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REVIEW ARTICLE

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Motion control of multi-actuator hydraulic systems for mobile machineries: Recent advancements and future trends

Abstract This paper presents a survey of recent advancements and upcoming trends in motion control technologies employed in designing multi-actuator hydraulic systems for mobile machineries. Hydraulic systems have been extensively used in mobile machineries due to their superior power density and robustness. However, motion control technologies of multi-actuator hydraulic systems have faced increasing challenges due to stringent emission regulations. In this study, an overview of the evolution of existing throttling control technologies is presented, including open-center and load sensing controls. Recent advancements in energy-saving hydraulic technologies, such as individual metering, displacement, and hybrid controls, are briefly summarized. The impact of energy-saving hydraulic technologies on dynamic performance and control solutions are also discussed. Then, the advanced operation methods of multi-actuator mobile machineries are reviewed, including coordinated and haptic controls. Finally, challenges and opportunities of advanced motion control technologies are presented by providing an overall consideration of energy efficiency, controllability, cost, reliability, and other aspects.

Keywords motion control, electrohydraulic control, energy efficiency, mobile machineries

1 Introduction

The advantages of high power-to-weight ratio and excellent control performance have prompted the extensive use of hydraulic systems in mobile and industrial applications. Compared with industrial hydraulic applications, mobile applications (e.g., excavators and cranes) are characterized by limited installation space and high emission requirement for the engine source. In addition, the pressure and flow demands of mobile machineries tend to vary frequently over time.

Current installation spaces limit the number and size of the hydraulic pumps in mobile applications, and such pumps usually supply more than one actuator at a time. Hence, the most important requirements of hydraulic systems for mobile machineries can be divided into two aspects.

1) Good dynamics: Like many other mechatronic systems, the hydraulic systems of mobile machineries should behave with adequate damping, robustness, stability margin, and response velocity.

2) High efficiency: Hydraulic mobile machineries are relatively inefficient because the hydraulic systems are inefficient, with efficiencies ranging only from 6% to 40%, depending on the application [1]. Recently, demand for energy savings has been amplified due to dwindling fossil energy sources and the need to reduce carbon dioxide. High-efficiency demand means that the required flow and pressure of multiple actuators should be exactly fulfilled by the hydraulic source.

Therefore, mobile hydraulic systems should be compact, energy-saving, and easily controllable [2]. Apart from the demands of dynamic behavior and energy efficiency, another characteristic of mobile machineries is the human-in-the-loop operation mode. Mobile machineries aim to enable the operator to control multiple actuators simultaneously with good response and dynamic behavior. Unlike many other mechatronic systems, the fully automatic control task is still one of the most challenging areas in mobile machineries. The operation mode is a typical human-in-the-loop control loop, which means that the control inputs are generated directly by the operators in real time. Hence, mobile machineries are housed in a

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highly unstructured and uncertain working environment. However, identifying the environment and automatically conducting a proper and prompt working task are extremely difficult. As can be seen, operators simultaneously control the boom, the arm, the bucket, and the swing motion using the joysticks (Fig. 1).

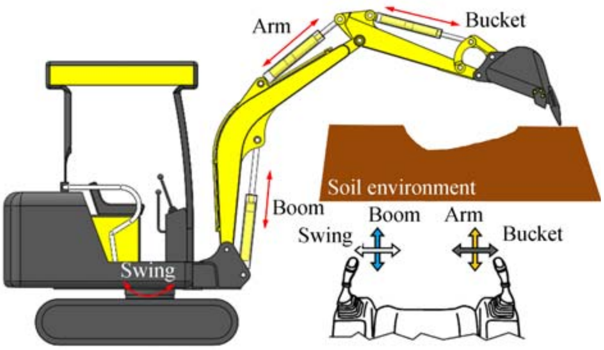

Fig. 1 Motion control of a typical hydraulic excavator [3]

Moreover, reliability, cost, noise, and some other aspects also require consideration. Therefore, advanced hydraulic circuits and control strategies have been developed to fulfill the diverse demands that have emerged in the last decades. This paper briefly summarizes motion control of the multi-actuator hydraulic systems. The rest of the paper is divided into sections. Section 2 briefly reviews the state-of-the-art hydraulic systems of mobile machineries. Sections 3 to 5 summarize the advanced motion control systems and strategies for mobile machineries. Section 6 discusses the challenges and trends in this field, and Section 7 presents the conclusions.

2 State of the art

The valve-controlled system is traditionally used to accurately divide the required oil flow into multiple hydraulic actuators. Its basic circuit is the open-center system featuring the open-center control valves and fixed displacement pumps [4]. This system is widely used in small-size mobile machineries (e.g., 2-ton or small excavators) because of its simplicity, robustness, and cost-effective control. However, excessive flow losses may lead to inefficiency; hence, the fixed displacement pump must be replaced by the variable displacement pump to improve energy efficiency. The negative flow control and the positive flow control [5] are introduced to regulate the pump displacement, thus fulfilling the demand requirements. However, bypass flow loss caused by the open-center valve structure may still occur. Different loads may also interfere with one another in open-center systems; thus, the variation of the flow or pressure can heavily influence the velocity of another actuator.

The hydro-mechanical load sensing (HMLS) system is equipped with a variable displacement pump and closed-center valves (Fig. 2). The pressure feedback is introduced to control the pump pressure as a preset value above the highest load pressure [6]. The supplied flow is simultaneously regulated to maintain consistency with the required flow. However, three kinds of energy waste can still be generated: 1) Waste caused by the preset pressure margin, 2) waste consumed by the throttling losses, and 3) waste caused by the load discrepancy and consumed by the pressure compensator of the lower load (Fig. 2).

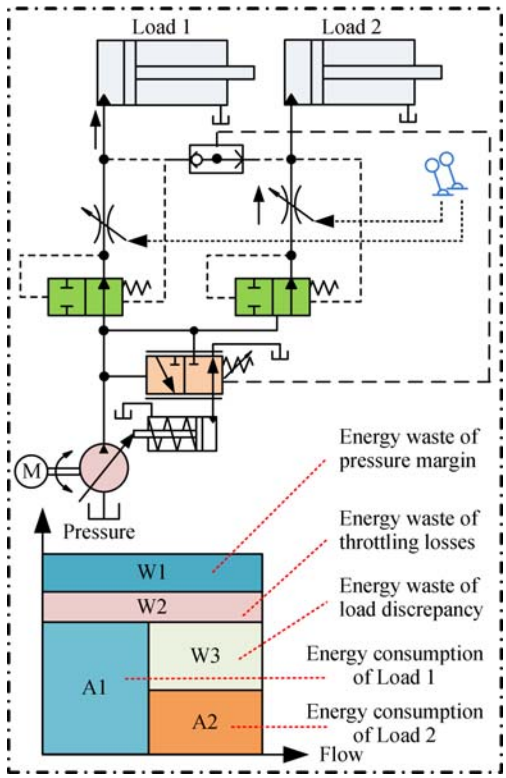

Fig. 2 Layout of the HMLS system and its energy consumption

In the HMLS system, a benefit on dynamic behavior includes the decoupling between velocity and load variation through the pressure compensator; however, the load information available to the operator is also lost simultaneously [7]. In addition, the systematic analysis and actual application indicate three disadvantages of dynamic behavior for the HMLS system [8–10].

