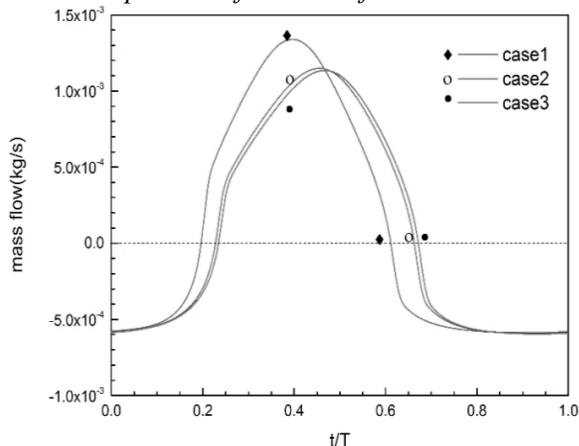
3.1.4 Comparison of the mass flow under the 200Hz

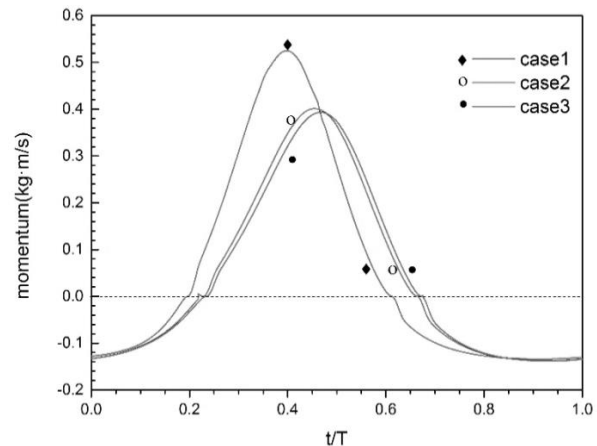**Figure 9.** Mass flow in 200Hz.

Figure 10. Momentum in 200Hz.

From the Figure 9, we can see the same tendency happening. Due to the obvious quick-return structure, the maximum mass flow in case 1 is obviously higher than case 2 and case 3. Besides, through the integration of the mass of the jet flow in one cycle, we can find that the total mass of the jet flow in case 1 is 8 percent more than case 3, and the case 2 is 0.4 percent more than case 3. In the suction process, both the pressure ratio and the mass flow are at the same level, it is expected not to be altered by the quick-return structure.

What's more, the dash line 0.0 is the boundary between ejection and suction, and the part under dash line is representative for suction. Time costed by suction in case 1 takes 58.5 percent of a cycle, by contrast, time costed by suction in case 2 and case 3 respectively are 56.3% and 56.1%. Considering the mechanical suction time of case 1 is 58.3%, the obvious quick-return characteristic facility performs better.

3.1.5 Comparison of the momentum under the 200Hz. The curve (**Figure. 10**) about the momentum has a slight wave around the line 0.0, because of the manual calculation, which shouldn't be noticed a lot. The trend of the momentum is similar to the former's, and the case 1 have a remarkable priority than the case 3. Through the integration of the ejection momentum, the whole jet momentum in case 1 is 22.3 percent more than case 3, and the case 2 is 1.5 percent more than case 3. So the quick-return piston-type SJA not only has a potential to jet velocity and pressure ratio, but also behaves better in the mass and momentum in a cycle.

4. Comparison of P_r in different frequency

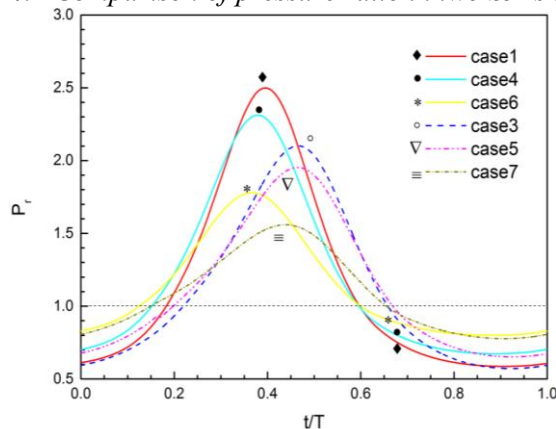*4.1 Comparison of pressure ratio in two SJAs types*

