Global Academic and Scientific Journal of Multidisciplinary Studies (GASJMS)

Volume 3 | Issue 10, 2025 Homepage: https://gaspublishers.com/gasjms/ ISSN: 2583-8970

A Method to Avoid the Stick-Slip in a Large Hydraulic Cylinder under Variable Load using a balanced Valve

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Received: *10.09.2025* | ***Accepted:*** *03.10.2025* | ***Published:*** *23.10.2025*

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DOI: *10.5281/zenodo.17426168*

Abstract **Original Research Article**

Stick-slip motion often appears for starting or at low speed of hydraulic cylinder. In this paper, a method to avoid stick-slip is proposed by using a balance valve in the outlet which develops the back pressure. The performance of the proposed system to avoid stick-slip motion is simulated by using AMESim software and compared with the conventional system which has a hydraulic lock in the outlet. The results confirmed that the critical velocity (Stribeck velocity), an important parameter of stick-slip, can be much higher than the conventional system. Also, orifice diameter of pilot spool must be smaller than the nominal value to reduce stick-slip motion when negative load applies on the hydraulic cylinder.

Keywords: Hydraulic cylinder, stick-slip, AMESim, Stribeck effect, Friction model.

1. Introduction

Hydraulic cylinder that converts pressure energy into mechanical energy is widely used, where accurate analysis on internal and external friction is a key to extend the life of the sealing and to ensure the stability of the mechanism. The internal friction of hydraulic cylinder includes the dry friction by the seal ring between piston and cylinder body or piston and cover, and the viscous friction by the oil in dynamic state. Hydraulic cylinder has to overcome not only the external load but also the internal friction to start moving.

Many researchers developed mathematical models to predict friction. Helouvry[3] divided the friction into two states : dry friction and viscous friction, and proposed a static + dynamic + viscous friction model. Márton and Lantos [4] provided parameter identification method based on low-speed and high-speed friction modeling. Tariku [5] proposed two improved friction models: force-balance and spring-damper models. Mathematical model for steady-state stick-slip motion was presented by modeling two contact bodies as a rigid substrate and an elastic block [7]. Many other friction models are developed including static + Coulomb friction model, reset integrator model [3], Karnopp model [15], LuGre model [13], etc.

Also there are many literatures related to analysis on stick slip motion based on the friction-predicting models [2, 3, 6, 8, 9, 12, and 14]. Stick-slip motion is caused by Stribeck effect, which decreases friction force rapidly under a critical velocity [2]. Critical velocity, an important parameter of stick-slip motion, is affected by static and dynamic friction forces between the contact surfaces [3] and inertia and elasticity of the friction bodies [6]. Using Monte Carlo method, Bustos analyzed the molecular dynamics of stick-slip phenomenon in a confined membrane and found that the influences of parameters such as sliding velocity, load, time, and temperature on stick-slip phenomenon [12]. Inverted stick, the transition from smooth sliding to stick-slip occurs above a certain threshold velocity [8, 9], and in a single plane friction state, this threshold velocity is in atomic-scale[14].

There are many researches to reduce stick-slip motion and compensate friction

The time variation of the frictional force between two surfaces, undergoing stick-slip sliding across a molecularly thin film of a confined model liquid, was examined at high time and force resolution, showing clearly that dissipation of energy occurs both during the slip, and at the instant of stick (via transfer of residual momentum). Detailed analysis indicates that, in marked contrast to earlier suggestions, of order 90% or more of the dissipation occurs by viscous heating of the confined shear-melted film during the slip, and only a small fraction of the energy is dissipated at the instant of stick.[11]. In [3] and [10], methods was proposed to eliminate stick-slip phenomenon by reducing the difference between static and dynamic friction forces and increasing the stiffness of the system.

In this paper, a method is proposed and verified to eliminate stick-slip phenomenon by increasing the stiffness of the system. In the case of a large frictional body and high load variation, lubrication conditions can't be satisfied, and the stiffness should be increased to overcome stick-slip. Based on the principle of reducing stick-slip by developing back pressure in the outlet of the hydraulic cylinder, the hydraulic circuit using balance valve is established and simulated.

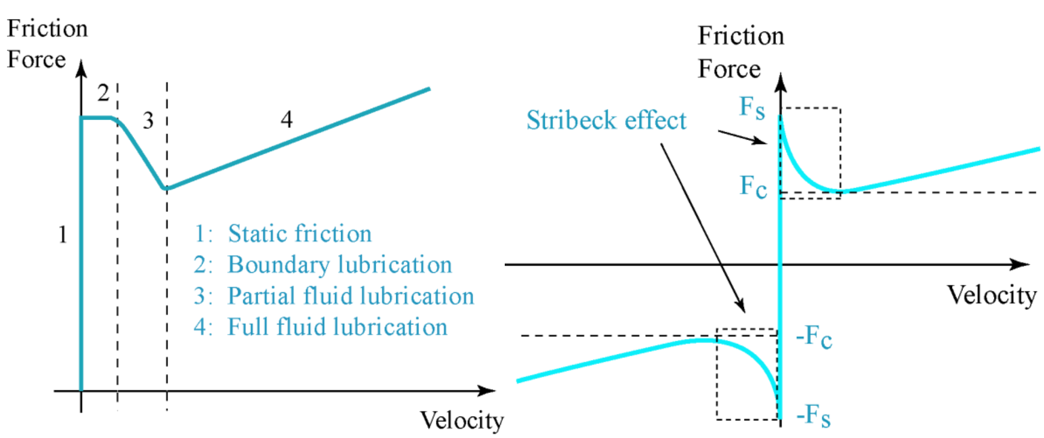
The paper is organized as follows.

