1991. Effect of sink flow on dual-valve electro-hydraulic excitation system

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Abstract. In this study, the main goal is to investigate the displacement gain characteristics of novel dual-valve Electro-Hydraulic Excitation system (EHES). Relative to conventional system, the dual-valve system can improve the amplitude range, but the range is always affected by some nonlinear factors. In order to analysis on the issue, a nonlinear mathematical model of dual-valve EHES is established based on Bernoulli and classical electro-hydraulic servo equation. Then, the results of numerical simulations by using of the MATLAB/Simulink software are compared with experimental results. Simulation and experimental results show that the sink flow mainly influences on the flow dynamic characteristics of dual-valve EHES. Because of that, dual-valve EHES only can improve 50 %-70 % of displacement within 5 to 50 Hz of excitation frequency and 45 %-80 % of displacement amplitude within 20 % to 100 % of command value.

Keywords: dual-valve EHES, vibration exciter, effect of sink flow, amplitude gain.

1. Introduction

The Electro-Hydraulic Excitation system (EHES) is a key component for modern simulation test of automobile or mobile machines and the seismic fatigue test of dams or tall buildings. The system is mainly worked by the reciprocating motion of valve spool, which varies the flow in cycles (Fig. 1). However, the vibration amplitude is restricted within a narrow range due to the characteristic of valve port [1]. Therefore, the optimization of vibration performance for EHES has been the focus of both academic and industrial field.

In conventional EHES, it usually adopts slide or nozzle flapper valve to control the hydraulic cylinder or torque motor [2]. In order to improve the response characteristics of the hydraulic valve, Han et al., Zhang et al., Lian et al. and Wang et al. replaced the slide valve with rotary valve [3-6]. Liu et al. and Ruan et al. proposed a special valve structure with two degree of freedom [7, 8]. For purpose of optimizing the output waveform, a series of controller was designed by introducing Lyapunov function method, self-adjustment quantitative feedback theory, varying error controls strategy, neurodynamic optimization and other mathematical method [9-16]. For the sake of researching the vibration performance, Han et al. simulated the vibration characteristics of a new electro-hydraulic vibrator by using the AMESim software [17]. Wei et al. and Kou et al. summarized the law of pressure pulsation [18, 19]. However, the studies all above have only focused on the frequency range and stability of the excited system, and ignored the displacement amplitude range. A little paper introduced the unique advantages of multi-valve system in enhancing displacement amplitude ranges. Ren et al. proposed the offset valve [20]. Chiang et al. applied the parallel switching valve to control the vertical vibration system [21]. But they only focused on the application effect, lacking studies on the excitation mechanism. In view of this, this article will introduce a novel EHES with dual-valve in order to enhance the vibrator performance, and investigate the vibration characteristics of the system, especially in the aspect of displacement amplitude.

In the first part of the paper, a mathematical model of dual-valve EHES is presented. The system is mainly described by Bernoulli and classical flow characteristic equation. Then, the effect of sink flow on displacement gain characteristic of the system within various vibration parameters

is analyzed by using the MATLAB/Simulink software. Meanwhile, the test platform is set up to validate the calculation results. The simulation and experimental data are presented and discussed in third part. Finally, the conclusions are given from a number of comparisons between the experimental and the numerical results.