1) Slow response: The HMLS system is characterized by a slow response caused by load pressure feedback and delayed pressure transmission of the hydraulic pipe.

2) Oscillation tendency: The system dynamics can be relatively undamped due to the pressure control loop and the pressure compensators. The control system thereby shows an oscillatory behavior.

3) System instability: Two kinds of stability problem are generally identified, namely, pump and pump-load

instabilities. Although several solutions have been proposed to stabilize the HMLS system (e.g., smaller pump volume [9]), obtaining the global stability of the overall system remains difficult.

The increasing usage of electronic control has led to the further development of electrohydraulic systems for intelligent mobile machineries. Correspondingly, different hydraulic control architectures have been presented to further improve the energy efficiency and dynamic performance of the HMLS system. Three advantages have been proven and reviewed in the latter sections of this paper.

1) Efficiency improvement: High-performance electrohydraulic components offer an opportunity to develop energy-saving circuits. Section 3 summarizes the valve control, pump control, and hybrid control, along with a systematic view.

2) Dynamic improvement: With the flexibility of electronic control, Section 4 establishes suggestions and discussions regarding advanced control methods in order to solve the dynamic problems in traditional systems and energy-saving circuits.

3) Operation improvement: The electronic control of hydraulic components also builds a bridge between hydraulic circuits and intelligent human interface. Section 5 discusses new operation methods and devices for mobile machineries.

3 Motion control with efficiency improvement

3.1 Valve control

The flexibility and adaptability of hydraulic components are improved as electrical concepts are used in a wide range of applications. To improve the energy efficiency of mobile machineries, several energy-saving hydraulic circuits based on high-performance electrohydraulic components have been developed. The energy-saving circuits aim to reduce or eliminate the three kinds of energy waste in the HMLS systems mentioned earlier.

To reduce metering losses of control valves, the use of individual metering control (IMC) systems has been considered a promising solution and a hot research topic since the early 1990s. Figure 3 shows the decoupling of the meter-in and meter-out orifices in the IMC system instead of a mechanical coupling in traditional valves [11].

Owing to the flexibility of electrohydraulic valves, different control modes can be configured and switched to fulfill the energy-saving demands under different load conditions. As shown in Fig. 4, the power extension (PE) mode can be activated in the boom-lifting process, while the meter-out orifice is fully opened to reduce valve loss (Fig. 4). The low side regeneration retraction (LSRR) mode can be used in the boom-descending motion to

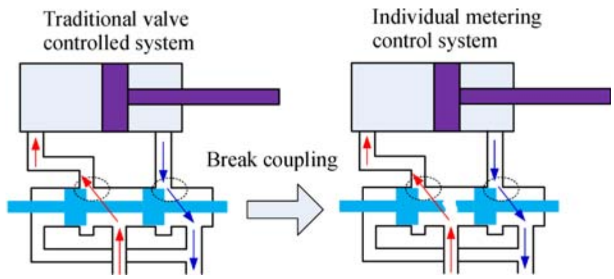

Fig. 3 Typical layout of the individual metering control system [11]

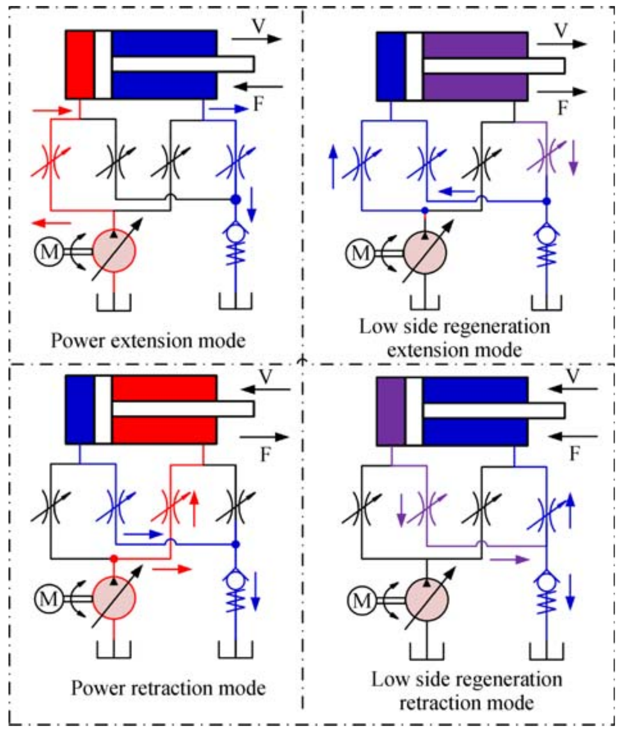

Fig. 4 Different control modes for energy regeneration

achieve energy regeneration [12]. With hydraulic accumulators, the valve network can help create an energy recuperation function, which can lead to further improvements in energy efficiency [13]. Some other advantages of the IMC systems have been identified, such as general hardware, control redundancy, and productivity improvement. Detailed information can be found in Ref. [14].

The fast switching valve (also called digital valve), which is introduced from power electronics and is based on IMC, is a potentially efficient solution to replace the traditional valve [15]. The fast switching valves effectively produce variable flow and pressure by rapidly switching between the pump and tank line [16]. The meterless control of the hydraulic actuator can be achieved due to the instant opening and closing of digital valves. The digital hydraulic system has several other advantages, including robustness, fault tolerance, and sensorless incremental actuation [17]. However, a negative correlation exists between the switching frequency and the flow capacity or the orifice area. Another challenge is achieving tradeoff between physical size on the one hand, and response time, production cost, and durability, on the other hand, prior to actual application. In addition, pressure oscillations [18] and system damping [19] require further reductions to improve the controllability of mobile machineries.

3.2 Pump control

In the HMLS system, the pressure margin is preset to construct a pressure control loop that can maintain consistency between the supplied and required flow rates. The pressure margin exists in the control circuit, thereby restricting the improvement of energy efficiency. Hansen et al. [20,21] proposed an electronic load sensing (ELS) scheme with a pressure controller by adding a feedforward term from the joystick command to decouple the input disturbance. The test result on a telehandler indicated that the pressure margin decreased to 0.7 MPa; however, the preset pressure margin still existed, further increasing the potential to improve system efficiency. The “Virtual Bleed Off VBO” system with pressure control, implemented by Bosch Rexroth, Inc., can create only the required pressure in each working mode [22].

To cope with the limitation of the load sensing concept, the control method of electrohydraulic flow matching (EFM) is presented [23]. Here, the variable displacement pump is directly governed by the input demand from the operators (Fig. 5). Pressure feedback is removed in the EFM systems, and the pressure margin is generally lower than the preset value in HMLS systems, depending on the specific working point. The pump and the valves work in a synchronous mode. The pump displacement is calculated through the flow characteristics and input demands of control valves as expressed by

$$V_\mathrm{p} = \frac{\sum_{i=1}^{n} C_\mathrm{d} A(u_{\mathrm{v}i})\sqrt{2\Delta p_i/\rho}}{n_\mathrm{p}}, \quad i = 1,2,...,n, \tag{1}$$

where n_p is the rotational speed of the prime mover, C_d is the flow coefficient, and $u_{\mathrm{v}i}$, $A(u_{\mathrm{v}i})$, and Δp_i are the input signals, cross-sectional areas, and pressure drops of the control valves, respectively. Another benefit is that the traditional control valves with pressure compensation can also be applied in the EFM systems. Thus, the application of the EFM system only requires minor modifications on the current hydraulic layout.