In section 2, we introduces a mathematical model of stick-slip and constructs a drive circuit of a large hydraulic cylinder using a balance valve to reduce stick-slip motion. In section 3, we presents an AMESim simulation model of the drive circuit using a balance valve. In section 4, we analyzes the influence of parameters to reduce stick-slip motion under the varying load condition.

2. Drive circuit construction of large hydraulic cylinder using a balance valve

2.1 Mathematical model of stick-slip

The lubricant friction between a fixed and a sliding body can be divided into four states according to the sliding velocity: static friction, boundary lubrication, partial fluid lubrication and full fluid lubrication [15]. As shown in the regime 2 and 3 of Fig. 1(a), the dip in the friction force at low velocities is called the Stribeck effect.



(a) Friction regime according to the velocity (b) Stribeck effect

Fig 1. Friction force on a lubricated body

A stiction(static friction) zone is defined by a small neighborhood of zero velocity $[-\upsilon_0,+\upsilon_0]$. Inside this neighborhood, the mass velocity υ is considered to be zero and the friction force compensates the other forces applied to the mass until the static friction force is reached.

$$\upsilon = 0 \;, \quad -\upsilon_0 \le \upsilon \le \upsilon_0 \tag{1}$$

Outside the neighborhood (once the velocity exceeds the [$\pm\upsilon_0$] threshold), the mass slips and the friction force equals the Coulomb friction force F_C (Stribeck effect is ignored),

$$\begin{cases} F_{friction} = \min(|F_{EXT}|, F_S)\cdot sign(F_{EXT}) & ,|\upsilon| \le \upsilon_0 \\ F_{friction} = F_C \cdot sign(\upsilon) & ,|\upsilon| > \upsilon_0 \end{cases} \tag{2}$$

where F_{EXT} is the sum of the external forces and the weight, N

F_S – stiction(static friction) force, N

υ - relative velocity, m/s

υ_0 - stick threshold velocity, m/s

F_C - Coulomb friction force, N

When the Stribeck effect is taken into account, the friction force $F_{friction}$ is computed as follows:

$$F_{friction} = \begin{cases} \min(|F_{EXTt}|, F_S)\cdot sign(F_{EXT}) & ,|\upsilon| \le \upsilon_0 \\ \left[F_C + (F_S - F_C)e^{\left(-3\frac{|\upsilon|}{\upsilon_S}\right)}\right] sign(\upsilon) & ,\upsilon_S \ge |\upsilon| > \upsilon_0 \\ \left[F_C + (F_S - F_C)e^{-3}\right] sign(\upsilon) + \mu_\upsilon \cdot \upsilon & ,|\upsilon| > \upsilon_S \end{cases} \tag{3}$$

where υ_S - Stribeck constant, m/s

μ_υ - viscous friction coefficient, N/(m/s)

F_{EXT} can be calculated from the external forces F_1 and F_2 at port 1 and 2 and the body weight as follows,

$$F_{EXT} = F_2 - F_1 + m\cdot g\cdot \sin\theta \tag{4}$$

where, F_1 - external force at port 1, N

F_2 - external force at port 2, N

m – mass of body, kg

g – gravitational constant , g = 9.801m/s^2

θ – inclination (+90 port 1 lowest, -90 port 1 highest), °(degree)

The relative velocity and displacement are as follows;

