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# Experimental research on the factors affecting the output flow of the piezoelectric stack-based electro-hydrostatic actuator

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**Abstract:** The piezoelectric stack-based electro-hydrostatic actuator incorporates a piezoelectric material and hydraulic systems through the rectification of the reed valve, make full use of the large displacement of the hydraulic system and high frequency operation of the smart materials, and avoid the defects of the complex pipelines of conventional hydraulic systems and the micro displacement of piezoelectric material. In this paper, a piezoelectric stack-based electro-hydrostatic actuator was designed, a prototype was manufactured. The working principle and output flow formation mechanism was introduced. And experiments were carried out under different conditions to explore the factors affecting output flow and analyze specific impacts. The experiments shows that the maximum no-load output flow of the prototype is close to 1.6 L/min at the peak frequency of 275 Hz, and the load capacity is apparently far more than 20 kg.

**Key words:** Piezoelectric materials, Electro-hydrostatic actuator, Output flow
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## 1 Introduction

Conventional hydraulic systems have been widely used in aeronautic fields because of its large force and output displacement. But on the other hand, its distributed pipelines have to take up a lot of room [1]. And this is a major drawback of the typical hydraulic actuators which limits its application in the modern aerospace industry. In order to solve this problem, a new type of actuator based on the intelligent material is proposed to replace the conventional hydraulic actuator system in modern aerospace field [2-3].

In recent years, an intelligent material-based electro-hydrostatic actuator has been a hot research field because of the elimination of the distributed pipelines. In the era of power-by-wire, an integrated, stable and high-bandwidth actuator system has become a necessity for modern airborne hydraulic system [4].

Piezoelectric material is a kind of intelligent material and possesses the ability to deliver large force and operate at high frequency [5]. Actually, piezoelectric stack-based electro-hydrostatic actuator (PEHA) is proposed with the ambition of delivering mechanical power through hydraulics with the elimination of the conventional hydraulic system distributed pipelines. The basic operation of the PEHA involves with high frequency bidirectional operation of the piezoelectric stack and the flow rectification by the reed valves, which lead to a unidirectional output of the hydraulic cylinder eventually [6-8].

One of the first reported PEHAs was developed by Konishi et al [9-10]. which had a power output of about 18 W and peak pumping frequency of around 300 Hz. The device was constructed using a piezoelectric stack of 22 mm diameter and 55.5 mm length. Tang et al [11] developed a piezo-hydraulic actuator

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for active vibration control of rotor dynamic systems. The actuator was built to transfer the large force, high frequency capability of the piezoelectric driver to a hydraulic system. Mauck and Lynch [2] developed a piezoelectric stack based device that produced around 4 W power and had a blocked force of 271.7 N. However, it operated at relatively low pumping frequency (less than 100 Hz) and performed frequency rectification using passive valves. Sirohi and Chopra [3] developed a compact hybrid hydraulic actuator that could be driven by magnetostrictive and piezoelectric stacks. Using piezoelectric stacks, this actuator had an output power of 2.5 W, blocked force of around 138 N and operated at relatively higher pumping frequency. Ullmann [4] developed a valveless piezoelectric pump that used appropriately shaped and directed nozzles to rectify the flow. Gi-Woo Kim [5] conducted a study of design and nonlinear force control of a power-by-wire piezoelectric hydraulic pump actuator for automotive transmissions.

This paper aims to research the factors affecting the output flow of the PEHA, find the best output performance of the PEHA and provide some guidelines for the design of the PEHA. Firstly, the structure configuration of the PEHA prototype is designed and the working principle of the actuator is analyzed. Secondly, the overall physical process of the output flow formation mechanism is introduced and the affecting factors are analyzed. Thirdly, the factors affecting the output flow and the peak frequency of the prototype are studied through experiments.

## 2 Configuration and working principle of the PEHA

### 2.1 Structure configuration

Firstly, a PEHA is shown by presenting its structure configuration. Its main structure composes of four parts: a piezoelectric stack-based pump (PSP), a hydraulic cylinder, an accumulator and the tubing & fittings.

As shown in Fig. 1, the PEHA consists of a pump, two one-way check valves and a hydraulic cylinder. The PEHA utilizes fluid rectification via two one-way check valves to amplify the small, high-frequency vibrations of the piezoelectric stack into large motions of the hydraulic cylinder. And an accumulator is connected to the low pressure side of the PEHA by a connecting tube.