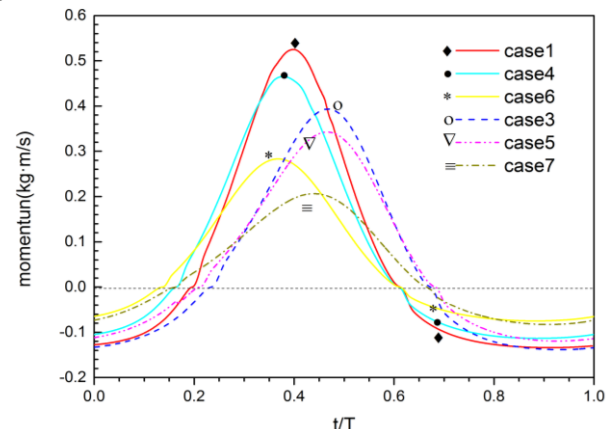| **Figure 11.** Pressure in different frequency in two types. | **Figure 12.** Momentum in different frequency in two types. |

There are six curves in Figure11, three full lines are all from the obvious quick-return SJAs, and the contrast group contains three dash curves, which are from the original SJA's. In the suction process, the beginning time of the suction is disparate from the frequency in terms of the same mechanical structure, but they have the same ending time of suction. SJAs can inhale fluid because of the pressure difference. In the suction process, during the piston moving to a special position where the critical pressure difference has just formed, the actuator is projected to inhale forced by the pressure difference, so it is not difficult to explain why piston in different frequency begin inhaling the fluid at the same moment. However, the faster the piston is, the more difficult suction process the piston is in. In order to breathe more fluid, SJAs have to expand the suction time, so the beginning of the ejection time are in diversity.

Another phenomenon can't be overlooked that the intersection points of the full lines and the P_r=1.0 line are look-ahead from the intersection point of the dash lines, because the quick-return piston-type SJA is predicted to meet the peak of velocity ahead in the ejection process.

Furthermore, contrasting with different frequency, the suction time in 100Hz in the non-quick-return SJA is 49.58 percent, it would need 3.4 percent addition time to inhale more fluid under 150Hz or 6.67 percent addition time under 200Hz. Nevertheless, the suction time in 100Hz in the quick-return SJA is 52.56 percent, it would need 2.94 percent addition time to inhale more fluid under 150Hz or 5.94 percent addition time under 200Hz. It needs a slightly less time to inhale fluid for the quick-return facility with the enhancement of the frequency. Last but not least, no matter what the frequency is, the quick-return piston-type SJA has a better performance in terms of the P_r, jet mass and momentum.

4.2 Comparison of momentum in two SJAs types
No matter what the frequency is, the quick-return piston-type SJA has a better performance in momentum in Figure 12. In the 200Hz circumstance, the whole momentum of ejection in a cycle in case 1 is 22.3 percent more than case 3, case 4 is 23.6 percent more than case 5, and case 6 is 24.4 percent more than case 7. Even though with the enhancement of the frequency, effect by the quick-return characteristic has a slight reduction, it is obvious that the obvious quick-return one can make a better influence on the fluent field because of the added momentum.

5. Conclusion
This paper puts forward a novel designed piston-type SJA with a quick-return characteristic structure. According to the requirement of the SJA performance, the rapid traverse is applied to the route, in which the piston is moving to the TDC. Besides, the quick-return piston-type SJA can take more time to inhale more fluid because of the slow-route in which the piston moves to the BDC. Then, two various quick-return characteristic structures and a non-quick-return SJA have been proposed to analyze how the different quick-return characteristic influence the performance.

The quick-return piston-type SJA has a significant influence on the pressure of the cavity, jet velocity, mass flow and momentum, and the more apparent the quick-return characteristic is, the better the performance is. For example, the peak of the pressure ratio for the obvious quick-return SJA is up to the 2.5, and the non-quick-return SJA is just 2.1 under the same frequency condition of 200Hz. Besides, the obvious quick-return SJA have a 22.3 percent more than the non-quick-return one in terms of the jet momentum.

Under the other cases of frequency, the quick-return SJA also performs better than the classical one. Besides, with the development of the frequency, the suction time would increase in the whole cases, but the quick-return structure can reduce the influence of the frequency. For example, the obvious one just need 5.94 percent addition time from 100Hz to 200Hz, but the non-quick-return one need 6.67 percent addition time from 100Hz to 200Hz.

In conclusion, the novel quick-return piston-type SJA have a potential to application, and it can be applied with other advanced improvement measures, such as the auxiliary air system, and so on.

6. Reference
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