$$d\upsilon = \frac{F_{EXT} - F_{friction}}{m}\cdot dt \tag{5}$$

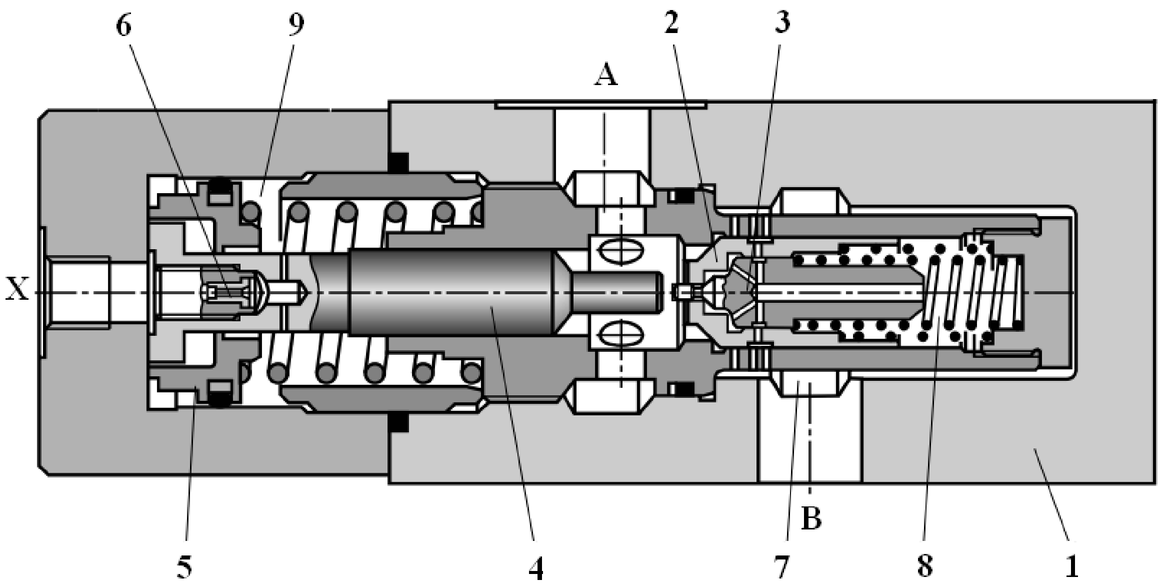
$$dx = \upsilon \cdot dt \tag{6}$$

When the velocity of the hydraulic cylinder is less than v_s, stick-slip occurs. A sliding body in contact reveals Stribeck effect and has a critical velocity. If the initial velocity of the hydraulic cylinder exceeds the critical velocity, stick-slip can be eliminated. Therefore, to eliminate stick-slip, the v_s is small enough for the cylinder to jump this stage or initial velocity of the cylinder is fast enough to exceed Vs. However, in large hydraulic cylinders, it is difficult to speed up for starting of the cylinder. Also a wide variety of materials and friction states which determine the critical velocity needs to eliminate the stick-slip even at high critical velocity.

2.2 drive circuit construction

There are several ways to eliminate low-speed stick-slip, and in this paper, we adopts the method of increasing the stiffness of the system by developing back pressure in the outlet of the hydraulic cylinder. Among the methods of creating back pressure, we adopt the method of using balance valve, which acts as a lock during the actuator shutdown and develops back pressure during the motion based on the principle of output throttling.

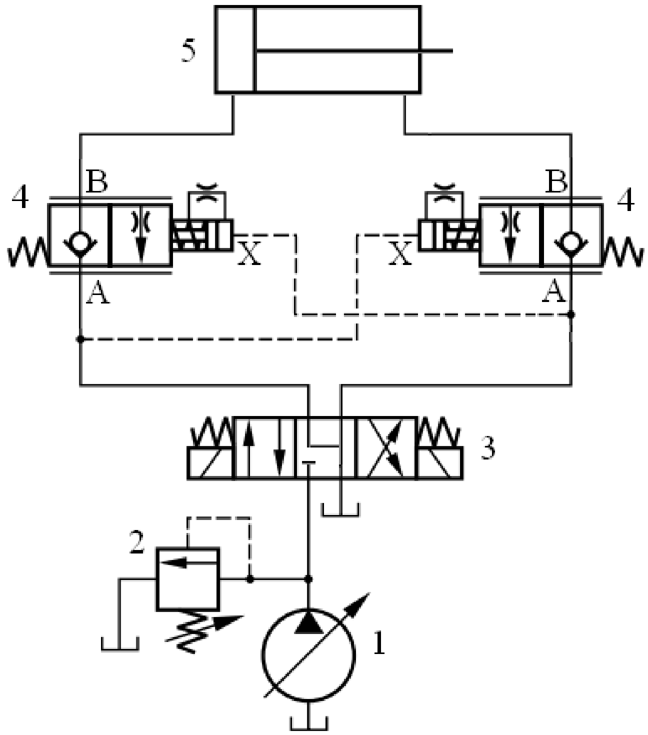
The schematic of the balance valve of the FD series of Mannesmann Rexroth is shown in Fig. 2 [17].



1-housing, 2-main poppet, 3-pilot part 4-pilot spool, 5-damping spool, 6-orifice, 7-load side, 8-chamer 9-spring chamber

