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INTELLIGENT HYDRAULIC DEVICES: EVOLUTION AND APPLICATION OF ADAPTIVE MECHANISMS

Abstract. This paper investigates an innovative hydraulic system with two degrees of freedom and a single input, featuring a patented closed hydraulic circuit. The adaptive hydraulic mechanism of this system is analyzed, showcasing a unique force adaptation effect. The speed adjustment of the output piston in the adaptive hydraulic mechanism depends on the current load. Upon reaching a predetermined resistance to movement, the output piston stops, transitioning the mechanism into a single-degree-of-freedom mode, while the input piston continues its motion. The effective force adaptation of the hydraulic system provides automatic regulation without the involvement of a control system. Our research aims to experimentally confirm the force adaptation effect in the proposed hydraulic mechanism and to provide a detailed description of the fundamental principles of its operation.

Keywords. Hydraulic adaptive mechanism, closed hydraulic circuit, self-regulation.

Introduction.

The research focuses on a hydraulic system with two degrees of freedom, comprising reservoirs, cylinders, and pistons. Existing hydraulic systems exhibit a "rigid" connection between the movement of the input and output pistons according to Pascal's principle, with the output piston moving at a constant speed. In applications with variable technological resistance, it is crucial to use hydraulic mechanisms with variable output piston speeds corresponding to varying loads. This paper proposes an innovative adaptive control scheme for the output force of hydraulic cylinders, based on direct force measurement using load cells [1]. Due to significant and uncertain piston friction forces, pressure control with Coulomb-viscous friction prediction proves insufficient for precise output force control. In the proposed approach, the measurement error of the output force is utilized not only for feedback but also for updating friction model parameters, including Coulomb-viscous sliding friction and output force dependence on sliding friction force.

The stability of both pressure force error and output force error is guaranteed, considering constraints on the required output force and its derivative, ensuring asymptotic stability. Experimental results indicate that effective pressure force control does not automatically guarantee control of the output force, and adaptive friction compensation outperforms fixed parameter compensations. Exceptional control performance of the output force, including torque, assumes dynamic equivalence between the hydraulic cylinder and electric drive for predefined bandwidths, enabling hydraulic robot drives to compete successfully with electric drives. However, such a control system proves excessively complex and does not guarantee efficient operation.

Previously, Ivanov K.S. conducted theoretical studies of a mechanical system where the degree of freedom is two and a single input [2, 3], demonstrating the force adaptation effect. This mechanical system where the degree of freedom is two and a closed loop adapts to variable external loads and operates without the use of a control system. The theoretical justification force adaptive effect of this mechanical system, along with its demonstration, is available on the website http://www.adaptation.kz. The hydraulic system where the degree of freedom is two and a single input can be considered an analogue of the mechanical system. Thus, a hydraulic system with two degrees of freedom, having a single input and a closed loop, also exhibits the force adaptation effect.

Analytical basis of the patterns of the hydraulic system where the degree of freedom is two, Ivanov K.S. developed and patented an adaptive hydraulic mechanism [4]. The main goal of our work is to describe the theoretical patterns of the hydraulic system where the degree of freedom is two, confirm the existence force adaptive effect in hydraulics, and present possible practical applications. The research is conducted based on the principles of mechanics and hydraulics.

Materials and methods.

Adaptive hydraulic mechanism design

The adaptive drive of the hydraulic mechanism piston is depicted in Figure 1. The drive comprises an input reservoir A, an output reservoir B, an input piston 1, intermediate piston blocks 2-4 and 3-5, and an output piston 6. Pistons 1, 2, 3 are located in the cylinders of the input reservoir A, while pistons 4, 5, 6 are situated in the cylinders of the output reservoir B. Let Si ,i=1…6 denote the piston areas, and Vi,i=1…6 represent the piston velocities.