However, due to system nonlinearities (e.g., nonlinear flow characteristic) and parameter uncertainties (e.g., uncertainties of oil temperature), one difficulty preventing the actual application of the EFM concept is accurately predicting the transient flow characteristics of pumps and valves. Thus, the flow matching accuracy between the supplied and the required flows is limited, potentially leading to flow excess and energy losses. A simple solution is to add a bypass unloading valve on the pump side, and the excessive oil goes through the bypass valve into the tank when the supplied flow is excessive [24]. However, fully eliminating the energy loss caused by excessive flow remains difficult. To solve this problem, Grösbrink and Harms [25] proposed an alternating pump control method, in which the pump is flow controlled under large flow demand and pressure controlled at small swash plate angles. Moreover, the dynamic flow mismatches can be minimized by compensating the control signals to synchronize the pump and the valves [26]. Axin et al. [27] proposed a hybrid pressure and flow control using a weighted sum of the EFM and ELS controllers as the pump signal, and reported a notably compromised energy efficiency between the EFM and HMLS systems. Xu et al. [28] proposed a flow/pressure control scheme that utilizes a switching rule according to the pressure margin; their proposed EFM system switches from displacement- to pressure-controlled mode when the pressure margin is greater than a preset threshold.

Another approach to address the flow mismatch issue is to adopt the flow sharing valve [29]. The flow sharing valve is a proven commercial technology developed and applied by several manufacturers (e.g., Linde Synchron Control LSC and Bosch Rexroth LUDV) [5]. In EFM systems with flow sharing, the supplied flow is distributed proportionally into multiple actuators based on the cross-sectional areas of the control valves. However, the main disadvantage of the flow sharing valve is the occurrence of motion disturbance between the lighter and highest loads [27].

The EFM concept offers an opportunity to improve energy efficiency by maximizing the control valves, considering that the pump is not related to the valve

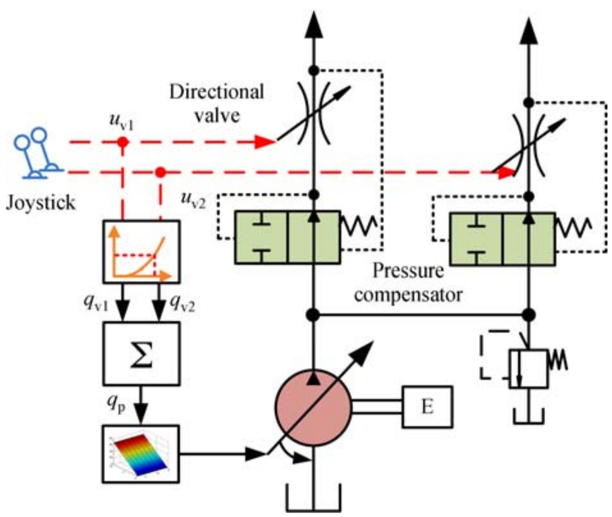

Fig. 5 Typical flow matching control concept with pressure compensation

opening but is directly managed by the input command [30]. To reduce the energy losses caused by load discrepancy, Finzel et al. [31] proposed the flexible dual-circuit system, shown in Fig. 6, which combines the advantages of the pump-controlled system in terms of minimizing throttling losses. The tests indicated that the energy consumption of a hydraulic excavator can be reduced by approximately 30% compared with the existing HMLS system. Combined with IMC, EFM, and pressure compensation, other complicated electrohydraulic circuits can be constructed to further improve energy efficiency [32–35].

The development of a high-performance electrohydraulic pump is simultaneously accompanied by a presentation of the displacement controlled concept to eliminate the three energy losses of the HMLS system. As shown in Fig. 7, each hydraulic actuator is controlled separately by a variable displacement-controlled pump [36,37], whereas the load velocity is controlled by regulating the pump displacement. The one-pump-per-actuator concept enables the elimination of the valve loss and the pressure margin, while simultaneously avoiding the pressure loss caused by load discrepancy. In addition, the pump is capable of working as pump or motor, depending on the load quadrant. Moreover, hydraulic energy can be regenerated through the pump shaft.

Power management methods are designed to improve fuel economy by adjusting the operating points of the hydraulic pumps and diesel engine [36]. The instantaneous rate of fuel consumption is minimized through operator commands and the detailed mapping of pump and engine efficiency, including hydraulic energy recovery. The displacement-controlled excavator prototype has been developed by Busquets and Ivantysynova [37], and their test results forecasted over 40% energy savings compared with the traditional valve controlled system.

However, a major obstacle threatens the commercialization of the displacement controlled system: The increase in the production costs and pump size, especially in large-size mobile machineries, due to the one-pump-per-actuator requirement. To overcome this issue, fewer pumps and a set of switching valves are utilized [38,39]. Moreover, the pump switching method is introduced to fulfill the flow requirement of the actuators (Fig. 8). This concept reduces installed pump power for multi-actuator machines, thereby minimizing parasitic losses and production costs. One core challenge of this technology is to address potential instability and unsmooth motion when switching between the movements of different actuators.

In displacement-controlled systems, large-sized pumps should be adopted due to the unequal fluid volumes of the single-rod cylinder. Heybroek [40] proposed an alternative displacement concept that features an open hydraulic circuit and four separate valves for mode selection (Fig. 9). The mode switching strategy is designed to allow the cylinder to be controlled over four load quadrants. Test results using the wheel loader in a short truck loading cycle confirm a 10% reduction in fuel consumption. Small-sized units can also be utilized in this system layout, but the control law needed to control several pumps and valves under different modes and conditions is complicated.

Meanwhile, the hydraulic transformer is an ideal option to eliminate the energy waste caused by the load discrepancy of multiple actuators. Hydraulic transformers [41] or buck converters (also called digital hydraulic transformers [15]) are designed to transfer pressure and flow rate, similar to an electrical transformer converting voltage and current; moreover, this function can be created using the multi-chamber cylinder [15]. However, an efficient transformer design with high dynamic performance at an acceptable cost has yet to be achieved, and as

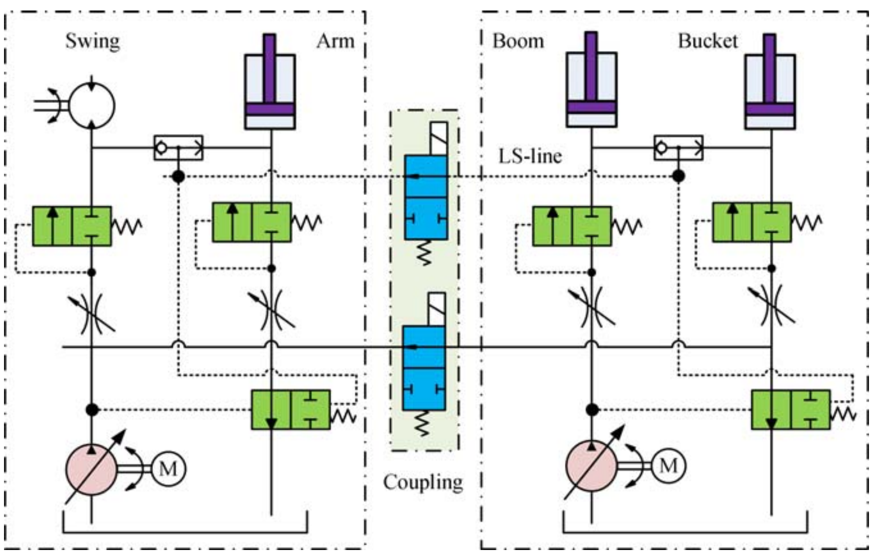

Fig. 6 Layout of the dual-circuit EFM system [31]