Fig 2. Schematic of the balance valve

The hydraulic cylinder driven circuit with balance valve is shown in Fig 3

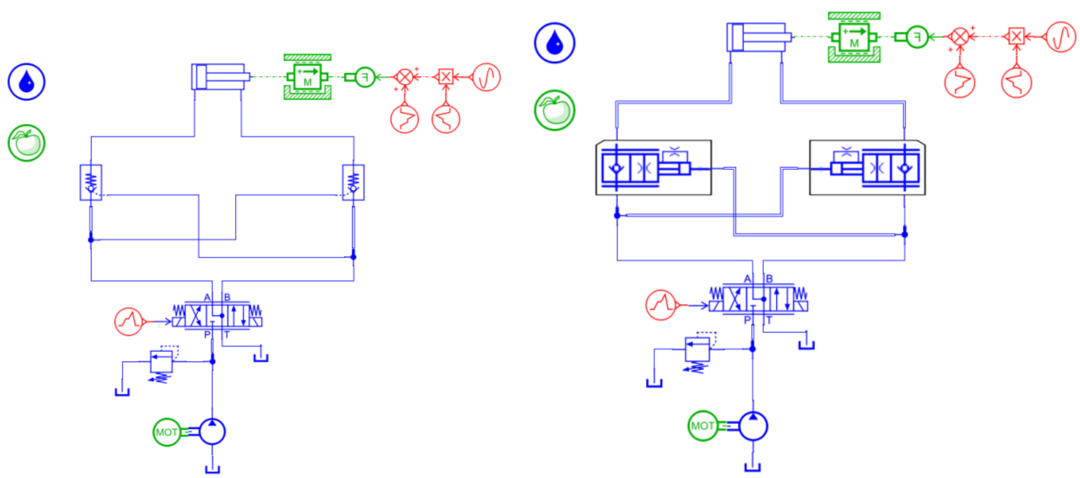


1-pump, 2-relief valve, 3-directional valve 4-balance valve, 5-hydraulic cylinder

Fig 3. The hydraulic cylinder driven circuit with balance valve

3. AMESim simulation model of drive circuit of a large hydraulic cylinder with a balance valve

AMESim is used to simulate stick-slip phenomenon occurring at low speed of a large hydraulic cylinder. The AMESim simulation model is shown in Fig. 4.



(a) hydraulic lock (b) balance valve

Fig 4. AMESim simulation model of hydraulic cylinder drive circuit

The AMESim model of balance valve from HCD library is shown in Fig 5

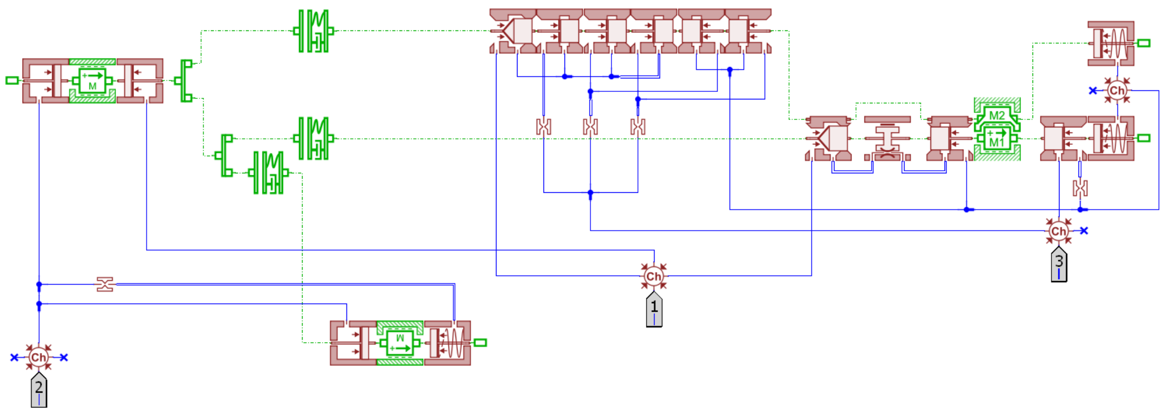


Fig5. AMESim model of balance valve using HCD library

Table 1 and 2 lists all the parameters used in the simulation.

Table 1. Simulation parameters

Component	Parameter	Symbol	Unit	Value
External load	Steady load	F_1	N	100000
	Load oscillation	F_2	N	200000
	Frequency of oscillation	f	Hz	1
Load mass element	mass	m	kg	5000
	Stiction(static friction) force	Fs	N	9000
	Coulomb friction	Fc	N	5000
	Stribeck constant	Fstri	m/s	0.01
	viscosity friction	μ	N/(m/s)	150000
Hydraulic cylinder	cylinder diameter	D	mm	400
	piston diameter	d	mm	280
	length of stroke	L	m	5
pump	geometric displacement	q	cm^2/r	50
	Shaft speed	n	r/min	1500
Relief valve	Max operating pressure	P_0	bar	264
Directional valve	Max flow rate	Q_{valve}	L/min	200

	valve rated current	i	mA	40
Pilot operated Check vale	cracking pressure	P_1	bar	3
	flow rate	$Q_{checkval}$	L/min	100