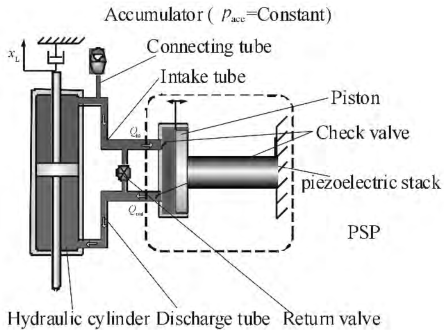



Fig. 1 Structure view of PEHA

### 2.2 Working principle

As shown in Fig. 1, the PSP provides energy for the system as the core element of the driving part. The periodic input voltage applied on the piezoelectric stack can form an electric field that induces polarization in the piezoelectric material, which eventually drives the piezoelectric stack to produce displacement and drive the pump cavity piston movement back and forth constantly. The pump chamber can absorb or drain fluid due to the change of the volume. This can provide output power by using the principle of frequency rectification which is performed by passive unidirectional reed valves. The pump chamber should be well designed to ensure the micro flow eventually contribute to the output of the hydraulic cylinder.

As Fig. 2 shows, the operation of the PSP can be divided into four distinct stages as follows: compression, exhaust, expansion, and intake.

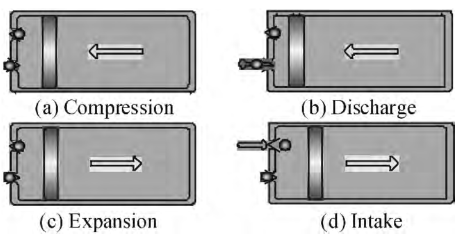



Fig. 2 Operation stages of PSP

1) Compression: With sinusoidal electricity supply, expansion of piezoelectric stack pushes hydraulic fluid in the closed pump chamber, resulting in the increase of pressure in the chamber.

2) Exhaust: The outlet valve opens due to the pressure difference, so fluid starts to flow out of the chamber into the outlet tube, and the pressure builds up in the high-pressure-driven side of the output cylinder and results in motion of the output shaft.

3) Expansion: The piezoelectric stack starts to re-

treat with decreasing applied field, causing the pressure drop in pump chamber.

4) Intake: The pressure in the pump chamber drops further to open the intake reed valve and allows fluid to flow from the low-pressure-driven side of the output cylinder back into the chamber.

These four stages are repeated every pump cycle and result in a flow rate out of the pump through the discharge tube and flow into the pump through the intake tube. Through this stepwise actuation process, the high frequency, small stroke of the piezoelectric stack is converted into a larger displacement of the output cylinder.

## 3 The physical process of the output flow formation mechanism and affecting factors

### *3.1 Physical process*

According to the structure and the working principle of the PEHA, apparently, the starting point of the output flow is the extension/contraction of the piezoelectric stack due to the application of a periodic electrical input. Then, a mechanical piston connected to the piezoelectric stack is forced to move back and forth constantly in the pump chamber at a certain frequency, causing the pump chamber volume to change continuously, as well as the pump chamber pressure. The changing pressure in the pump chamber can build up a changing pressure difference on the two sides of the one-way valve and control its open and close. Once the pressure difference is greater than the one-way valve opening pressure, the pressure difference in the pump chamber will drive a micro fluid flow out of the chamber into the discharge tube and accumulate in the hydraulic cylinder. And this will cause the pressure to rise in the high-pressure-driven side of the hydraulic cylinder and push the piston in the cylinder to move. This process is repeated in every pumping cycle and ultimately results in the output motion of the hydraulic cylinder. In general, this is the physical process of converting the electrical input into the mechanical output.

### *3.2 Affecting factors*

According to the description above, the PEHA is an electromechanical coupling system. Its working process is rather complicated and affected by many factors. From the start, the strain magnitude and vibration frequency of the piezoelectric stack are controlled by the amplitude and frequency of the input signal. Then, the fluid bias pressure is one of the main factors that determine the compressibility of the fluid while the compression of the fluid will consume a lot of energy and reduce the energy transfer efficiency. Meanwhile, the PEHA load capacity is one of the performances that should be concerned about. At last, the accumulator plays an important role in the system obviously. It can provide a bias pressure to prevent cavitation, improve the stiffness of fluid, compensate for leakage of fluid and assist in applying a pre stress on the piezoelectric stack. Furthermore, the natural frequency of the accumulator is relatively low which will have a serious impact on the performance of the actuator. All of these factors mentioned will be discussed and corresponding experiments will be presented in the next section.