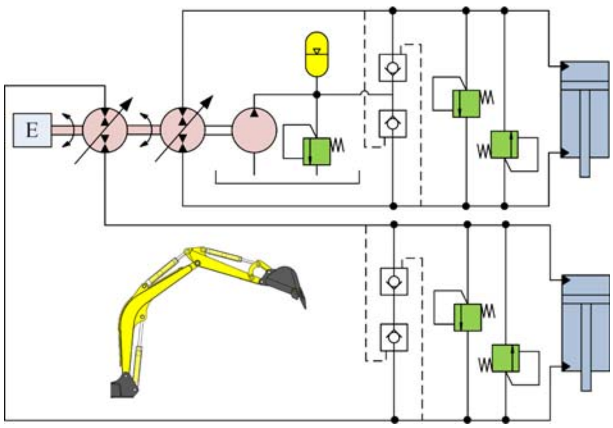

Fig. 7 Typical layout of the displacement controlled system

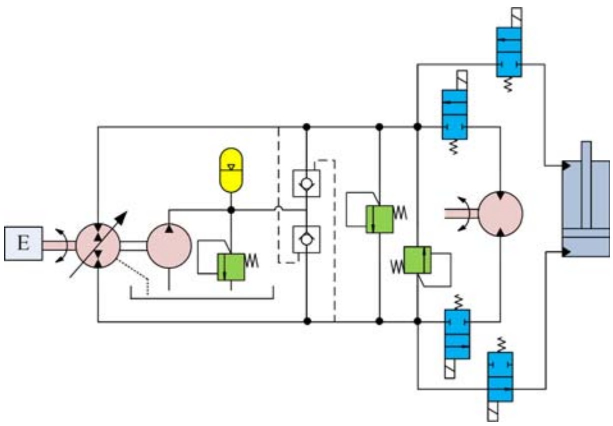

Fig. 8 Displacement controlled system with pump switching

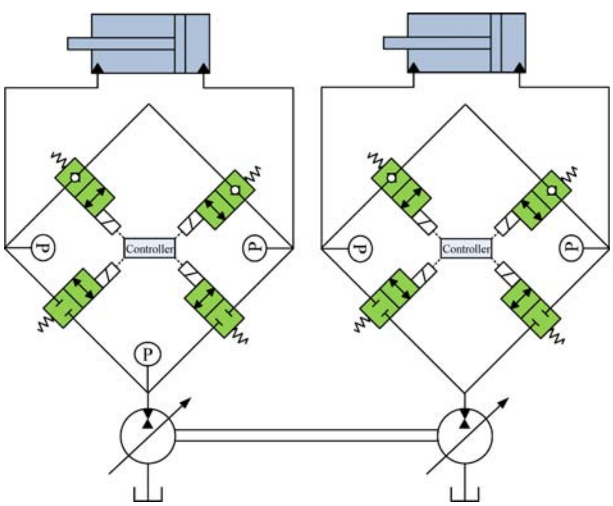

Fig. 9 Circuit diagram of the open-loop displacement controlled system

such, actual applications in the commercial market may take many more years before they happen [5].

3.3 Hybrid control

Hybrid control mainly aims to achieve energy recovery that can be then be reused in other conditions. Energy recovery technology can be classified into two types: Potential energy recovery (e.g., descending operation of the excavator boom) and kinetic energy recovery (e.g., slew motion of the excavator). The basic hybrid control methods are introduced below and summarized in Fig. 10.

Similar to the capacitor in electric circuits, the hydraulic accumulator (Fig. 10(m)) is a feasible energy recovery unit. The advantages of the hydraulic accumulator include the seamless interface and storage density in hydraulic systems [42]. Another solution is electronic energy recovery (Fig. 10(n)), in which the hydraulic motor-generator is installed in the return oil line [43–45]. When the boom is lowered, the gravitational potential energy is converted into an electrical form. Instead of being dissipated in the throttle valve and translated into heat, the recovered energy is stored in the electric storage unit (e.g., super capacitor, battery) and reused under subsequent load conditions. The boom velocity can be adjusted by controlling the rotational speed of the generator or the displacement of the hydraulic motor (if the variable displacement motor is introduced).

Moreover, the traditional pressure compensator can be replaced by an electric pressure compensator to reduce energy loss of load discrepancy [46]. The electric pressure compensator consists of a hydraulic motor, an electric generator, and a close-loop controller to adapt the electromagnetic torque of the generator to the load (Fig. 10(h)).

3.4 Comprehensive view of the energy-saving principles

Figure 10 provides a comprehensive view of the existing energy-saving principles and circuits to reduce the energy consumption of the HMLS system. The energy-saving methods can be achieved from several aspects listed below.

1) Reduction of throttling loss: This is achieved through the individual metering control (Fig. 10(a)), the digital hydraulic control (Fig. 10(b)), or the displacement controlled system (Fig. 10(c)).

2) Reduction of pressure margin: This is achieved with the ELS control (Fig. 10(d)), the virtual bleed off (VBO) control (Fig. 10(e)), or the EFM control (Fig. 10(f)).

3) Reduction of load discrepancy: This is obtained by using the hydraulic transformer (Fig. 10(g)), the electric pressure compensator (Fig. 10(h)), or the multi-chamber cylinder (Fig. 10(i)).

4) Energy regeneration: Here, the pressurized oil is used to drive the cylinder itself (Fig. 10(j)), drive the pump for other actuators (Fig. 10(k)), or directly drive the other cylinder (Fig. 10(l)) [47].

5) Energy recuperation: Here, the energy is recovered and reused in later load conditions. Then, excessive energy