Table 2. Parameters of the balance valve

z	Parameter	Symbol	Unit	Value
Pilot spool	piston diameter	D_c	mm	28
	rod diameter	d_c	mm	16
Pilot spool mass	mass	mass	kg	0.1141
	coefficient of viscous friction	rvisk	N/(m/s)	1000
	high displacement limit	xmax	m	0.02
Damping spool	spool diameter	dp	mm	43
	rod diameter	dr	mm	14
	spring force at zero displacement	f0	N	80
	number of active coils	ncoil	---	5
	spring diameter	sdiam	mm	31
	wire diameter	wdiam	mm	3.5
Damping spool mass	Spool mass	mass	kg	0.0788
	coefficient of viscous friction	rvisk	N/(m/s)	1000
	high displacement limit	xmax	m	0.0135
Damping orifice	diameter	ordiam	mm	0.3
Main poppet	poppet diameter	dpop	mm	20
	diameter of hole	ds	mm	18
	under lap of spool 1	x_1	mm	-4
	under lap of spool 2	x_2	mm	-8
	under lap of spool 3	x_3	mm	-11.5
	under lap of spool 4	x_4	mm	6
	under lap of spool 5	x_5	mm	9
throttle	diameter of throttle	ordiam	mm	5

Main spring chamber	diameter	dp	mm	18
	spring force at zero displacement	f_0	N	5
	spring stiffness	k	N/mm	2.2
Pilot stage	diameter of poppet	dpop	mm	13
	diameter of hole	ds	mm	6
	under lap of spool	x_0	mm	3
leakage spool	diameter	dp	mm	6
	clearance on diameter	dc	mm	1.2
	length of contact	lcfixed	mm	3
Pilot stage spring	diameter	dp	mm	10
	spring force at zero displacement	f_0	N	3
	Spring stiffness	k	N/mm	3.1
mass	main poppet mass	mass2	kg	0.035
	pilot stage mass	mass1	kg	0.0218
	coefficient of viscosity	rvisc	N/(m/s)	1000
Main poppet of elastic end stop	gap or clearance	gap1	mm	4
Pilot stage of elastic end stop	gap or clearance	gap2	mm	2
Damping spool of elastic end stop	gap or clearance	gap3	mm	5

Fig 6 represents the pressure differential vs flow curve of the balance valve from AMESim model which is the same as [17].

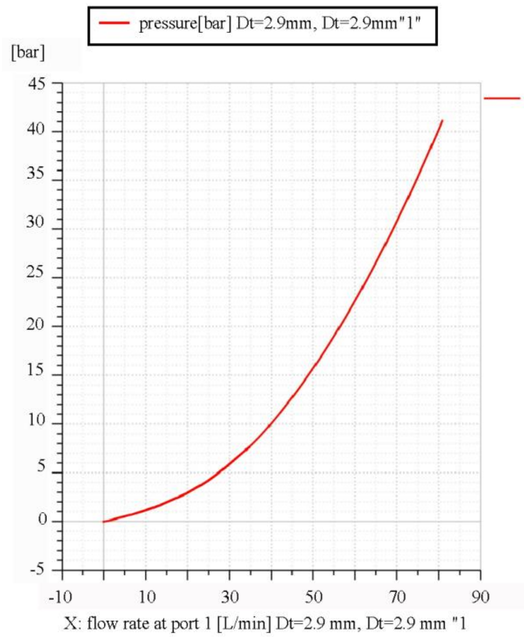
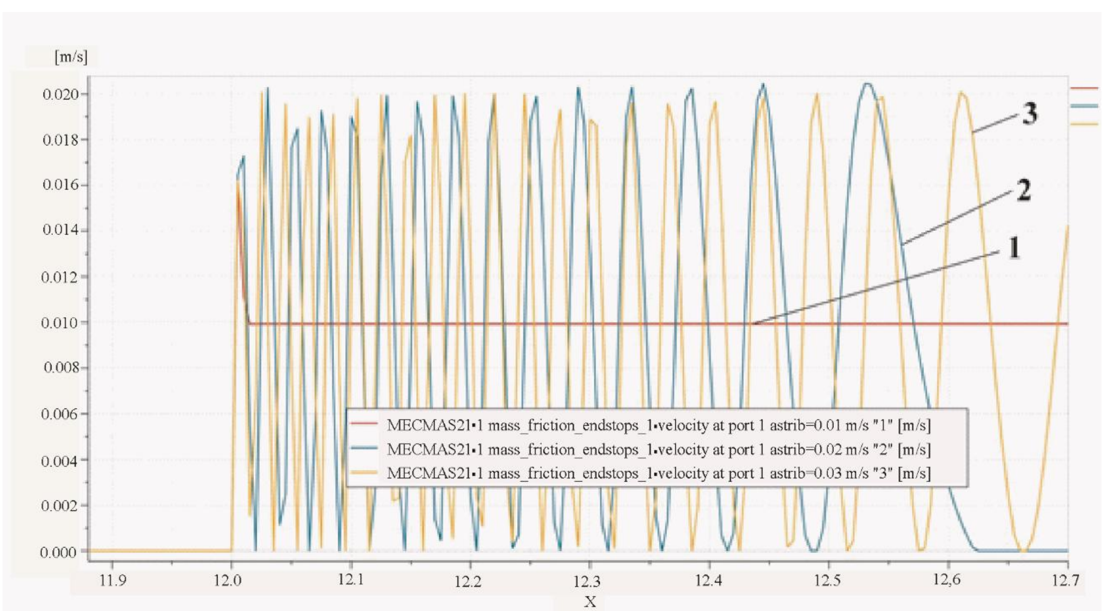