## 4 PEHA experimental investigation

The prototype was constructed using a multiplayer piezoelectric element of 40 mm height and length and width are 14mm. According to the performance test result performed by product vendor, the piezoelectric stack can achieve a free stroke of 50 μm when maximum 150 Volt is applied.

Considering that the piezoelectric stack cannot withstand the reverse voltage, a sinusoidal voltage signal with DC bias is chosen as the driving signal. And in order to avoid the input voltage exceeding the maximum allowable voltage of the piezoelectric stack, three peak-to-peak values are chosen here: 100 Vpp, 120 Vpp, 140 Vpp.

### *4.1 Driving voltage*

According to the inverse piezoelectric effect, the electric field applied in the polarization direction of the piezoelectric ceramics will generate strain or stress in the piezoelectric ceramics. Moreover, the strain magnitude and electric field intensity are positively correlated.

As Fig. 3 shows, in the 450 Hz range, the output flow reaches the maximum at 275 Hz for different peak-to-peak values. And the 275 Hz is the peak frequency within 450 Hz. The strain of the piezoelectric stack is a major factor that should be concerned firstly as the energy source of the system. Under a certain power to weight ratio, a larger strain means a larger output flow. It is concretely represented in the amplitude of the input voltage. It is easy to understand that in order to achieve a larger flow output, a larger amplitude voltage that the stack can withstand will help. In addition to this, a proper pre stress can help to increase the external response of the piezoelectric stack and vice versa. What else we can learn from Fig. 3 is that 140 Vpp input corresponds to the maximum output flow of nearly1.6 L/min at about 275 Hz.

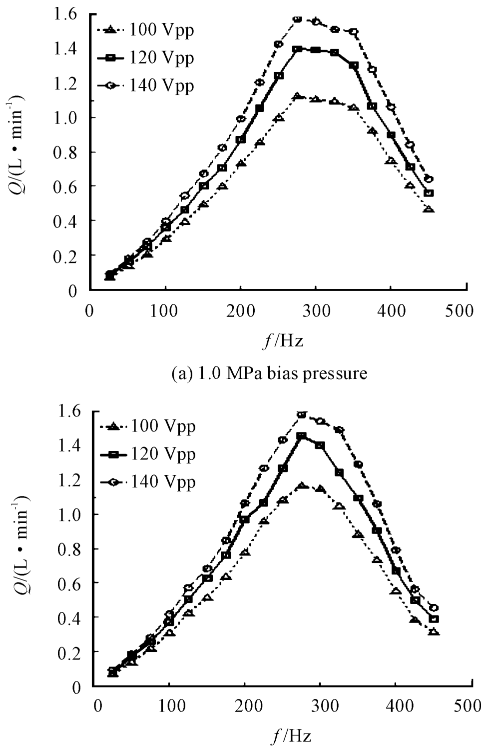



Fig. 3 Output flow under different peak-to-peak values for 1.0 MPa bias pressure and 1.2 MPa bias pressure

*4.2 Fluid bias pressure*

To a certain extent, it can be assumed that the proper fluid bias pressure can help to improve the output flow. There are two advantages here: the stiffness of the fluid is increased so that the energy loss on the liquid compression is reduced; and the external response of the piezoelectric stack is increased because of the increase of the pre stress on the stack through the promotion of fluid bias pressure. The prototype is tested with the 140 Vpp sinusoidal bias voltage. The experimental result is presented in Fig. 4.

As Fig. 4 shows, the output flow reaches the maximum at 275 Hz. The 275 Hz is the peak frequency within 450 Hz. According to the mechanism of inverse piezoelectric effect, applying a certain stress in the polarization direction of the piezoelectric stack will lead to the change of the initial direction of the electric domain, which helps to increase the external response of the piezoelectric stack and enhance the output flow. And the fluid bias pressure provided by an accumulator helps to pre stress the piezoelectric stack. Meanwhile, the energy transfer efficiency in this process is improved as the stiffness of the liquid increases because of the fluid bias pressure improvement.