2. Dual-valve EHES model

The dual-valve EHES is shown in Fig. 2, which consists of two parallel servo valves and a vibration cylinder. Similar to conventional system, the dual-valve system also relay on the cyclic flow to achieve the continuous reciprocating vibrations. For the purpose of improving the displacement amplitude, the valves must be controlled by the same exciting signal.
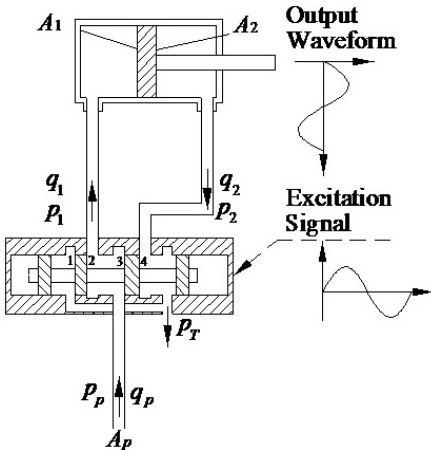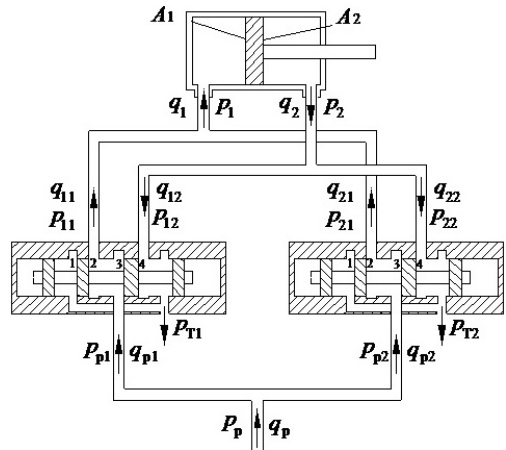

Fig. 1. Electro-hydraulic excitation system   Fig. 2. Dual-Valve EHES

2.1. Valve port flow

As shown in Fig. 2, the valve spool will move left when the excitation signal is positive, and the high pressure oil will flow into the left cavity of cylinder. In contrast, the high pressure oil will flow into right cavity when the signal is negative. Therefore, the flow equation of valves is:

$$\begin{cases} q_{i1} = C_d \omega_i x_{vi} \sqrt{\dfrac{2(p_{pi} - p_{i1})}{\rho}}, \\[2mm] q_{i2} = C_d \omega_i x_{vi} \sqrt{\dfrac{2p_{i2}}{\rho}}, \end{cases} \quad x_{vi} > 0, \tag{1}$$

$$\begin{cases} q_{i1} = C_d \omega_i x_{vi} \sqrt{\dfrac{2p_{i1}}{\rho}}, \\[2mm] q_{i2} = C_d \omega_i x_{vi} \sqrt{\dfrac{2(p_{pi} - p_{i2})}{\rho}}, \end{cases} \quad x_{vi} < 0, \tag{2}$$

where p_{pi} is the supply pressure of ith valve, p_{i1} and p_{i2} is the pressure of flowing out and in ith valve. q_{i1} and q_{i2} is the flow out and in ith valve ($i = 1, 2$).

2.2. Sink flow model

As shown in Fig. 2, sink flow will appear on the tee joint when the oil flows to cylinder. According to Bernoulli's equation:

$$
\begin{cases}
p_{11} + 0.5\rho\left(\dfrac{q_{11}}{A_{11}}\right)^2 = p_1 + 0.5\rho\left(\dfrac{q_1}{A_1}\right)^2, \\
p_{21} + 0.5\rho\left(\dfrac{q_{21}}{A_{21}}\right)^2 = p_1 + 0.5\rho\left(\dfrac{q_1}{A_1}\right)^2,
\end{cases}
\tag{3}
$$

$$
\begin{cases}
p_{12} + 0.5\rho\left(\dfrac{q_{12}}{A_{12}}\right)^2 = p_2 + 0.5\rho\left(\dfrac{q_2}{A_2}\right)^2, \\
p_{22} + 0.5\rho\left(\dfrac{q_{22}}{A_{22}}\right)^2 = p_2 + 0.5\rho\left(\dfrac{q_2}{A_2}\right)^2,
\end{cases}
\tag{4}
$$

where p_1 and p_2 is the pressure of the left and right cavity. The flow into and out of the cylinder is q_1 and q_2. A_1 is the area of piston, and A_2 is the cross sectional area of right cavity. A_{i1} and A_{i2} are the cross sectional area of pipeline ($i = 1, 2$):