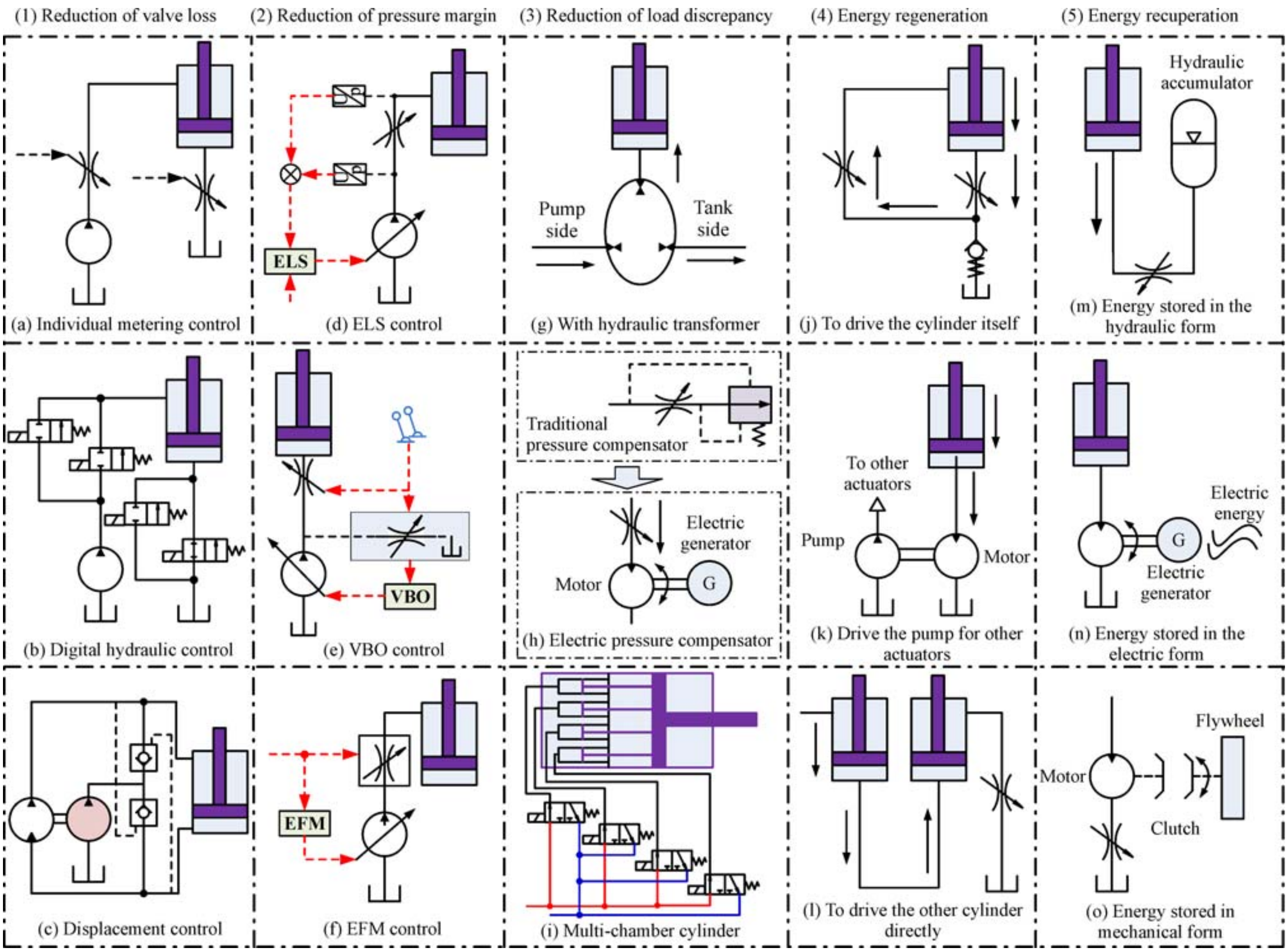

Fig. 10 Comprehensive view of the energy-saving principles and circuits. (a) Individual metering control; (b) digital hydraulic control; (c) displacement control; (d) ELS control; (e) VBO control; (f) EFM control; (g) with hydraulic transformer; (h) electric pressure compensator; (i) multi-chamber cylinder; (j) to drive the cylinder itself; (k) drive the pump for other actuators; (l) to drive the other cylinder directly; (m) energy stored in the hydraulic form; (n) energy stored in the electric form; (o) energy stored in mechanical form

could be directly stored in the hydraulic accumulators (Fig. 10(m)), in the electric form (Fig. 10(n)), or in the mechanical form by the flywheel (Fig. 10(o)) [48].

4 Motion control with dynamic improvement

Compared with energy efficiency, dynamic behavior is also crucial or may even be more important than the former, given that the latter determines whether a working task could be completed successfully. The electrohydraulic control concept offers a solution not only to deal with the dynamic issue in traditional HMLS systems but also to overcome the difficulties arising from the energy-saving systems mentioned in Section 3. Three main aspects of the dynamic behavior (i.e., response improvement, the oscillation reduction, and the smooth switching of electrohydraulic systems) are discussed below.

4.1 Response improvement

For the current HMLS system layout, the valve opening and the pump displacement are controlled by hydraulic-operated joysticks or pedals. The control valve initially receives hydraulic signals through the hydraulic pipes; then, the pump displacement is regulated by the load sensing circuit. However, delivering hydraulic signals and regulating the pump displacement prolong the process and consequently delay the movements of hydraulic actuators. The following two types of solutions have been proposed to reduce the response time: Development of high-response components and improvement of system dynamic through advanced control strategies.

The valve response time can be reduced using fast response electromechanical drives, such as high-speed on/off solenoids, magnetorheological fluids, piezoelectric actuators [49]. The step response time can be reduced to less than 0.3 ms through fast response drives [50].

However, the valve flow capacity is reduced as the response time is shortened. A general solution for this issue is using the parallel connected implementation of the high-speed on/off valves to replace the traditional proportional valve, as shown in Fig. 11 [51]. The method can be considered a general solution by replacing the low response/high flow component through the parallel high response/low flow digital components.

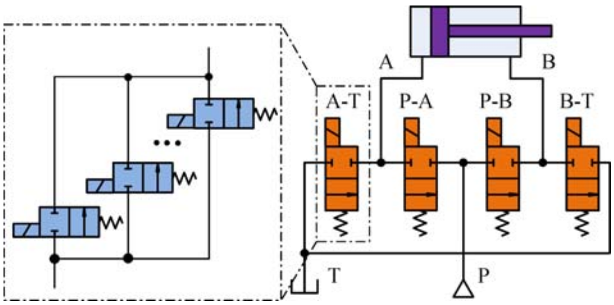

Fig. 11 Parallel high-speed on/off valves for dynamic improvement

Generally, the system dynamic is significantly lower than the valve dynamic while being nearly consistent with the pump dynamic. Thus, the improvement of pump dynamic is effective in reducing the response time of the mobile machineries. Manring and Mehta [52] analyzed the axial piston pump bandwidth and achieved a high response by reducing the swept volume and increasing the flow capacity of the control valve. Grabbel and Ivantysynova [53] proposed a second-order regulating controller to reduce the response time of the pump by 50% or more, and demonstrated that the displacement controlled system of high response can be established.

Second, advanced control strategies and circuits can be adopted to improve the response performance. As mentioned above, the EFM control concept is a promising alternative to the HMLS system, given that the load sensing control with slow response is replaced by the feedforward control loop [54]. As illustrated in Fig. 12, the test on a 2-ton hydraulic excavator indicated that the response time of the boom movement can be reduced by nearly 0.5 s [28], and the pressure building-up process can also be shortened. The multiple-input and multiple-output (MIMO) control strategies of the IMC systems have been proposed to improve the dynamic performance and ensure the system damping [55,56].

4.2 Oscillation reduction

Given that hydraulic systems commonly suffer from low damping, oscillation tendency can also lead to the deterioration of control performance. Excessive oscillations cause safety hazards that negatively affect machine productivity and controllability. Oscillations can affect human health and reduce the comfort level when transmitted to the operator. Unfortunately, high efficiency and less oscillation are usually on the opposite sides. Therefore, additional oscillations are generated when energy-saving methods are introduced. Axin et al. [57,58] revealed that maximizing the valve opening contributes to reduced throttling losses; however, such process simultaneously leads to lower damping (Fig. 13). They also established the design rules of the meter-out orifice for high damping, but the system damping can only be optimized under some specific load conditions. The tradeoff between good damping and high energy efficiency is also a significant challenge in hybrid control systems, considering that the dynamic behavior of the energy recovery unit (e.g., the hydraulic motor and the generator) is usually incompatible with the dynamic behavior of the hydraulic system. Thus, the load motion is more oscillatory despite the reduced energy consumption.