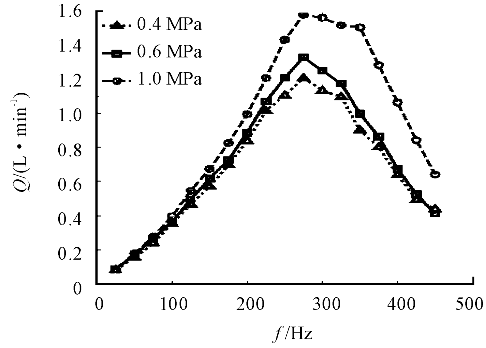



Fig. 4 Output flow under different bias pressures

*4.3 External load*

The load capacity is one of the most concerned performances, the prototype is tested with the 140 Vpp sinusoidal bias voltage under the 1.0 MPa and 1.2 MPa bias pressure.

As Fig. 5 shows, the output flow drops as the load mass ($m_L$) increases, but the trend of the output flow curve does not change with the increase of load. And the output flow reaches the maximum at 275 Hz.

In order to research the maximum load capacity and show the change trend of the output flow with the increase of load mass more clearly, three operating frequencies are selected: 225 Hz, 275 Hz and 325 Hz. The frequencies are chosen because the output flow reaches best at 275 Hz and the output flow is relatively large in this frequency range. And this helps to find the optimum operating frequency of the prototype.

As shown in Fig. 6, the output flow drops steadily as the load increases, and the maximum load capacity is apparently far more than 20 kg at certain frequencies, which shows that the prototype has a relatively good load capacity. And the load capacity is the best while the operating frequency is 275 Hz.

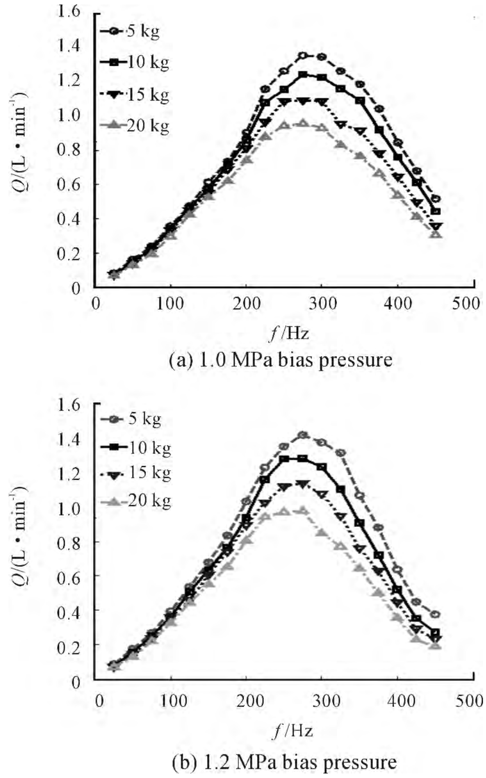



Fig. 5 Output flow under different loads for 1.0 MPa bias pressure and1.2 MPa bias pressure

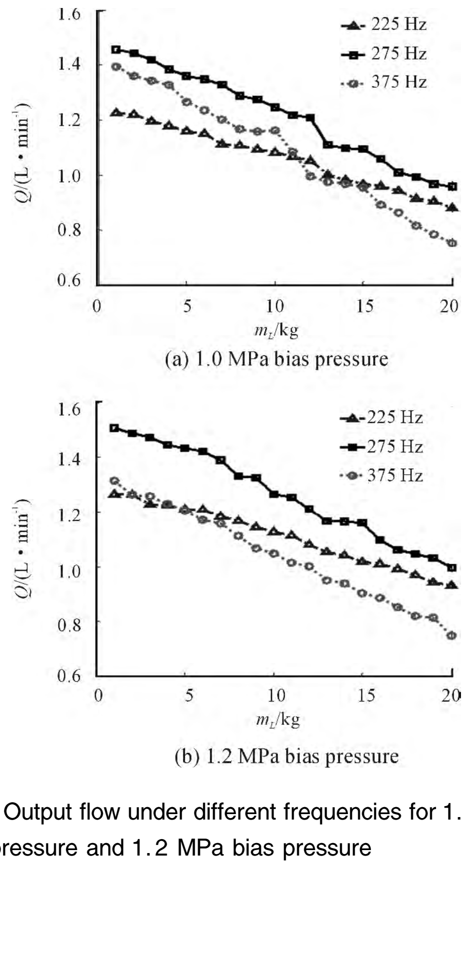



Fig. 6 Output flow under different frequencies for 1.0 MPa bias pressure and 1.2 MPa bias pressure