Fig 6. Pressure difference vs flow rate curve of balance valve

4. A method to avoid stick-slip in a large hydraulic cylinder under varying condition

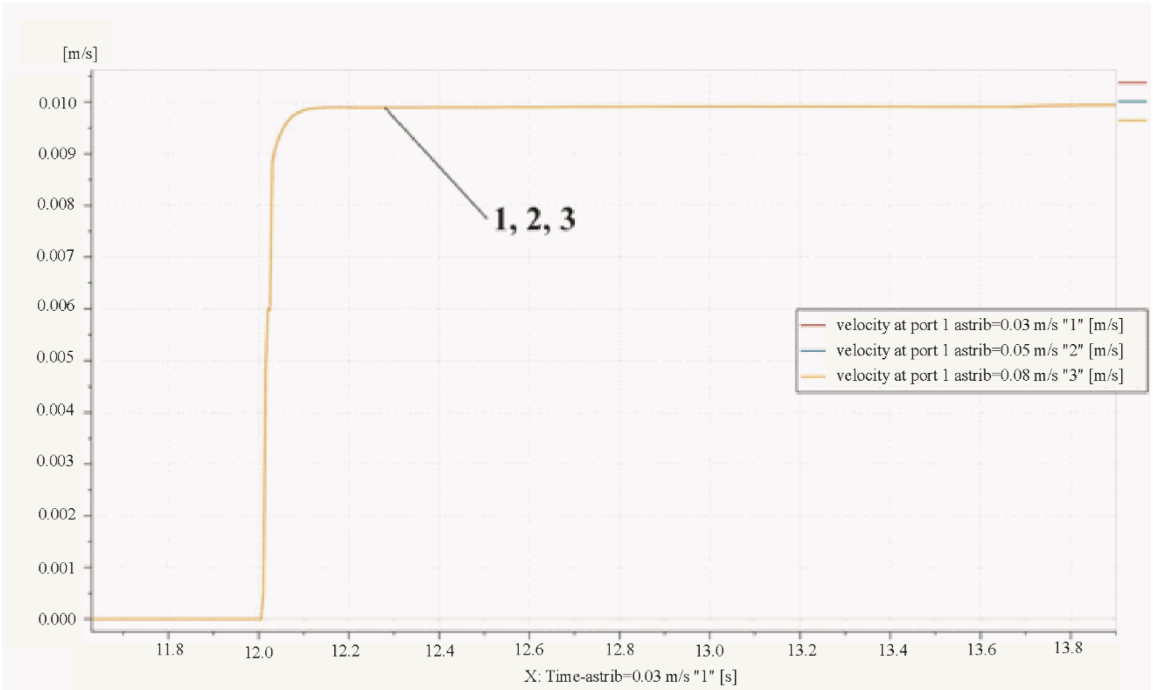
4.1 Comparison with the conventional system using a hydraulic lock

The results of analyzing the influence of critical velocity (Stribeck velocity) on stick-slip are shown in Fig. 7 and 8.



(1-υ_S =0.01m/s, 2-υ_S =0.02m/s, 3-υ_S =0.03m/s)