$$
\begin{cases}
q_1 = \left(C_d\omega_1 x_{v1}\sqrt{\dfrac{2(p_p - p_1)}{\rho}} + C_d\omega_2 x_{v2}\sqrt{\dfrac{2(p_p - p_1)}{\rho}}\right), & x_{v1} > 0, \\
q_2 = \left(C_d\omega_1 x_{v1}\sqrt{\dfrac{2p_2}{\rho}} + C_d\omega_2 x_{v2}\sqrt{\dfrac{2p_2}{\rho}}\right), & x_{v2} > 0,
\end{cases}
\tag{5}
$$

$$
\begin{cases}
q_1 = \left(C_d\omega_1 x_{v1}\sqrt{\dfrac{2p_1}{\rho}} + C_d\omega_2 x_{v2}\sqrt{\dfrac{2p_1}{\rho}}\right), & x_{v1} < 0, \\
q_2 = \left(C_d\omega_1 x_{v1}\sqrt{\dfrac{2(p_p - p_2)}{\rho}} + C_d\omega_2 x_{v2}\sqrt{\dfrac{2(p_p - p_2)}{\rho}}\right), & x_{v2} < 0.
\end{cases}
\tag{6}
$$

The first equation of Eq. (3) multiplies by q_{11}, and the second one multiplies by q_{21}. Then, substituting Eq. (1) into Eq. (3) yields Eq. (5). The first equation of Eq. (4) multiplies by q_{12}, and the second one multiplies by q_{22}. Then, substituting Eq. (1) into Eq. (4) yields Eq. (6). Due to the connection pipe is hard and short, the energy loss can be neglected. Therefore, the sink flow equation can be expressed as follow.

2.3. Dual-valve coupling model

According to Fig. 2, the flow into and out of cylinder can be expressed by:

$$
\begin{cases}
q_1 = C_{np}(p_1 - p_2) + C_{ep}p_1 + \dfrac{V_1}{\beta_e}\dot{p}_1 + \dot{V}_1, \\
q_2 = C_{np}(p_1 - p_2) - C_{ep}p_2 - \dfrac{V_2}{\beta_e}\dot{p}_2 + \dot{V}_2.
\end{cases}
\tag{7}
$$

According Newton's second law, the equilibrium equation of piston is given by:

$$
A_1 p_1 - A_2 p_2 = m\ddot{x}_p + B_p\dot{x}_p + F_L.
\tag{8}
$$

Combing Eqs. (5)-(8), the dual-valve EHES are defined mathematically as follows:

$$\begin{cases} KC_d\omega(x_{v1} + x_{v2})\sqrt{(\alpha_1 p_p + \alpha_2 p_L)} = \dfrac{L_s A_1(1+\eta^4)}{2(1+\eta^3)\beta_e}\dot{p}_L + A_1\dot{x}_p, \\ A_1 p_L = m\ddot{x}_p + B_p\dot{x}_p, \end{cases}$$

(9)

where:

$$K = \sqrt{\frac{2}{\rho(1+\eta^3)}},$$

$$\alpha_1 = \begin{cases} 1, & x_{v1} > 0, \ x_{v2} > 0, \\ \dfrac{\eta^3}{(1+\eta^2)^2}, & x_{v1} < 0, \ x_{v2} < 0, \end{cases}$$

$$\alpha_2 = \begin{cases} -1, & x_{v1} > 0, \ x_{v2} > 0, \\ \dfrac{1}{(1+\eta^2)^2}, & x_{v1} < 0, \ x_{v2} < 0. \end{cases}$$

3. Simulation and experiment

3.1. Simulation test

The simulations have two parts. Part I: it is mainly to investigate the effect of sink flow on characteristics of output displacement. Firstly, the characteristics of the system with sink flow are numerically calculated by using Matlab/Simulink software. Then, the results are compared with the output displacement of the model without sink flow. Part II: it is mainly to analysis the relationship between the sink flow and the exciting parameters. Firstly, it is to simulate and analysis the output displacement of dual-valve EHES with and without sink flow under various excitation frequencies. Then, the results are compared with the output displacement under various command values of valve (valve opening).