*4.4 Accumulator stiffness*

The accumulator is a very important component as mentioned above and the concept of accumulator stiffness is used here. The accumulator consists of a chamber with a metal diaphragm that separates the fluid filled tube from a nitrogen tank. If the accumulator is in open state, the air bag of the accumulator is connected to the low pressure side of the PEHA directly through the connecting rubber tube. This situation corresponds to the low stiffness of the accumulator. If the accumulator is in off state, the low pressure side of the actuator is only connected to the connecting rubber tube and this condition corresponds to the medium stiffness of the accumulator. If the accumulator is an off state and the rubber tube is replaced by an iron tube of the same size, this condition corresponds to the high stiffness of the accumulator.

In addition to the influences that have been mentioned above, there are many other factors associated with accumulator that need to be studied through experiments. The corresponding results and discussions are presented next.

*4.4.1 Accumulator open-off state*

Comparing with the previous experiments, the state of the accumulator is a factor affecting the performance of the PEHA, the corresponding experiments are carried out and the output flow curves are shown in the Fig. 7

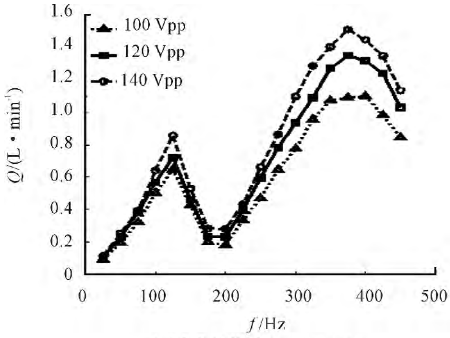
As Fig. 7 shows, although the state of accumulator has little effect on the maximum output flow, it has a significant impact on the peak frequency. There are two peaks within 450 Hz when the accumulator is open, while there is only one peak when it is off.

For a short summary, a simple comparison of the output flow is made, while the PEHA works under different conditions of the accumulator state and the external load. The experiments are carried out with the input of 140 Vpp voltage, and the results are shown in Fig. 8.

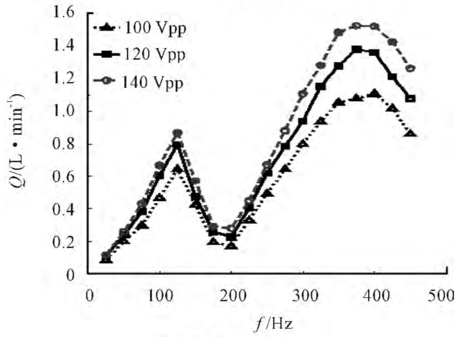
As Fig. 8 shows, it illustrates that the switch of the accumulator has a significant impact on the peak frequency, but does not change the maximum flow very much, no matter the PEHA is loaded or not.

*4.4.2 Connecting tube material*

According to the structure of the PEHA, there is a connecting tube connecting the accumulator and the intake tube. Apparently, the material of the connecting tube will affect the performance of the actuator because of the fluid-solid coupling problem when the fluid flows in the tube. In order to explain this problem more directly, the rubber tube is replaced with an iron tube of the same size and the corresponding experiments are carried out.

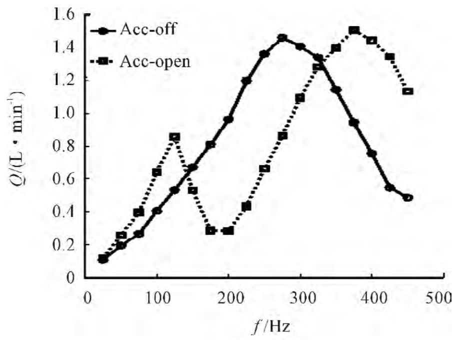



(a) 1.0 MPa bias pressure

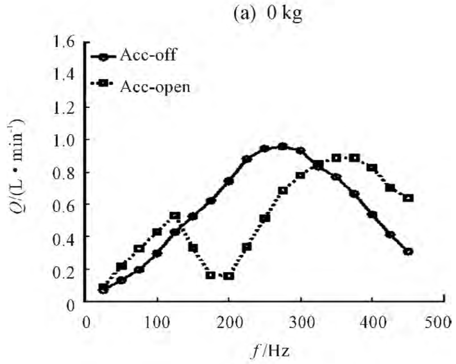



(b) 1.2 MPa bias pressure

Fig. 7 Output flow with accumulator open for) 1.0 MPa bias pressure and 1.2 MPa bias pressure