Fig 7. The influence of critical velocity on hydraulic lock circuit

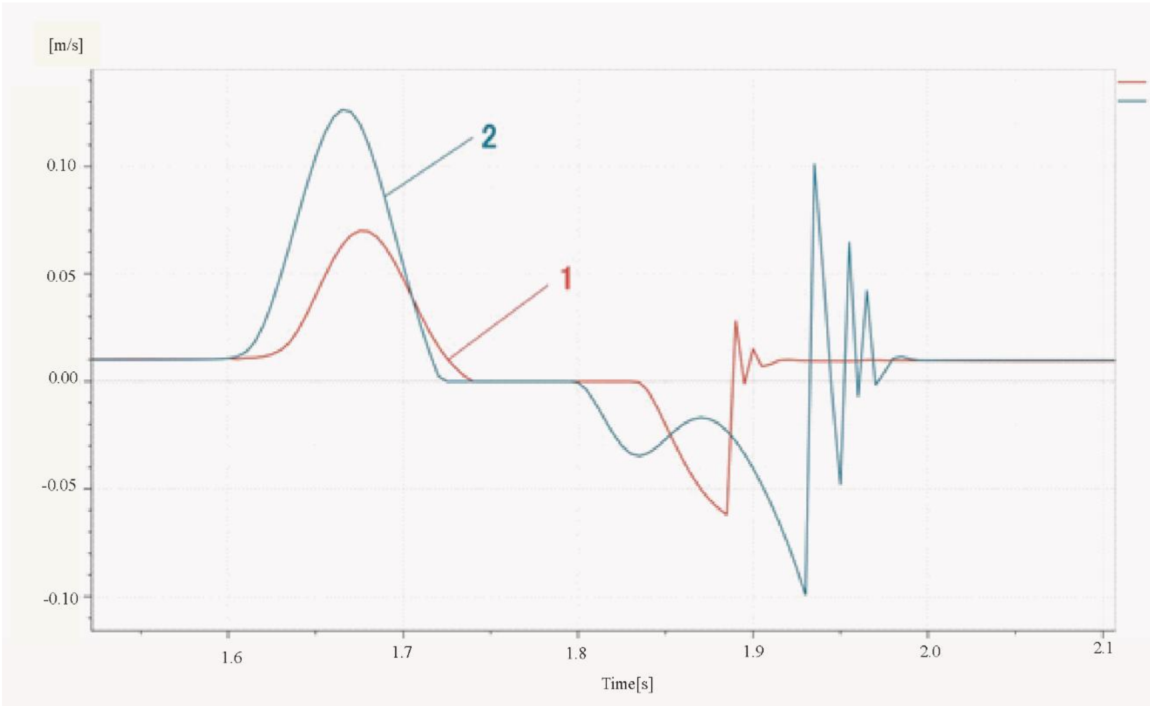


(1-υ_S =0.03m/s, 2-υ_S =0.05m/s, 3-υ_S =0.08m/s)

Fig 8. The influence of critical velocity on balance valve circuit

As shown in Fig. 7, the drive circuit with hydraulic lock has no back pressure effect, so the critical velocity should be below a certain threshold value (0.01 m/s in our calculations) to eliminate stick-slip. However, as shown in Fig. 8, the drive circuit with balance valve can effectively reduce low-speed stick-slip even at a much higher velocity than the critical velocity of hydraulic lock drive circuit.

We simulated stick-slip phenomenon by varying load in two drive circuits with the same critical velocity, where the load is given as F_W= [$1+2\times\sin(2\pi t)$] $\times10^5$.



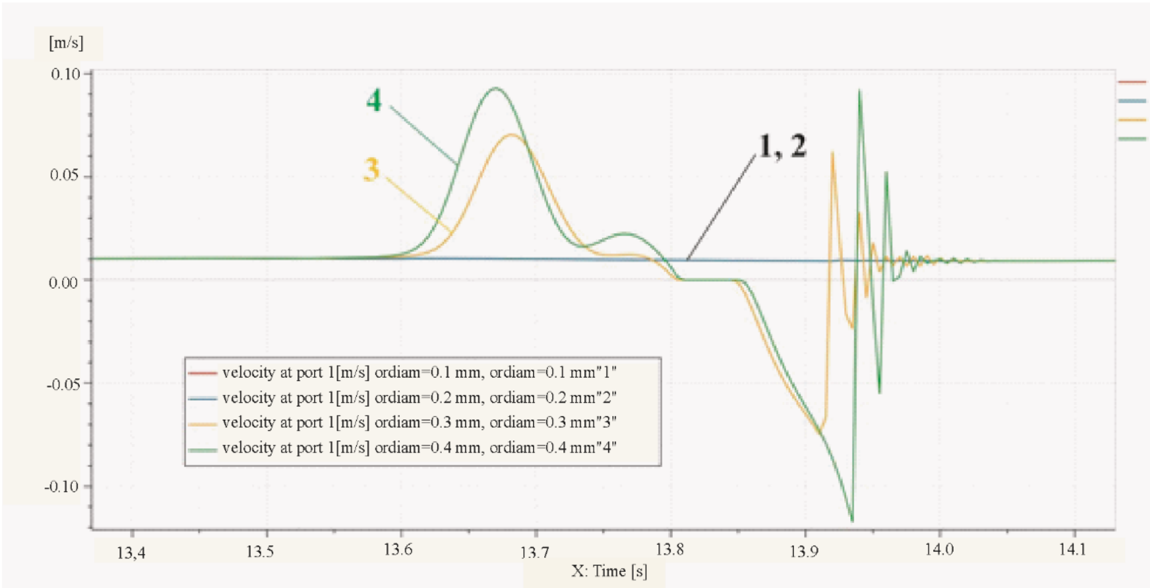
1-balance valve, 2-hydraulic lock

Fig 9. The simulation curve of eliminating stick-slip by varying load

As shown in Fig. 9, the drive circuit with balance valve has the good ability to eliminate the negative load-induced backward oscillation. In practice, it is necessary to avoid such a large negative load, but it can be concluded that the balance valve is very effective for a system to cope with the sudden changes of disturbance.