Especially, the model with and without sink flow are simulated under the same condition. The main parameters in the simulation are shown in Table 1.

Table 1. Main parameter of the system

Parameter	Symbol	Value	Unit
Voltage Gain	K_v	0.1	mm/V
Valve port area of gradient	W	5.65	mm
Valve flow coefficient	C_d	0.6	
Working pressure	p_p	6	MPa
Oil density	ρ	900	kg/m³
Piston diameter	A_1	60	mm²
Rod diameter	A_2	35	mm²
Cylinder stroke	L_s	100	mm
Asymmetric ratio	H	0.583	
Oil elastic modulus	β_e	700	MPa
Viscous damping coefficient	B_p	300	N·s/m
Total mass	M	10	Kg
Vibration frequency	f	5-50	Hz
Command value of valve	x_v	20, 40, 60, 80, 100	%

According to the equations above, the dual-valve EHES model without sink flow can be simply considered the superposition of single valve system. And, the single valve EHES can be expressed

by:

$$\begin{cases} C_d \omega x_v \sqrt{\dfrac{2(p_p + \lambda p_L)}{\rho(1 + \eta^3)}} = \dfrac{L_s A_1 (1 + \eta^4)}{2(1 + \eta^3)\beta_e}\dot{p}_L + A_1\dot{x}_p, \\ A_1 p_L = m\ddot{x}_p + B_p\dot{x}_p, \end{cases} \tag{10}$$

where, if $x_v > 0$, then $\lambda = -1$; $x_v < 0$, then $\lambda = 1$.

In order to intuitively reflect the effect of sink flow on the system, this paper introduce the bias gain, which is defined as follow:

$$gain_e = gain_s - gain_d, \tag{11}$$

where the $gian_s$ is the displacement gain without sink flow. The $gian_d$ is the gain with sink flow. And the $gian_s$ can be expressed as follow:

$$gain_s = \frac{x_{ps} - x_s}{x_{sm}}, \tag{12}$$

where x_{ps} is the displacement of the system without sink flow. x_s is the displacement of single valve model. x_{sm} is the maxim value of x_s.

The $gain_d$ can be expressed by:

$$gain_d = \frac{x_{pd} - x_s}{x_{sm}}, \tag{13}$$

where x_{pd} is the displacement of the system with sink flow.

3.2. Experimental test

In order to verify the simulation results, the experimental tests also have two parts, and the goal of each part is the same as the simulation. As shown in the Figs. 3-4, the experimental platform of dual-valve EHES has been developed and designed, which is divided into three modules: excitation controller, vibration generator and measuring instrument. The controller sent the same signals to dual valve at the same time, which used is S7-300 PLC produced by SIMENS, and it is programmed by PCC using STEP 7 software. The generator, including servo valves and excitation cylinder, excites vibration waveform following the signals. The servo valves used are 4WSE2EM6 produced by Rexroth, which are controlled by the voltage signal. The excitation cylinder is special customized by referencing the CD 210 B63/35-100. The instrumentation is mainly measuring for vibration displacement. The measuring instrument is VIBXPERT II VIB5.325 produced by PRUFTECHNIK, and the vibration sensor is VIB 6.142R, which is mounted on the top of the piston rod by magnetic base. And the specifications of the system are summarized in Table 2.