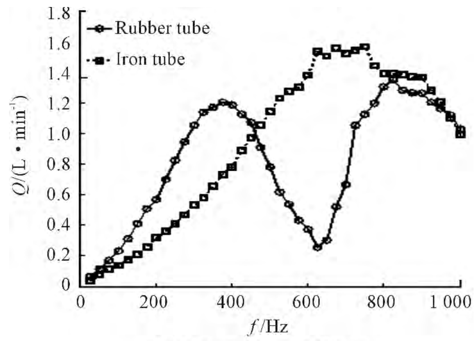

(a) 0 kg



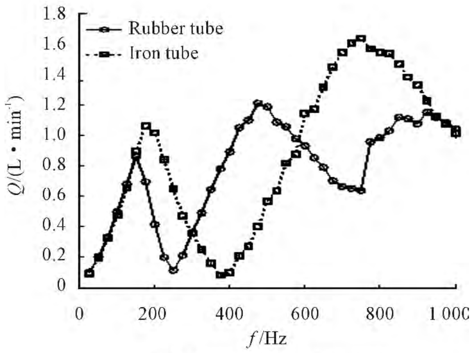

(b) 20 kg

Fig. 8 Output flow under different accumulator condition for 0 kg and 20 kg

Also, limited by the load capacity of the drive power supply, the 100 Vpp sinusoidal bias voltage is chosen as input signal, and 1.0 MPa bias pressure is applied. As Fig. 9 shows, the peak value of output flow means the output flow increases firstly and then decreases in the vicinity of the frequency. And no matter the state of accumulator is open or off, the peak frequency and corresponding output flow using an iron tube is higher than those using a rubber one. While the accumulator is off, there are two peaks using a rubber tube while there is only one peak using an iron tube within 1 000 Hz. There is one more peak using a rubber tube than an iron one when the accumulator is open. And the first peak frequency using a rubber tube is lower than using an iron tube no matter the state of accumulator is open or off.




(a) Accumulator off state




(b) Accumulator open state

Fig. 9 Output flow with different tube material for accumulator off state and accumulator open state

According to the working principle of the PEHA, output flow will increase as the operating frequency increase under ideal conditions. However, the experiment results show the different trends. In practical application, as a distributed electromechanical coupling system, there are many restricting factors affecting the performance of the PEHA, for example, the resonance of the system. The output flow vibration with the increase of frequency is mainly caused by the resonance of the system. Because the output flow decreases rapidly near the resonance frequency of the system, and increases only over a certain frequency range. So there is a vibration of the output flow. And the resonance frequency of an iron tube is higher than the resonance frequency of a rubber tube. Apparently, there are more than one resonant frequency points in the PEHA system. Therefore, the output flow curve has more than one peak within 1 000 Hz. And the enhancement of the peak frequency of each part is helpful to improve the peak frequency of the system.

Based on the accumulator stiffness concept, the experiment results show that the stiffness of accumulator is one of the main factors that affect the performance of PEHA. At the current stage, it can even be considered as the most important factor. An accumulator with higher stiffness helps to increase the peak frequency of the PEHA significantly as well as the maximum output flow.

## 5 Conclusions

1) The maximum no-load output flow of the prototype is more than 1.5 L/min at the peak frequency of 275 Hz. And the load capacity is apparently more than 20 kg at certain frequencies.

2) The strain of the piezoelectric stack is a major factor that should be concerned firstly. Under a certain power to weight ratio, a larger strain means a larger output flow. It is concretely represented in the peak-to-peak value of input voltage. In order to achieve a larger output flow, a larger peak-to-peak value that the stack can withstand will help.

3) To a certain extent, the improvement of the fluid bias pressure is helpful to the increase of the output flow. The compressibility of oil is mainly determined by the pressure of the system and the volume fraction of gas mixed in the system. Increasing fluid bias pressure is helpful to improve the stiffness of the system, so as to reduce the energy loss due to the compression of the oil and improve the energy transfer efficiency of the system. However, there are two issues that need to be considered as the bias pressure is improved. One problem is the pre stress on the stack will increase as the fluid bias pressure improved, and the total pre stress should not exceed the optimal pre stress of the stack. The other problem is that the leakage should be concerned.