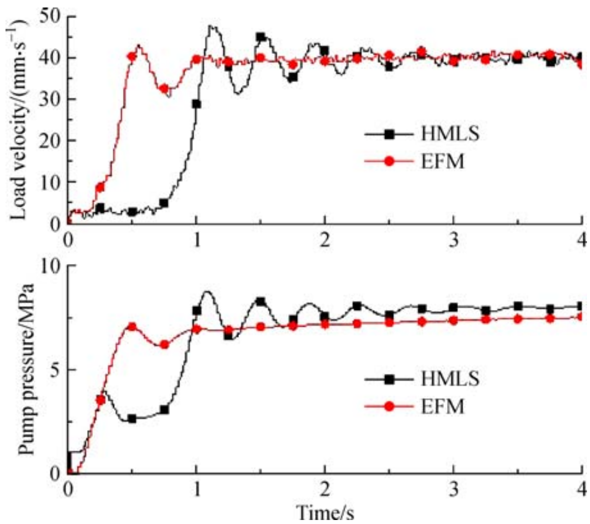

Fig. 12 Response improvement of the boom movement based on the EFM concept [27]

Two types of damping methods have been proposed in the literature, namely, pure hydraulic and electrohydraulic methods. The pure hydraulic method uses orifices or hydraulic accumulators, but the dynamic behavior is only optimized under one operating point without adaptation [59]. Meanwhile, the electrohydraulic method initially senses and subsequently reduces the oscillation by controlling the electrohydraulic valve or pump. Different feedback signals, such as load force, cylinder velocity, structure acceleration, and chamber pressure, are utilized to represent oscillations of mobile machines. Compared with other feedback signals, the pressure feedback has found other applications due to the higher reliability and lower cost of pressure sensors.

As shown in Fig. 14, dynamic pressure feedback (DPF) is an effective method as it compensates the valve or pump through pressure variation [60]. The difficulty of using

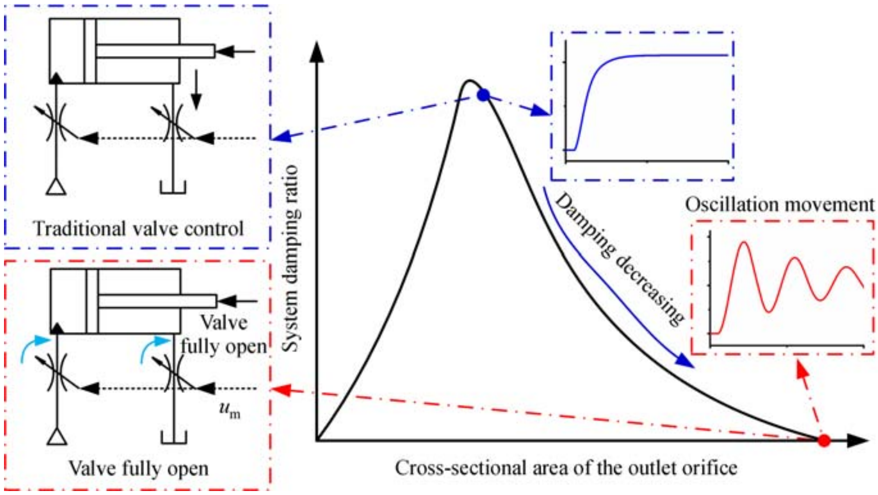

Fig. 13 Additional oscillations when the valve is fully open [52]

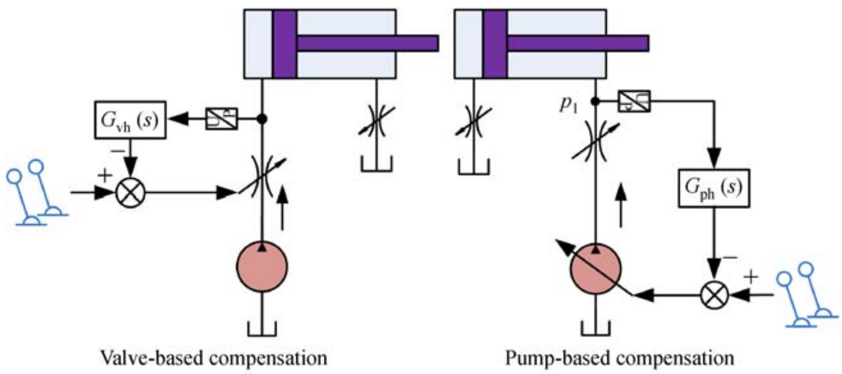

Fig. 14 Dynamic pressure feedback by valve-based or pump-based compensations

simple DPF methods, however, lies in selecting proper parameters under complex load conditions. The trial-and-error procedure has the disadvantages of low adaptability and a tedious tuning process. To achieve the tradeoff between damping and bandwidth, linear analysis tools have been adopted in mathematical models, such as Root locus [61], Bode graph [62], and linear-quadratic regulator (LQR) method [63]. The input shaping concept is also a promising technology, but the main challenges of this concept include identifying the system model and generating the proper control input [64,65]. Moreover, optimized damping is only obtained under a specified operating point.

Parameter auto-tuning methods have also been proposed to obtain the optimized dynamic under different load conditions, such as model predictive control [66] and extremum seeking [67]. Prior knowledge on the machine is unnecessary, but identifying the system states is a complicated task due to the highly frequent and abrupt load variations. Ding et al. [68] designed a hybrid control method combining DPF and active damping control. The control parameters are tuned online by a guaranteed dominant pole placement, after which optimal damping is accurately obtained under considerable operating conditions. Cheng et al. [69] proposed a pump-based compensation method to reduce oscillations, in which a parameter-searching method based on stability analysis and particle swarm optimization is designed to determine the optimized control parameters. In contrast to other pump-based compensators, both the pump dynamic and load variation are synthesized in the mathematical model with higher adaptability.

The oscillations are also easily excited in the energy recovery process with hybrid control. However, the electric motor introduces negative damping due to electromagnetic characteristics between the rotor and the stator; in addition, the system stiffness and robustness are adversely affected. To solve this problem, Jin et al. [70] presented a sliding mode control method to suppress the swing vibration. The proportional-integral-derivative (PID) control and the fuzzy sliding mode control have been chosen in a past study to weaken torsional vibration by controlling the motor speed and torque [71]. Moreover, system accuracy is reduced because of the leakage in the hydraulic motor.

Wang et al. [72] presented a composite control strategy to improve robustness and accuracy, including leakage compensation and load torque observation to increase speed stiffness.

4.3 Smooth switching

Except for unexpected vibrations, the mode switching problem arises when energy-saving circuits are applied in mobile machineries. The electronic control allows for extra flexibility, thereby enabling the construction of different control circuits through the mode switching of valves, pumps, or controllers. As mentioned in Section 3.1, the IMC system can switch between the PE and LSRR modes, possibly improving energy efficiency. However, the system instability or unsmooth movement could be potentially generated when switching between different control modes (Fig. 15). These discontinuities of the control signal can lead to the fluttering of the valve spool or the pump displacement, resulting in velocity oscillations and pressure peaks [73].