Table 2. Experimental instruments

Instrument	Model	Range	Signal
Servo valve	4WSE2EM6	25 L/min	± 10 V
Program controller	S7-300 CPU 314	–	–
A/D module	SM332	± 27648	± 10 V
FFT data collector and signal analyzer	VIB5.325	10 KHz	–
Mobile accelerometer	VIB 6.142R		

To compare the simulation results, the experimental parameters are the same and are shown in Table 1.
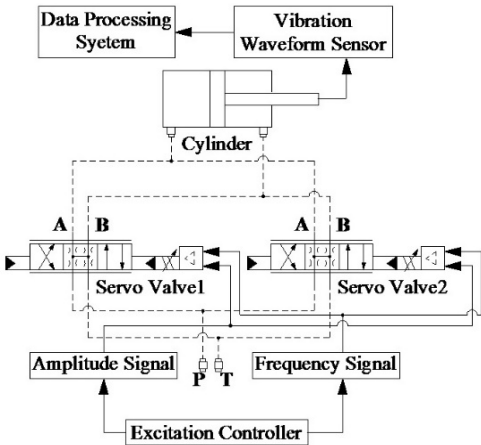

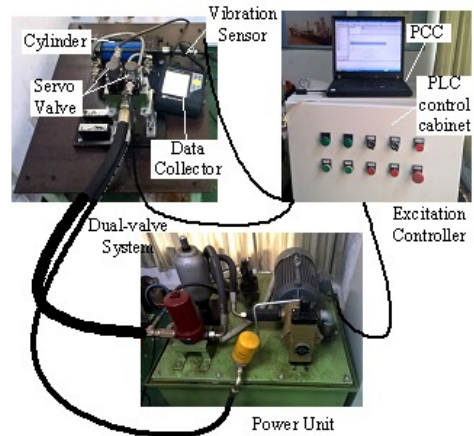**Fig. 3.** EHES controlled by dual-valve

Fig. 4. Experiment system

4. Results and discussion

Fig. 5 shows the amplitude gain of displacement from simulation part I. It can be seen that the gains without sink flow by numerically simulation are almost from –1 to 1. And the gains with sink flow are only from –0.52 to 0.52. It indicates that the sink flow restricts the ability of dual-valve EHES on enhancing displacement range. As can be seen from Fig. 5, the bias gains are obviously asymmetry in one period. The characteristic of asymmetry means the sink flow lead to saturated pressure appearing earlier than that of the system without sink flow when piston moving to the end of cylinder. Therefore, the sink flow mainly affects the characteristics of cavity pressure by simulation analysis.
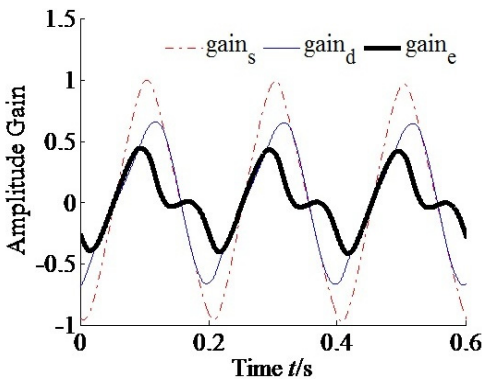

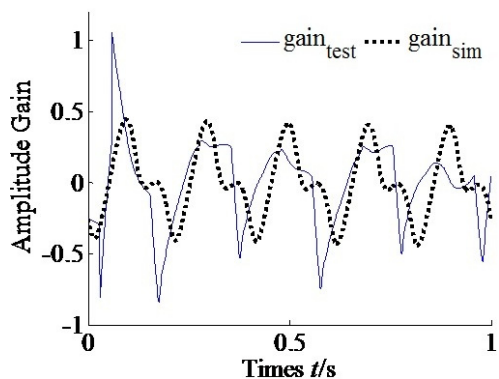**Fig. 5.** Simulation results

Fig. 6. Experimental results

As Fig. 6 shown, the curve $gain_{sim}$ represents the simulation results of bias gain. The curve $gain_{test}$ represents the experimental results. By comparing two curves, it is shown that the experimental data have been validated the simulation results. The asymmetry characteristics of displacement gain also exist in actual system. As the curve $gain_{test}$ shown, the positive data are more smoothly, and the negative data are more acute. It means that the sink flow characteristic more obvious on small cavity of cylinder than big. That is the smaller volume of cavity, the sink flow effect more obvious.