4.2 In the case of varying load

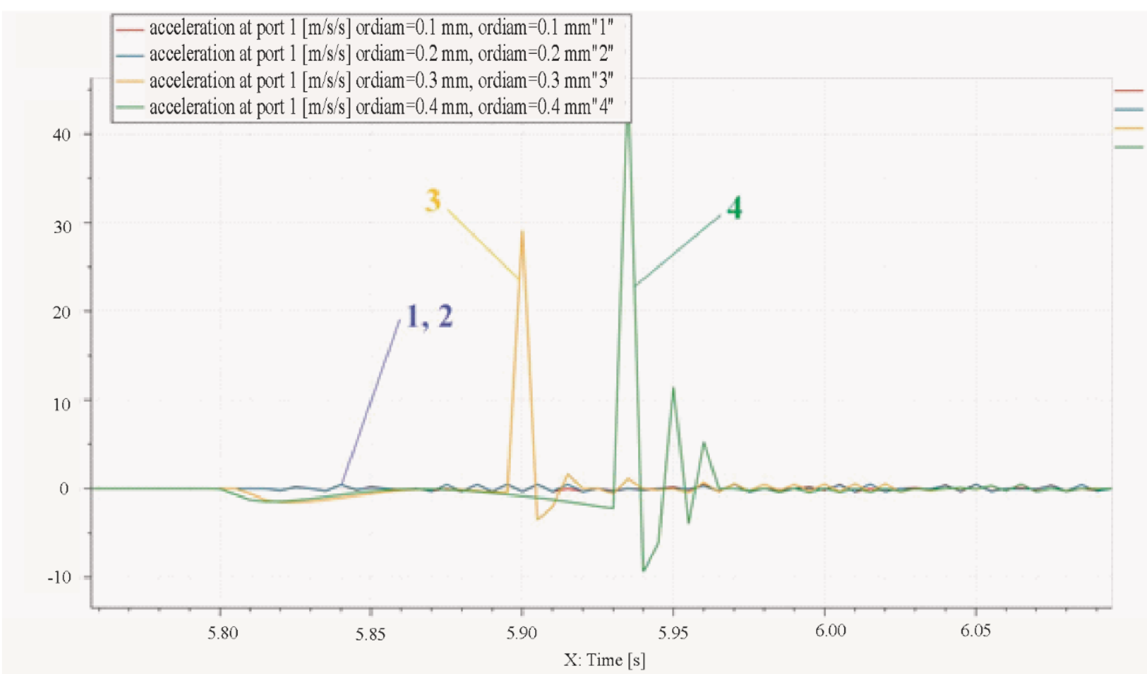
The effect of the throttling orifice size of the damped spool on the stick-slip is analyze. The velocity characteristics of the damping hole at 0.1, 0.2, 0.3 and 0.4(mm) are analyzed (Fig. 10).



(1-orifice diameter=0.1mm, 2-orifice diameter=0.2mm,

3-orifice diameter=0.3mm, 4-orifice diameter=0.4mm)

Fig 10. Velocity curve of damping spool in relation to orifice diameter



(1-orifice diameter=0.1mm, 2-orifice diameter=0.2mm,

3-orifice diameter=0.3mm, 4-orifice diameter=0.4mm)

Fig 11. Acceleration curve of damping spool in relation to orifice diameter

As shown in Fig. 10 and Fig. 11, it can be seen that stick-slip can be effectively suppressed if the diameter of the orifice is less than 0.2 mm, but it cannot reduce the stick-slip if the diameter of the orifice is larger than 0.3mm.

5. Discussion

The pressure of the hydraulic cylinder space decreases when negative load is applied. This means that the pressure of the control port at balance valve in the outlet is decreased. When the pressure-driven force of the control port is less than the sum of pressure force and spring-driven compression force due to back pressure of the outlet, the damping spool will return, the main poppet and pilot part of the balance valve, which are connected to the outlet space, will close and the hydraulic cylinder will stop.

The variation of the load direction (from negative to positive) will result in stick-slip phenomenon at low speed such as the start-up of the hydraulic cylinder. Therefore, to prevent balance valve from closing, the orifice diameter of the pilot spool must be less than a certain value to increase the restoring resistance. Such control cannot be achieved in drive circuit using conventional hydraulic locks, but it can be effectively implemented using balance valve.

In other words, the drive circuit with balance valve can effectively avoid not only low-speed stick-slip at start-up of the hydraulic cylinder, but also stop-start phenomenon caused by the negative load in the steady state.

6. Conclusion

The paper proposes a hydraulic drive circuit using a balance valve to avoid stick-slip by developing back pressure in the outlet of the hydraulic actuator at high critical velocity, and the AMESim simulation analysis shows that the damped throttle diameter of the pilot spool of the balance valve has a great influence on stick-slip under negative load condition.

First, balance valve can effectively eliminate low-speed stick-slip phenomenon even at much higher velocity than the critical velocity of the hydraulic lock drive circuit.

Second, when the amplitude of varying load is large, the diameter of the pilot spool orifice of balance valve must be small enough to effectively eliminate stick-slip phenomenon. Therefore, if a standardized balance valve is used, the diameter of the pilot spool orifice has to be changed according to the load variation characteristics.

The results from this paper can be used for the design and operation of large hydraulic devices with load variation and poor lubrication conditions.

Acknowledgment

I would like to take the opportunity to express my hearted gratitude to all those who make a contribution to the completion of my article.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Disclosure statement

No potential conflict of interest was reported by the authors.

Data Availability

The data that support the findings of this study are available within the article.

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