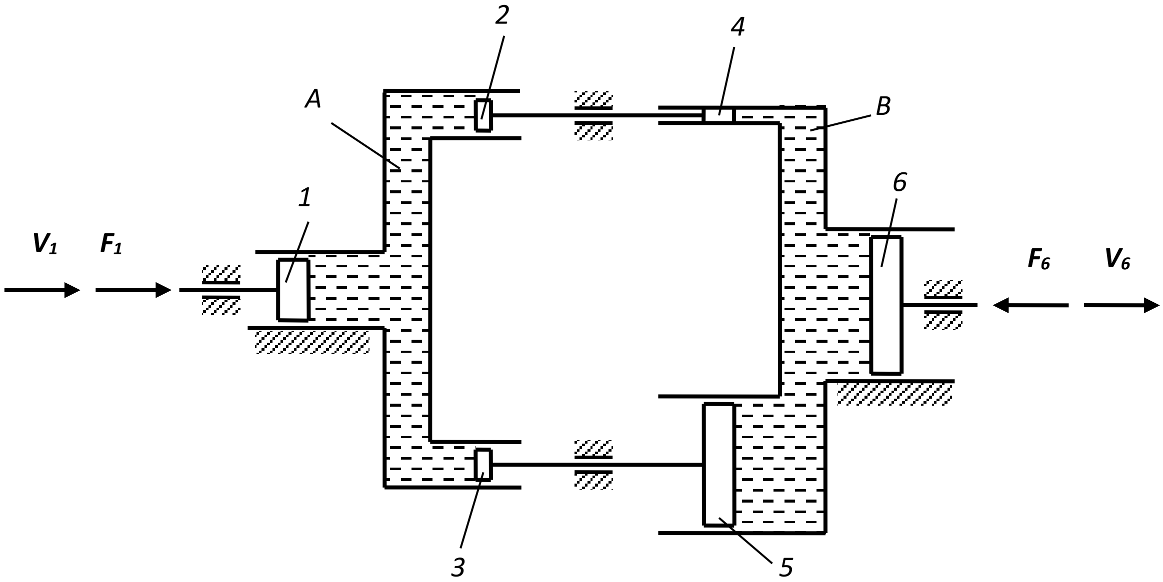

Figure 1 - Adaptive Drive of the Hydraulic Mechanism Piston

The piston blocks 2-4 and 3-5, along with reservoirs A and B, form a closed hydraulic circuit positioned between the input piston 1 and the output piston 6. The input piston 1 is subjected to a driving force F_d, while the output piston 6 experiences a resistance force F_r. During operation, the force F_d on the input piston 1 creates pressure P in the input cylinder, moving the piston blocks 2-4 and 3-5. Pistons 4 and 5 generate pressure P′ in the output cylinder, displacing the output piston 6.

The closed hydraulic circuit facilitates the system's adaptation to the output load.

Results and **Discussion.**

Relationship between hydraulic mechanism parameters.

Compose the equations of fluid flow in tanks A and B.

Piston 1 moves to the right. Piston block 2-4 moves to the right as $S_2 > S_4$.

Piston block 3-5 moves to the left as $S_3 < S_5$. Piston 6 moves to the right. The velocity directed inside the reservoir will be considered positive.

The Fluid Flow Rate Equation in the Reservoir A

$$S_1 \cdot V_1 - S_2 \cdot V_2 + S_3 \cdot V_3 = 0\,. \tag{1}$$

The equation for fluid flow rate in the reservoir B

$$S_4 \cdot V_4 - S_5 \cdot V_5 - S_6 \cdot V_6 = 0\,. \tag{2}$$

or accounting for $V_4 = V_2, V_5 = V_3$

$$S_4 \cdot V_2 - S_5 \cdot V_3 - S_6 \cdot V_6 = 0 \tag{3}$$

let's multiply equation (1) by p_1 and equation (3) on p_6. Taking into account $p \cdot S = F$ after rearrangements, we obtain

$$F_1 \cdot V_1 = F_2 \cdot V_2 - F_3 \cdot V_3\,, \tag{4}$$

$$F_6 \cdot V_6 = F_4 \cdot V_2 - F_5 \cdot V_3\,. \tag{5}$$

Subtracting equation (5) from equation (4), we get

$$F_1 \cdot V_1 - F_6 \cdot V_6 = F_2 \cdot V_2 - F_3 \cdot V_3 - F_4 \cdot V_2 + F_5 \cdot V_3\,. \text{ or}$$

$$F_1 \cdot V_1 - F_6 \cdot V_6 = (F_2 - F_4) \cdot V_2 - (F_3 - F_5) \cdot V_3\,. \tag{6}$$