Therefore, based on the results of test part I, the conclusion is that the sink flow affects mainly

on the pressure characteristics of cylinder, and then restricts the flow of dual-valve EHES. Thus, the dual-valve EHES cannot further enhance displacement range.

Fig. 7(a) and (b) show the bias gain of displacement under various frequencies from test part II. Fig. 8 shows the peak values of bias gain. As Fig. 7(a) and (b) shown, it can be seen that the trend of experimental data is similar to the simulation results in a certain period. The bias gain would not vanish as excitation frequency change. As Fig. 8 shown, the curve of simulation results fluctuates smoothly, but the curve of experimental data rise slowly. The peak values of bias gain are steady in general. It means the excitation frequencies have effect on bias gain, but the effect is not very significant. Thus, the effect of sink flow on displacement gain under various frequencies is not obvious. The reason is that the high frequency movement of spool induces the pressure transient on valve port. In fact, the characteristic of pressure would exhibit the displacement amplitude range of single-valve system. But it has a relatively minimal impact on sink flow.
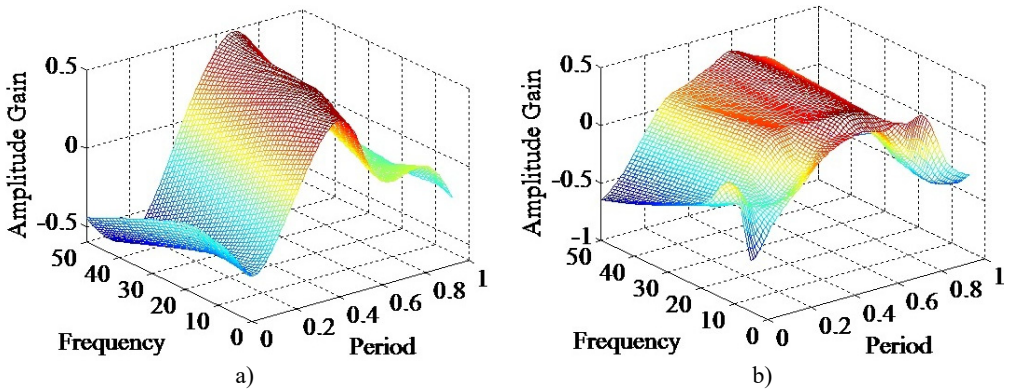

a)   b)

Fig. 7. Bias gain with varying frequency

As Fig. 8 shown, the peak values of experimental data are generally smaller than simulation results, which just vary from 0.28 to 0.34. It means the mathematic model of dual-valve EHES only can explain the trend of the dynamic characteristic of bias gain under various frequencies, but not quantitative analysis of actual displacement gain. The reason is that the actual system has more nonlinear and uncertainty parameters than simulation model.
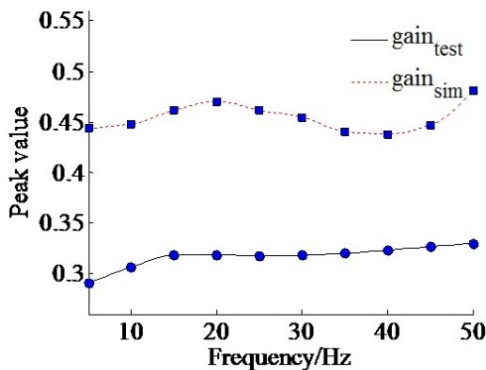

Fig. 8. Peak gain with varying frequency

Figs. 9(a) and (b) show the bias gain under various command value of valve from test part II. Fig. 10 shows the peak values of bias gain arise with varying command value. As Fig. 9(a) and (b) shown, it can be seen that the trend of experimental data is also similar to the simulation results. The bias gain would not vanish as command value change as well. Therefore, the sink flow is the generic characteristics of dual-valve EHES. As Fig. 10 shown, the curve of simulation results rises

from 0.3 to 0.46, and the curve of experimental data rises from 0.2 to 0.37. It means that the more command value, the bias gain more obvious. The reason is that the more command value of valve induces the more flow on valve port. And the characteristics of flow have a relatively obvious impact on sink flow comparing to the results under various frequencies. Otherwise, as Fig. 10 shown, the experimental data are also smaller than simulation results.