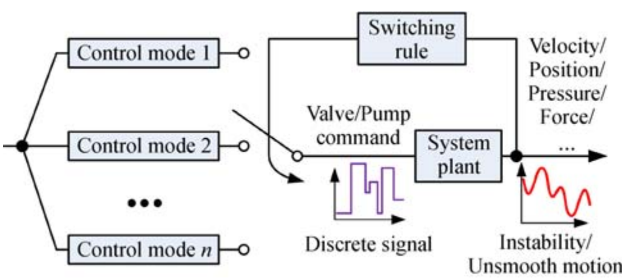

Fig. 15 Instability/unsmooth motion of the switched hydraulic system

An electrohydraulic system with mode switching can be considered as a switched dynamic system, whose dynamic behavior can be described by a finite number of dynamic subsystems with a set of rules [74]. The subsystems are usually described by a collection of indexed differential equations. The overall system can be described as

$$\dot{x}(t) \in f_\sigma[x(t),u(t)],\ \sigma \in A = \{1,2,...,N\}, \tag{2}$$

where the states $x(t) \in \mathbb{R}^n$, $u(t) \in \mathbb{R}^k$, and f_σ are a group of continuously differentiable functions parameterized as σ, which $\in A$. The finite set A is an index set and states for the collection of discrete modes. One main feature of the switched system is that the system stability depends not only on the stability of each subsystem but also on the switching rule. Accordingly, the switching condition should be optimized to ensure global stability and achieve smooth switching.

Many specific stabilization theories for switched control systems, such as optimal control, multiple Lyapunov function (MLF), dwell-time switch, have been introduced into electrohydraulic systems. Shenouda and Book [75] determined the optimal switching time through optimal control in terms of a cost function. Xu et al. [76] presented a hybrid control scheme based on the pressure margin and the candidate MLF method by utilizing a nonlinear switching rule to ensure the displacement/pressure switched system. Using a common Lyapunov function, Kemmetmüller et al. [77] proposed a nonlinear two degrees-of-freedom (DOFs) control strategy to deal with the nonlinear switched control issue of variable displacement of axial piston pumps.

Another general solution is to use the dwell-time switching method to avoid frequent switching. However, the system must continuously stay at a control mode for a specifically long time so that the transient instability can be avoided. Heybroek et al. [78] employed this approach to the mode switching with an open-loop circuit; however, the author did not consider the optimization of dwelling time. Meanwhile, Ding et al. [73] designed a boundary value solution of dwelling time to solve the unstable switch problem in individual systems; moreover, they used the bidirectional latent tracking method to eliminate control discontinuity. The proper dwelling time can be precisely obtained based on MLF theory, thus ensuring both stability and quick response. Furthermore, the nonlinear MIMO closed-loop control [79] and supervisory control [80] have been proven to be feasible in achieving smooth switching of the electrohydraulic switched systems.

5 Motion control with operability improvement

As mentioned in Section 1, various and complex working tasks are involved in mobile machineries; thus, human operation cannot be predictably replaced by full robotic autonomy. An attractive and promising research is developing other effective operation modes and human-machine interfaces. Many related works have proven via simulation and actual tests that advanced operation methods and interfaces are capable of improving the efficiency, safety, training time during the operation work as well as alleviating mental fatigue and stress for the operators. Moreover, quick accomplishment of a task means less fuel consumption; thus, determining other effective operation methods from the view of energy-saving is also significant.

5.1 Improvement of the operation mode

In traditional mobile machineries, one joystick is used to control 2 DOFs (Fig. 1). The joystick meets the velocity demands of hydraulic actuators to rotate the joint, which can be referred to as rate control in operation areas. For the excavator with a 3-DOF serial arm, the operator should initially decouple the mechanical linkage and then provide proper commands to complete the task by experience.

Understanding the inverse kinematics of the hydraulic manipulator requires a long training time; moreover, the process causes mental fatigue and erroneous tendency for operators. One more intuitive operation mode is the coordinated rate control (CRC), as illustrated in Fig. 16 [81]. Here, two electronic joysticks with potentiometers are used to control the end-effector position: One is for the height and bucket motions; the other is for the radial distance and swing motions. Therefore, the decoupling task is completed by the controller, and the operators must only intuitively control the motion of the end-effector. The test results have proven that the intuitive coordinated position control (CPC) interface facilitates faster and more precise operation than traditional control schemes. Based on the CPC concept, other similar operation modes with different input devices are available for other mobile machineries [82–85].

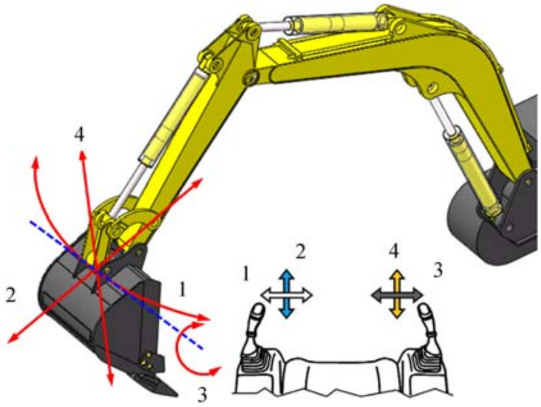

Fig. 16 Typical operation mode of the CRC concept [3]

Another manual mode named, position control, suggests that the joystick provides the position commands of the actuators instead of velocity commands. The human operator performance using these two modes have been evaluated and compared under different joystick gain, joystick type, and manipulator size [86]. The test results validate the assumption that position control is superior to the ideal rate control, except for the large manipulation with low dynamic (natural frequency lower than 3 Hz) [86]. Actually, most mobile machines are categorized into the exception range, and research on position control is not hampered due to its attractive advantages, including effective and intuitive operation. Similar to the CRC concept, the CPC and the joint position control concepts have also been presented to achieve effective control (Figs. 17(a) and 17(b), respectively).

The input devices used to generate position control commands can be divided into two types: Kinematically similar joysticks [87–92] and kinematically dissimilar joysticks [93,94]. The kinematically similar joysticks intuitively relate to the operator’s command and achieve

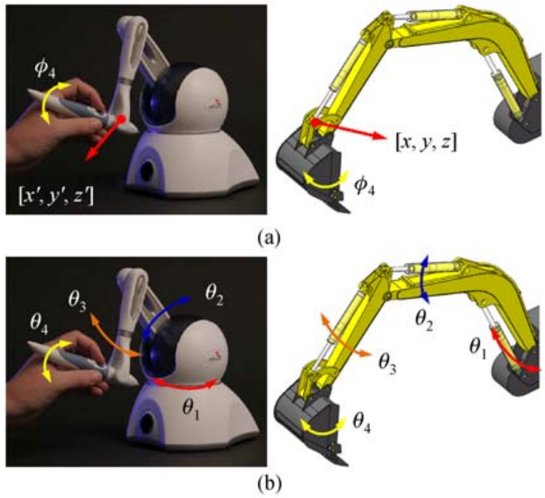

Fig. 17 Position control interface using SensAble Omni devices [89]. (a) Coordinated position control; (b) joint position control

easier control. The geometric similarity has prompted the use of common haptic input devices to generate position commands, such as Phantom Premium [87,88] and SensAble Omni [89–92]. Therefore, the slave excavator arm must only mimic the movement of the master input device with position scaling, which is generally referred to as master-slave control. Then, the CPC concept actually allows for more effective control than the CRC, resulting in short training time and effective operation for novice operators. Kim et al. [95] used a human arm as the input device, as shown in Fig. 18. As can be seen, three inclinometers are attached to the operator's arm to detect his movements; then, the commands are transmitted via Bluetooth. The operation method is evidently simpler, more cost effective, and lighter compared with those using typical haptic devices. Moreover, the virtual reality technology can also be utilized to realistically simulate the motion of the mobile machineries and assist the operator to ensure intuitive operability [96].