Left side of equation (6) represents an algebraic sum of external force powers. right side of equation (6) represents an algebraic sum of internal force powers. If the hydraulic system is in equilibrium, according to the principle of virtual displacements, the sum of power (or work) of internal forces with ideal constraints present will be equal to zero.

$$(F_2 - F_4) \cdot V_2 + (F_3 - F_5) \cdot V_3 = 0\,. \tag{7}$$

Therefore, the left-hand side of equation (6) is also equal to zero.

$$F_1 \cdot V_1 - F_6 \cdot V_6 = 0\,. \tag{8}$$

Equation (8) represents an additional analytical relationship among the parameters of the hydraulic system with two degrees of freedom. This connection imposes a constraint on the motion of the system's components and ensures the determinability of the system when there is only a single input.

Equation (8) allows you to determine the output speed for a given constant input power $P_1 = F_1 \cdot V_1$ and given variable output resistance force F_6

$$V_6 = F_1 \cdot V_1 / F_6\,. \tag{9}$$

Equation (9) defines a fundamentally new property of a hydraulic system with two degrees of freedom - hydraulic adaptation. With an arbitrary setting of the output resistance force F_6 output speed V_6 automatically takes the appropriate value. The hydraulic system where the degree of freedom is two autonomously adapts to external loads without the use of any control systems. The external load governs the output velocity. Such a hydraulic system is self-regulating.

The closed loop in a hydraulic system where the degree of freedom is two establishes a fundamentally new precedent: firstly, it introduces an additional constraint leading to the determinability of motion, and secondly, it generates a force adaptation effect.

In equation (7) we denote $F_{35} = F_3 - F_5$ - full force on piston block 3 – 5, $F_{24} = F_2 - F_4$ - full force on piston block 2 - 4. We have $-F_{53} = F_5 - F_3$, because $F_5 > F_3$. Then from equation (7) we obtain

$$F_{24} \cdot V_2 = F_{53} \cdot V_3. \quad (10)$$

Equation (10) is the equation for internal circulating energy. Internal forces F_{53}, F_{24} in the general case, they are not equal to each other, however, the equilibrium is carried out according to the principle of possible displacements due to velocities.

Internal speeds V_3, V_2 piston blocks 3-5 and 2-4 are determined by solving the system of equations (1), (3) at known speeds V_1, V_6. Speed V_1 is given, and the speed V_6 is determined by equation (9).

We multiply equation (1) by S_5, and equation (3) is multiplied by S_3. We got:

$$S_1 \cdot S_5 \cdot V_1 - S_2 \cdot S_5 \cdot V_2 + S_3 \cdot S_5 \cdot V_3 = 0, \quad (11)$$

$$S_3 \cdot S_4 \cdot V_2 - S_3 \cdot S_5 \cdot V_3 - S_3 \cdot S_6 \cdot V_6 = 0. \quad (12)$$

We add equation (12) with equation (11), we get $S_1 \cdot S_5 \cdot V_1 - S_3 \cdot S_6 \cdot V_6 = (S_2 \cdot S_5 - S_3 \cdot S_4) \cdot V_2$. From here

$$V_2 = \frac{S_1 \cdot S_5 \cdot V_1 - S_3 \cdot S_6 \cdot V_6}{S_2 \cdot S_5 - S_3 \cdot S_4}. \quad (13)$$

From equation (1)

$$V_3 = \frac{S_1 \cdot V_1 - S_2 \cdot V_2}{S_3}. \quad (14)$$

Internal forces are determined by the formulas

$$F_{35} = p_1 \cdot S_3 - p_6 \cdot S_5. \quad (15)$$

$$F_{24} = p_1 \cdot S_2 - p_6 \cdot S_4. \quad (16)$$

Using formulas (13), (14), (15), (16), you can check the balance of circulating energy according to equation (10).