Therefore, the command values of valve mightily influence the bias gain comparing to excitation frequency. That is the characteristic of flow directly affects the sink flow; and then it further restricts the displacement gain of the dual-valve system. But the command values can promote the displacement amplitude of single-valve system increase. In a word, sink flow influence on the displacement gain of dual-valve system. But the varying excitation parameters can affect both the bias gain and the output amplitude of the system. Thus, the excitation parameters must be chosen reasonably to reduce sink flow influence and achieve a better performance on the output displacement of the dual-valve system.
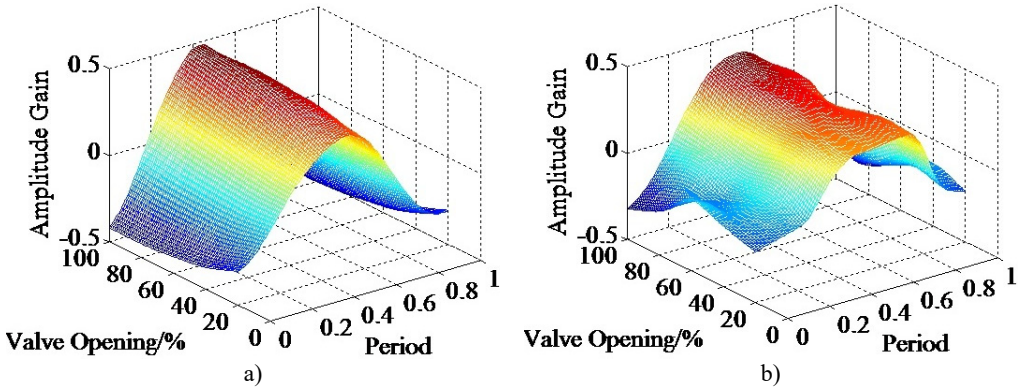

a)   b)

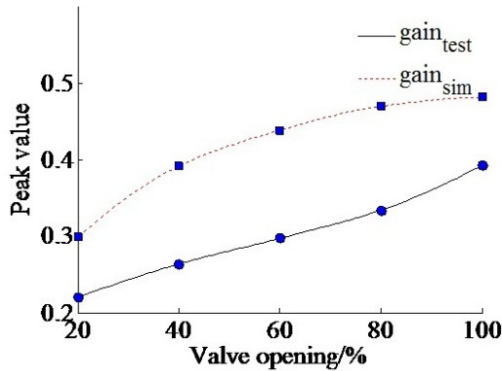**Fig. 9.** Bias gain with varying command value

Fig. 10. Peak gain with varying command value

5. Conclusion

From the experimental data and simulation results, the conclusions are summarized as follows:

1) A mathematical model for studying the sink flow effect of dual-valve EHES has been presented. Considering the simulation and test results, the dual-valve EHES only can improve 50 %-80 % displacement ranges compared to the system without sink flow under pressure 6 MPa.

2) The sink flow affects mainly on the pressure characteristics of cylinder, and then restricts the ability of dual-valve EHES on enhancing displacement range.

3) The bias gain, which intuitively reflects the effect of sink flow on the system, varies from 0.29 to 0.34 when the excitation frequencies are from 5 Hz to 50 Hz, and it varies from 0.2 to 0.38

when the command value are from 20 % to 100 %.

4) The experimental results suggest that the command value have more influence on bias gain. That is the command value directly affects the sink flow, and restricts the displacement range of dual-valve EHES.

5) The excitation parameters should be properly matched to reduce sink flow influence.

Acknowledgements

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