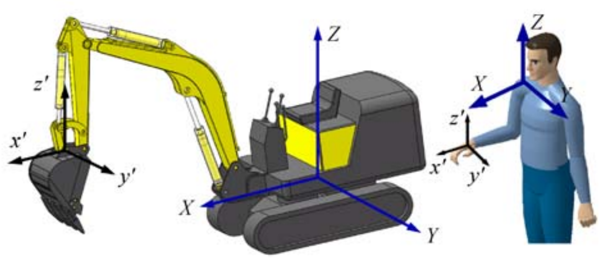

Fig. 18 Coordinate system of the excavator and the operator using a human arm [95]

The test results on actual machines indicate that the CPC methods are characterized by safety, comfort, precision, and effectiveness. However, several problems also emerged and are subsequently discussed in the CPC control methods, as listed below.

1) Workspace limitation: The mechanical arm of mobile machineries mimics the motion of master input devices with position scaling. A position command that the slave arm cannot reach can be generated by the operator if the workspace of the master side fails to match that of the slave side. Special input devices with the kinematic similarity [97–99] can be developed to overcome this difficulty.

2) Accuracy limitation: Control accuracy can be reduced due to position scaling, given that a tiny motion is scaled as an apparent movement of the mobile machineries. The combination of CPC and CRC control is a solution in selecting the control mode based on the actual requirements [3]. Another problem for the application of CPC is the oscillation or low control accuracy caused by the biodynamic feedthrough phenomenon. The biodynamic feedthrough occurs by the hand motion induced from the vibration of the entire machine. This problem can be addressed using the active compensation methods [100,101] to measure the motion condition of the machine.

5.2 Haptic enhancement

In open-center systems, the velocity of the hydraulic actuator given by the operator is related to the actual load conditions. Therefore, the operator can obtain the environment information via the load velocity. However, this feedback information is lost in the HMLS systems due to the decoupling between the load and the velocity. Thus, the operators are unable to operate properly depending on the load condition. The advanced operation methods offer a solution called "haptic control." The word "haptic" is related to the sense of touch or something that is tactile. The force feedback function can be integrated into the haptic input devices to give the operator's senses an acceptable version of the environment information. Therefore, haptic control has a significant potential to increase operation efficiency because it offers an intuitive sense of the environment while improving task efficiency. Haptic control also has three main advantages in facilitating operation, as listed below.

1) Reflection of load force: Reflection of load force assists the operator in gathering load information. The load force is initially measured and then simulated proportionally on the haptic devices. Considering the low reliability and high cost of force sensors, the use of a pressure sensor helps in obtaining the reaction force of the environment [95]. The high-frequency force generated by oscillation or impact can be filtered through a lowpass filter to avoid buzzing in the operator's hand [102,103].

2) Reflection of position error: Position error between the master and slave sides can be transmitted as feedback force of the haptic device. Considering that the haptic device can move faster than the slave arm, knowing the actual positon of the slave arm would be difficult for the operator. Then, this function is proposed to overcome the response difference between the master and slave sides.

3) Workspace virtual wall: A workspace virtual wall is an effective method that can be used to address the workspace mismatch of the haptic device and the slave arm [87]. The haptic device could generate a visible force once the desired position is outside the scaled workspace. Accordingly, the operator is reminded to change the position commands. Moreover, this device can be used to guide the end effector toward a specific trajectory, such as the sloping and levelling task of excavators [97].

6 Challenges and trends

The development of electrohydraulic components and systems offer new possibilities to achieve further improvements on energy efficiency and operability. The development tendency must be energy efficient with good controllability; however, only acceptable cost increase in the overall machine is accepted in the commercial market. Although both manufacturers and consumers have shown increasing confidence in the reliability of electrohydraulic systems, electrohydraulic control may require further research before it becomes adaptive and robust under the terrible working environment of mobile machineries.

In the last decades, energy-saving demand has been considered the most important motivation to develop new electrohydraulic systems. Several advanced control circuits have been proposed, and their energy-saving potential has been proven through simulations and actual tests on mobile machineries. However, none of these energy-efficient circuits have found impressive applications due to increasing cost, poor controllability, or low reliability. Yet, one encouraging application is hybrid control (e.g., hybrid excavators and hybrid cranes); however, this application is still unsatisfactory due to increasing cost and high maintenance. An acceptable tradeoff between energy saving and other demands should be made before applying advanced control circuits. For example, pump switching control [38] is a potential solution due to the high cost of the displacement controlled system, but the flow management and switching method should be further developed to achieve robust, acceptable cost, and with good controllability. Table 1 [104,105] presents the main challenges of the energy-saving circuits, which require further attention in the near future. Developing other energy-saving principles is necessary to cut emissions of mobile machineries.

Specific challenges to translate advanced operation methods to practical implementation should be further addressed, including operator fatigue and comfort, potential for unwanted machine motion, loss of accuracy due to position scaling, and a lack of knowledge on the commanded position due to the slow dynamics of the

Table 1 Main challenges of the energy-saving control circuits

No.	Energy-saving circuits	Main challenges and trends
1	Individual metering control system	➢ Smooth switching between different control modes ➢ Combination with advanced pump control technology (e.g., EFM) ➢ Better maintainability and redundancy strategy
2	Digital control system	➢ System pressure oscillations and low damping properties ➢ Digital components with low noise and high reliability ➢ integrated automation in production systems [104]
3	Displacement controlled system	➢ Energy management and smooth switching methods with less pump ➢ Electrohydraulic pumps with low cost and high dynamic
4	Hybrid control system	➢ Compact energy recovery unit with high dynamic [105] ➢ Energy storage unit with high power density and energy density ➢ Low cost, high reliability, and easy maintainability

excavator arm. Moreover, time delay and lost information lost in the operation process are also considered potential instabilities that must be further studied in the future. Finally, the ergonomics and robustness of haptic input devices should be improved before actual application.

7 Conclusions

The motion control employed in mobile machineries aim to achieve high energy efficiency, low environmental impact, good dynamic performance, and effective operation. This paper surveys recent methods in achieving motion control of multi-actuator electrohydraulic systems. Specifically, the survey is focused on energy efficiency, dynamic performance, and system operability. From the latest related research, many promising circuits have demonstrated their energy efficiency while also revealing problems, such as adverse effects on the dynamic performance, increasing costs, or poor reliability. The advanced CRC or CPC methods are capable of achieving safety, comfort, precision, and effective operation. However, widespread application may not yet happen because of the disadvantages of high cost and low reliability. Moreover, other operation tests are expected to prove the increase in productivity with the haptic devices.

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