Equation (8) implies $S_1 \cdot p_1 \cdot V_1 - S_6 \cdot p_6 \cdot V_6 = 0$. From here we get the relationship between the pressures in the tanks A and B

$$p_1 = \frac{S_6 \cdot V_6}{S_1 \cdot V_1} \cdot p_6. \quad (17)$$

The gear ratio of the hydraulic system

$$u_{16} = V_1 / V_6 = F_6 / F_1. \quad (18)$$

At constant input power $P_1 = F_1 \cdot V_1$ gear ratio is variable depending on the output resistance force F_6.

Numerical example.
Given: F_1=20 H, V_1= 2 m/s, F_6=80H, S_1=20 cm^2, S_6=40 cm^2,
$S_2 = 10\ cm^2$, $S_3 = 10\ cm^2$, $S_4 = 8\ cm^2$, $S_5 = 40\ cm^2$
Define: V_6, p_1, p_6, V_2, V_3, F_{24}, F_{35}.
Solution
1) From (9) $V_6 = F_1 \cdot V_1 / F_6 = 20 \cdot 2/80 = 0.5\ м/s$.
2) Tank pressure A $p_1 = F_1 / S_1 = 20/20 = 1\ H/cm^2$.
3) Tank pressure B $p_6 = F_6 / S_6 = 80/40 = 2\ H/cm^2$. +
4) Equation check (17)

$$p_1 = \frac{S_6 \cdot V_6}{S_1 \cdot V_1} \cdot p_6. \quad 1 = \frac{40 \cdot 0.5}{20 \cdot 2} \cdot 2,\ 1=1.$$

5) Determination of the speeds of the internal links (piston blocks 3-5 and 2-4) according to the formulas (13), (14)

$$V_2 = \frac{S_1 \cdot S_5 \cdot V_1 - S_3 \cdot S_6 \cdot V_6}{S_2 \cdot S_5 - S_3 \cdot S_4} = \frac{20 \cdot 40 \cdot 2 - 10 \cdot 40 \cdot 0.5}{10 \cdot 40 - 10 \cdot 8} = 4.375\ m/s.$$

$$V_3 = \frac{S_1 \cdot V_1 - S_2 \cdot V_2}{S_3} = \frac{20 \cdot 2 - 10 \cdot 4.375}{10} = -0.375\ m/s.$$

We assumed that the velocity is directed V_3 inside the reservoir, however, the obtained negative value rejects this assumption. Speed V_3 is directed to the right.

6) Determination of internal forces by equations (15), (16)

$$F_{35} = p_1 \cdot S_3 - p_6 \cdot S_5 = 1 \cdot 10 - 2 \cdot 40 = -70\ H.\ F_{53} = 70\ H.$$

Force F_{53} directed to the left.

$$F_{24} = p_1 \cdot S_2 - p_6 \cdot S_4 = 1 \cdot 10 - 2 \cdot 8 = -6\ H.$$

Force F_{24} turned out to be also directed to the left.
7) Checking the balance of circulating energy according to the equation (10)

$$F_{24} \cdot V_2 = F_{53} \cdot V_3, \quad (-6) \cdot 4.375 = 70 \cdot (-0.375), \quad -26.25 = -26.25.$$

8) Input power $P_1 = F_1 \cdot V_1 = 20 \cdot 2 = 40\ Hm/s$. The power of circulating energy is equal to $P_{53} = F_{53} \cdot V_3 = -26.25\ Hm/s$.
9) The gear ratio of the hydraulic system according to the equation (18)

$$u_{16} = V_1 / V_6 = 2/0.5 = 4 = F_6 / F_1.$$

With constant input power, the gear ratio is variable, depending on the variable output resistance force F_6.

Adaptive hydraulic drive of the manipulator gripper.