4) In view of the concept of accumulator stiffness, there are three kinds of accumulators with different stiffness are tested in the experiments, and larger accumulator stiffness helps to increase peak frequency and the corresponding output flow.

Research on the output flow affecting factors is helpful to provide some guidelines for the design of the PEHA. And relevant theoretical research needs to be carried out in the future.

## Acknowledgements

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## References

[1] LI J, FU Y, WANG Z. Present development status and key technology research of airborne electro-hydrostatic actuation system [J]. Aeronautical Manufacturing Technology, 2005(11): 73-77.

[2] LI J, FU Y, WANG Z. System design and simulation of a new aircraft electro-hydrostatic actuator [J]. Journal of System Simulation, 2004,16(6): 1-4.

[3] Murphy J R E, Peter W J, Hydraulic control system [M]. USA: U.S. Paten, 1962.

[4] SHA N, LI J. Research on airborne power-by-wire integrated electrical actuation and control systems [J]. Journal of Beijing University of Aeronautics and Astronautics, 2004, 30(9): 1-4.

[5] LI W, ZHAO W, ZHAN H. New technologies and applications of piezoelectric and electrostrictive materials and actuators [J]. Piezoelectrics & Acoustooptics, 2001,23(4): 1-6.

[6] TAO B Q, Intelligent Material Structure [M]. [S.l.]: National Defend Industry Press, 1997: 22-123.

[7] SANDERS B, CROWE R, GARCIA E, Defense advanced research projects agency-smart materials and structures demonstration program overview [J]. Journal of Intelligent Material Systems and Structures, 2004,15(4): 227-233.

[8] SIROHI J, CHOPRA I. Design and development of a high pumping frequency piezoelectric-hydraulic hybrid actuator [J]. Journal of Intelligent Material Systems and Structures, 2003,14(3): 135-147.

[9] KONISHI K, YOSHIMURA T, HASHIMOTO K, et al. Hydraulic actuators driven by piezoelectric elements [J]. Journal of Japanese Society of Mechanical Engineering, 1993: 59(564): 213-220.

[10] KONISHI K. Hydraulic actuators driven by piezoelectric elements, Intelligent Materials and Robots, Sendai [M]. Japan: [S. N.], 1995.
[11] TANG P, PALAZZOLO A B, KASCAK A F, et al. Combined piezoelectric-hydraulic actuator based active vibration control for rotor dynamic system [J]. Journal of Vibration and Acoustics, 1995, 117 (3): 285-293.
[12] MAUCK L D, LYNCH C S. Piezoelectric hydraulic pump development [J]. Journal of Intelligent Material Systems and Structures, 2000, 11(10): 758-764.
[13] SIROHI J, CHOPRA I. Design and development of a high pumping frequency piezoelectric-hydraulic hybrid actuator [J]. Journal of Intelligent Material Systems and Structures, 2003, 14 (3): 135-147.
[14] ULLMANN A, FONO I. The piezoelectric valve-less pump-improved dynamic model [J]. Journal of Microelectromechanical Systems, 2002, 11(6): 655-664.
[15] KIM G W. Enhanced control performance of a piezoelectric-hydraulic pump actuator for automotive transmission shift control [J]. Journal of Automobile Engineering, 2010, 224(2): 161-174.

## 压电叠堆电静液作动器输出性能影响因素的实验研究

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**摘要: 基于压电叠堆的电静液一体化作动器通过单向阀的整流作用将压电材料和液压系统进行整合,发挥液压系统大位移、大出力的特点和智能材料高频响、高功率密度的优势,同时避免传统液压系统复杂的分布式管路以及智能材料微位移量级太小的缺陷,设计了一种压电叠堆电静液作动器。制造了样机,介绍了其工作原理并分析了其输出流量的形成机制及影响因素。在不同条件下对样机进行输出性能实验,探究影响作动器输出性能的因素并分析具体的影响。实验结果显示: 输入** 140 V **正弦偏置电压,作动器峰值流量接近** 1.6 L/min,**峰值频率可以达到** 275 Hz,**带负载能力超过** 20 kg。

**关键词: 压电材料; 电静液作动器; 输出性能**