Capturing and holding objects are key tasks for automated manipulators. The adaptive hydraulic mechanism possesses a unique property. It can operate both in a self-regulating mode where the degree of freedom is two and in an extreme mode with a single degree of freedom. The extreme mode occurs when the maximum load exceeds the allowable limit. In this case, the output piston of the mechanism stops, and the mechanism transitions into a state with a single degree of freedom, while the input piston continues its motion. This mode of operation can be referred to as a stop mode. The stop mode helps avoid damage to the mechanism during overload. Overload leads to the stopping of the working element, with the possibility to resume work after eliminating the overload or changing working conditions. The transition of the mechanism into the stop mode occurs automatically without the use of a control system. One possible application of the stop mode is in the adaptive hydraulic grip drive of a manipulator.

Currently, tactile control systems are commonly used for adapting grip force to an object. The development of universal gripping devices capable of lifting unfamiliar objects with widely varying shapes and surfaces is a highly challenging task. Petcovic D. and Pavlovic N. D. introduced a new rule for a universal gripping device with an adaptively transforming surface [5]. Adaptive surfaces are controlled by a compliant system with embedded actuators and sensitive elements. The sensing system must be made of conductive silicone rubber or foam. These are carbon-filled silicone materials with sensible properties, whose electrical resistance changes with compression. The implemented controlled system is qualified to adapt the gripping device's morph form to various objects. However, such a system has low reliability, efficiency, and high complexity.

It is suggested to use an adaptive gripping device for observed situations [4]. Another option for creating a tactile system using a hydraulic regulator was proposed by Kourosh Zareinia and Nariman Sepehri [6].

In this report, a remote adjustable circuit is developed for a stable tactile sensation feedback from mechanically manipulators. The regulator achieves stable position tracking of the hydraulic system drive (slave) in both voluntary and forced movements. Force responsiveness tactile (master) side is a combination of two different sensations. For free movement, haptic device provides position-dependent tactile force error between master and slave displacements. This force also serves to alert the operator when the follower is ahead or behind position tracking. Once the slave comes into contact with the environment, the haptic force related to touch sensation is increased by the interaction force. The uniqueness, continuity, and existence of Filippov's solution for this system with sliding surfaces are first proven. The stretching of the Lyapunov stability theory to non-smooth systems is then used to prove stability by constructing a Lyapunov function. The controller's effectiveness is affirmed through experimental studies. It is shown that while stable, the system performs well in terms of position tracking of the hydraulic drive and providing the operator with a sense of touch. The measurements required by the controller are supply pressure, drive line pressures, interaction force, and master and slave displacements.

Such a control system is extremely complex and not sufficiently reliable. It is proposed to use the stop mode of the adaptive hydraulic mechanism to create a self-regulating grip.

The adaptive grip (Figure 2) has a drive in the form of an adaptive hydraulic mechanism.

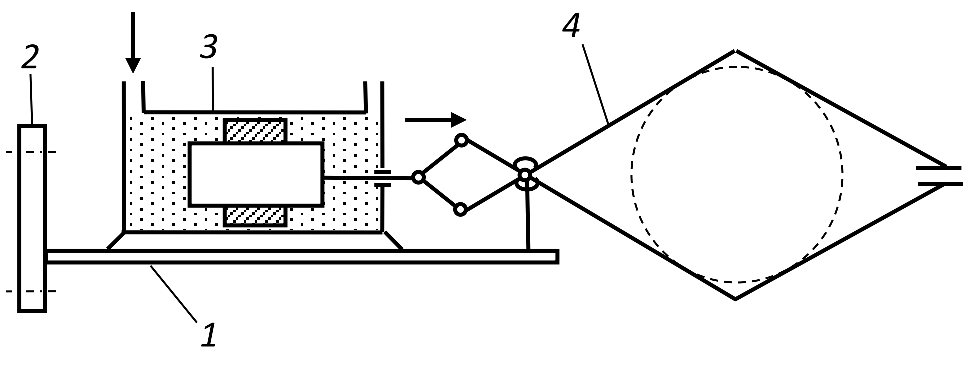

Figure 2 - Adaptive grip of the manipulator

The adaptive grip comprises a base 1 with a joint 2, an adaptive hydraulic drive 3, and a gripping mechanism 4. The item being gripped is shown in dashed lines.

During operation, the adaptive hydraulic drive 3 moves the output piston of the hydraulic adaptive mechanism to the right. The output piston transfers motion to the gripping mechanism 4, which ensures grasping the item. The gripping force impedes the movement of the output piston and stops it when the specified gripping force is reached. The adaptive drive mechanism transitions to a single-degree-of-freedom state, after which a position sensor turns off the drive and locks it in the final position. The resistance force to the movement of the output piston is determined by the required gripping force and depends on the size ratio of the links in the gripping mechanism 4. Therefore, achieving the specified gripping force does not require the use of tactile sensors. The release of the grip occurs when the input piston moves in the opposite direction.

The force adaptation effect allows the creation of an adaptive self-regulating manipulator grip, capable of limiting the force applied to the object without a control system with tactile sensors.

Conclusion.

Thus, the analysis of the interaction of parameters in a hydraulic system with two degrees of freedom, featuring a closed hydraulic circuit, confirms the existence of additional coupling and the presence of the force adaptation effect in hydraulics. The identified regularities enable the creation of highly efficient self-regulating hydraulic mechanisms with variable transmission ratios dependent on the load.

The adaptive hydraulic drive is structurally straightforward. The stop mode helps prevent overloads. The force adaptation effect allows for the development of an adaptive self-regulating manipulator grip, capable of limiting the force applied to the object without a control system with tactile sensors.

Undoubtedly, hydraulic adaptive systems will find widespread application in modern technology.

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ИНТТЕЛЕКТУАЛДЫ ГИДРАВЛИКАЛЫҚ ҚҰРЫЛҒЫЛАР: БЕЙІМДЕЛГЕН МЕХАНИЗМДЕР ЭВОЛЮЦИЯСЫ МЕН ҚОЛДАНЫЛУЫ

Аңдатпа. Бұл жұмыс патенттелген жабық гидравликалық схемасы бар екі еркіндік дәрежесі және бір кірісі бар инновациялық гидравликалық жүйені зерттейді. Бұл жүйенің бейімделгіш гидравликалық механизмі талданады, күшке бейімделудің бірегей әсерін көрсетеді. Бейімделетін гидравликалық механизмдегі шығыс поршеньдің айналу жылдамдығын реттеу ағымдағы жүктемеге байланысты. Қозғалыс үшін алдын ала белгіленген кедергіге жеткенде, шығыс поршень тоқтап, механизмді бір еркіндік дәрежесі режиміне ауыстырады, ал кіріс поршені қозғалысын жалғастырады. Гидравликалық жүйенің тиімді күшке бейімделуі басқару жүйесінің қатысуынсыз автоматты реттеуді қамтамасыз етеді. Біздің зерттеуіміз ұсынылған гидравликалық механизмдегі күштердің бейімделу әсерін эксперименталды түрде растауға және оның жұмысының негізгі принциптерінің толық сипаттамасын беруге бағытталған.

Түйінді сөздер. Гидравликалық бейімдеу механизмі, тұйық гидравликалық контур, өзін-өзі реттеу.

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ИНТЕЛЛЕКТУАЛЬНЫЕ ГИДРАВЛИЧЕСКИЕ УСТРОЙСТВА: ЭВОЛЮЦИЯ И ПРИМЕНЕНИЕ АДАПТИВНЫХ МЕХАНИЗМОВ

Аннотация. В данной статье исследуется инновационная гидравлическая система с двумя степенями свободы и одним входом, имеющая запатентованную замкнутую гидравлическую схему. Проанализирован адаптивный гидравлический механизм этой системы, демонстрирующий уникальный эффект адаптации силы. Регулировка скорости выходного поршня в адаптивном гидромеханизме зависит от текущей нагрузки. При достижении заданного сопротивления движению выходной поршень останавливается, переводя механизм в одностепенный режим свободы, а входной поршень продолжает движение. Эффективная силовая адаптация гидросистемы обеспечивает автоматическое регулирование без участия системы управления. Целью наших исследований является экспериментальное подтверждение эффекта силовой адаптации в предлагаемом гидромеханизме и детальное описание основных принципов его работы.

Ключевые слова. Гидроадаптивный механизм, замкнутый гидроконтур, саморегулирование.

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